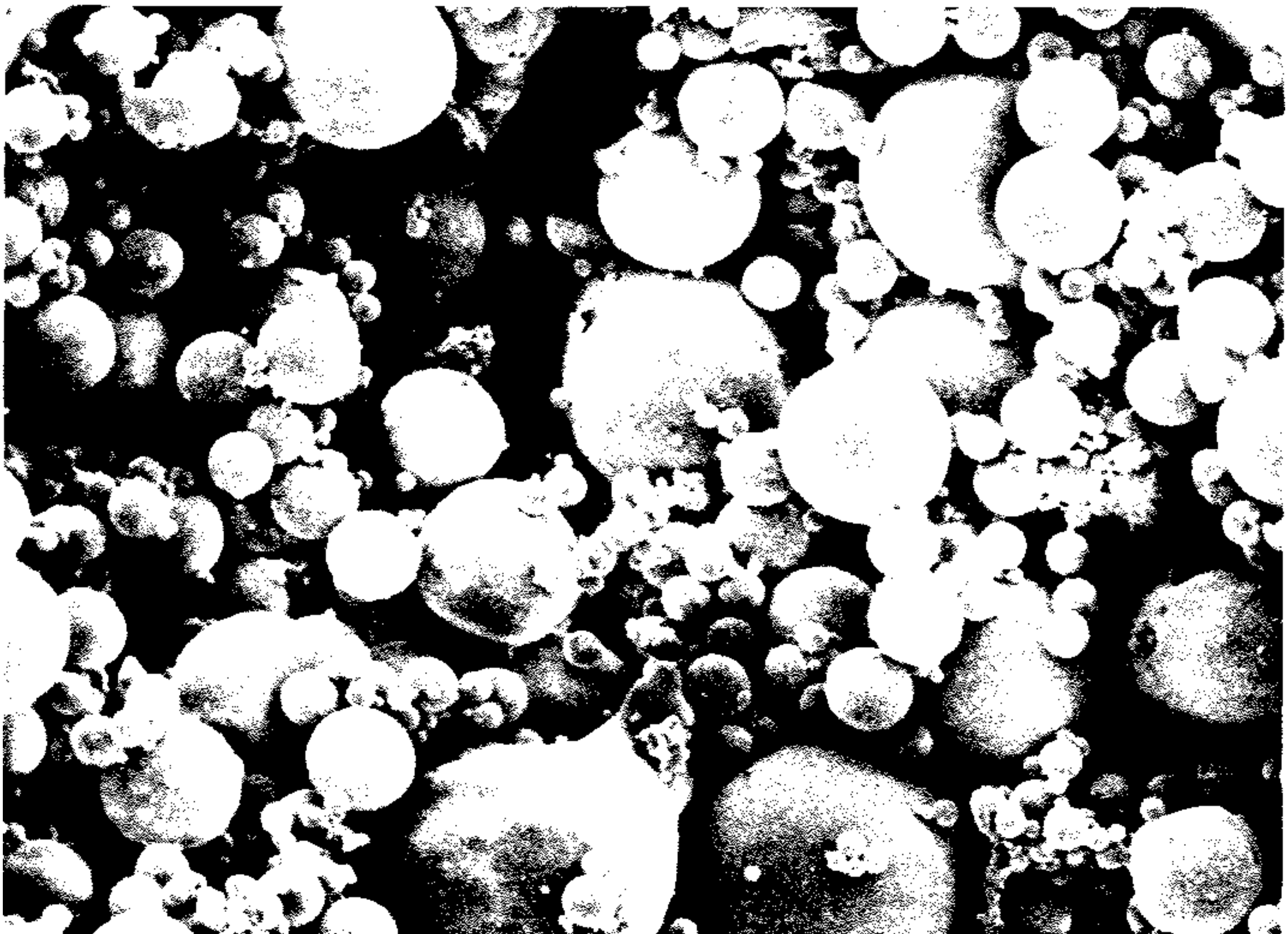
Particulates: Matter of Priority

ELECTRIC POWER RESEARCH INSTITUTE
EPRI JOURNAL

OCTOBER
1978



EPRI JOURNAL is published by the
Electric Power Research Institute.

EPRI was founded in 1972 by the nation's electric utilities to develop and manage a technology program for improving electric power production, distribution, and utilization.

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

Cover: The biggest of these glassy gray fly ash particles measures barely 10 micrometers across—only 40 millionths of an inch. Spherical shape reveals their origin: condensed and congealed aluminosilicates vaporized at the coal burner. Faint beige tones, authentic but invisible to the scanning electron microscope, have been added to aid visualization in this 2800X enlargement. *Micrograph courtesy G. L. Fisher, M. Brummer, and B. A. Prentice, Radiobiology Laboratory, University of California at Davis.*

EPRI JOURNAL

Volume 3, Number 8 October 1978

Air Pollution: A Pragmatic View

In the past, high levels of air pollution during acute episodes over industrial areas caused premature deaths among the general population. However, commonsense control of fuel burning and simple engineering have ensured that such circumstances just don't occur any longer. Today, the important issues are whether ambient air conditions—at levels near those of present standards—are injurious to health and whether the costs of further control are in the best interests of society. Our knowledge of health effects is evolving rapidly, and we now suspect that some of our expensive control efforts may have been misguided.

To properly deal with air pollution, we need to know just what substances are responsible for health effects. During the "killer" episodes in London, Donora, and elsewhere, sulfur dioxide (SO_2) and smoke (particulates) were obviously present and easily measured. As a result, SO_2 and particulates have been regarded since then as the prime culprits. However, we now know that SO_2 itself is relatively innocuous, and there is considerable question as to whether sulfate (SO_4)—the secondary particulate formed from SO_2—is responsible for adverse health effects. The attention given to particulates is justified, but unfortunately there has not been sufficient emphasis on the removal of fine particles, which are the ones most likely to enter the lung and least likely to be controlled by electrostatic precipitation. Thus, the most important question is whether the large-scale and expensive processes now advocated for particulates, and especially SO_2 removal, do indeed remove those components of the flue gas that actually cause adverse health effects. In light of present knowledge, the most effective approach would probably be to minimize the emission of fine particles and perhaps to reduce the heavy metals that catalyze SO_2 oxidation and are adsorbed on fine particles.

We also need to know about the health effects at existing levels of air pollutants. In recent years, data from epidemiological studies have been used to estimate the numbers of premature deaths and increased cases of respiratory disease that could be associated with existing levels of air pollutants, especially sulfates. However, detailed examination of the data from these studies has convinced us that there is no scientific basis for making a judgment that such effects do or do not occur at levels near the existing standards. This is the usual dilemma whenever large populations are exposed to low levels of pollutants that are known to cause harmful effects at high levels. There are two aspects worthy of pondering. In contrast to carcinogenic effects, the respiratory effects from fossil fuel combustion are expected to have a threshold; that is, there may be a level below which no effects would occur. If the risks are calculated, taking the above-mentioned studies at face value, they fall lower than the risks traditionally accepted as a trade-off for societal benefit. We suspect that such risks are also lower than those that might result from abrupt shortages of electricity or from economic constraints produced by electricity shortages before adequate socioeconomic adaptations have occurred. This, of course, does not mean that any easily avoidable risk should be accepted.

So far these comments have been concerned with health effects. It may turn out that effects on visibility, ecosystems, or materials will be more important. For the short term, the demonstrated effects on visibility reduction (related to particulates, with sulfur playing an important role) have a large impact on national perceptions and represent a driving force for cleanup. Effects of increased acidity in rain on plants, fish, and materials may gain prominence, but there is time to study these processes before important damage occurs. The most serious ultimate effect could arise from climatic changes because of increased CO_2 levels in the atmosphere; but again, even though this is a very complex problem, there is ample time for necessary research, which should be done on a global scale.

Where does all this leave us? It is an article of faith that the gross manifestations of air pollution that aggravate anyone who glances skyward will be reduced, and further, that real adverse effects on health must be avoided. But there can be no guarantee that zero health effects from air pollution can be achieved without simultaneously creating overriding adverse health and socioeconomic impacts. We must work toward a fair balance by trial and error, by iteration, by the application of reason.

Realistically, there is now so much inertia in the minds of decision makers and so great a momentum in ongoing, large-scale activities that there is little hope of very much change in the near future in accordance with evolving knowledge. The regulations will become more and more stringent and the control technology more and more sophisticated, elegant, expensive, and perhaps not even directed at the most important culprits. Despite this, we must continue to increase our biological understanding and stress the need for accountability—every regulatory and technology decision should be based on the criterion of whether it produces more benefit than harm to society and individuals.

Cyril Comar, Director
Environmental Assessment Department
Energy Analysis and Environment Division

Authors and Articles

Soot. Fly ash. They were unsightly nuisances in the Pittsburgh air at the turn of the last century. They were also a symbol of coal-fired power, steel, jobs, goods, and thus the economic health of society.

Eighty years later, our view is much clearer. Soot and fly ash are far less evident in the atmosphere. More efficient combustion processes and a combination of mechanical and electrostatic collectors have taken care of most of the fly ash in power plant emissions. However, our quest for clean air is more than a matter of esthetics. The obvious flakes of soot may be gone, but there are other, invisible elements of pollution to be dealt with.

Society seeks to resolve the quality of ambient air through regulation. Electric utilities, as well as other industries, seek to resolve the quality of their own emissions through technology, with due regard for the impact on the ambient air.

Public representatives, businessmen, economists, utility operators, air pollution control technologists, chemists, doctors—all have a stake, and each seeks to do the right thing in his own way. The skills and perceptions of many such specialists are represented among EPRI program and project managers, the people who chart and manage R&D on particulate emissions from power plants.

Nearly a dozen EPRI staff members and a wealth of reports from their professional colleagues are the *Journal*'s resources for this month's focus on particulates.

The first group represents EPRI's Environmental Assessment Department, which appraises the pollution problem, defines specific causes, and identifies utility effluents that contribute to the problem.

The second group represents the Fossil Fuel Power Plants Department. Within that department, the Air and Water Quality Control programs are coming up with answers to meet today's regulations and tomorrow's needs.

■

Cyril Comar, director of the Environmental Assessment Department since 1975, has dealt with problems of airborne emissions for over 30 years. He is a professor emeritus of Cornell University, where he headed the Department of Physical Biology and was director of the Cornell Energy Project.

Ralph Perhac led a National Science Foundation program on the environmental effects of energy before coming to EPRI in 1976 as program manager, Physical Factors. He also researched trace contaminants as a consultant to the Environmental Science Division, Oak Ridge National Laboratory.

James McCarroll, program manager, Health Effects, is nationally recognized for his work in air pollution and respiratory diseases. From 1961 to 1966 he directed the Cornell Air Pollution and Illness Study, the largest epidemiological study on the health effects of air pollution at the time. McCarroll also served as professor and chairman, Department of Environmental Health, School of Public Health and Community Medicine, University of Washington.

Leonard Sagan was a consultant to EPRI for four years before joining the staff in February as program manager, Biomedical Studies. Sagan spent 10 years as associate director of the Department of Environmental Medicine, Palo Alto Medical Clinic, Palo Alto, California.

Anthony Colucci joined EPRI in April as project manager, Health Effects. His previous position was vice president, Health Programs, Flow Resources Corp. The programs explored the adverse effects of particulates and trace elements on human health. Earlier, Colucci worked with EPA's National Environmental Research Center as chief of two research branches.

■

Kurt Yeager, director of the Fossil Fuel Power Plants Department, joined EPRI in 1974. Before that, he was director of energy R&D planning for EPA's Office of Research. There, Yeager was responsible for the planning and integration of all EPA energy-related R&D and its translation into agency policy.

Stephen Baruch, technical manager, Environmental Affairs, came to EPRI in 1977 from Edison Electric Institute's New York office, where he was manager of environmental projects. Baruch advised EEI's 198 member companies on evolving air pollution control issues and coordinated EEI's Sulfate Task Force.

Donald Teixeira, program manager, Air Quality Control, was an engineer for Southern California Edison Co. (SCE) before he came to EPRI in 1973. He was responsible for SCE's programs to reduce fossil-fueled power plant emissions.

Robert Carr, project manager, Particulates and Combustion, joined EPRI in 1974 after working as a test engineer for KVB Inc. While there, he was a consultant to SCE on the reduction of nitrogen oxides and particulates from boilers.

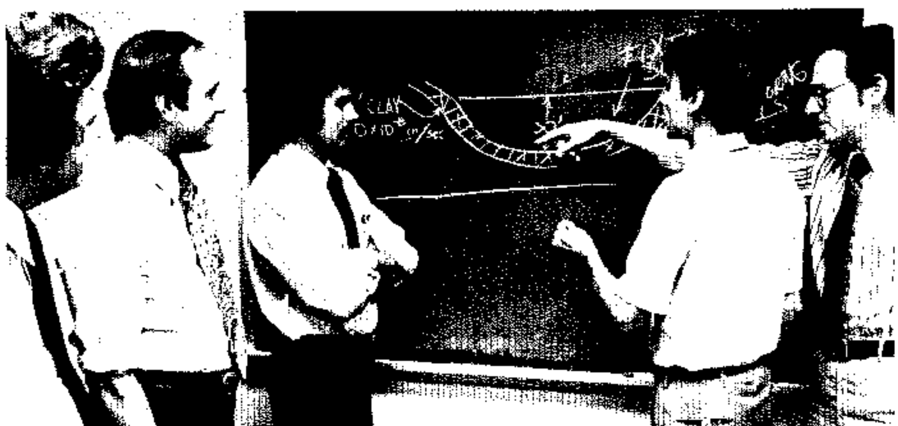
John Maulbetsch, program manager, Water Quality Control and Heat Rejection, arrived at EPRI in 1975 after eight years as director of the Energy Technology Center at Dynatech R/D Co., where he identified and explored new research areas in mechanical and chemical engineering.

Dean Golden, project manager, Solids By-product Disposal, arrived at EPRI early this year after six years with SCE. There, in the Environmental Controls Engineering Section, Golden reviewed and drafted company responses to proposed environmental legislation. He was also responsible for obtaining waste water discharge permits.

■

Turning from particulates and environmental effects to more economical ways of generating electricity, this issue looks at ways to improve nuclear fuel reliability in an article by Adrian Roberts and Howard Ocken. Roberts, program manager, Core Materials, came to EPRI in 1974 after working as a metallurgist with Argonne National Laboratory. Ocken, nuclear fuels project engineer, is also a metallurgist. Before joining EPRI in 1974, he worked in the Netherlands at N. V. Philips and at Bettis Atomic Power Laboratory of Westinghouse Electric Corp.

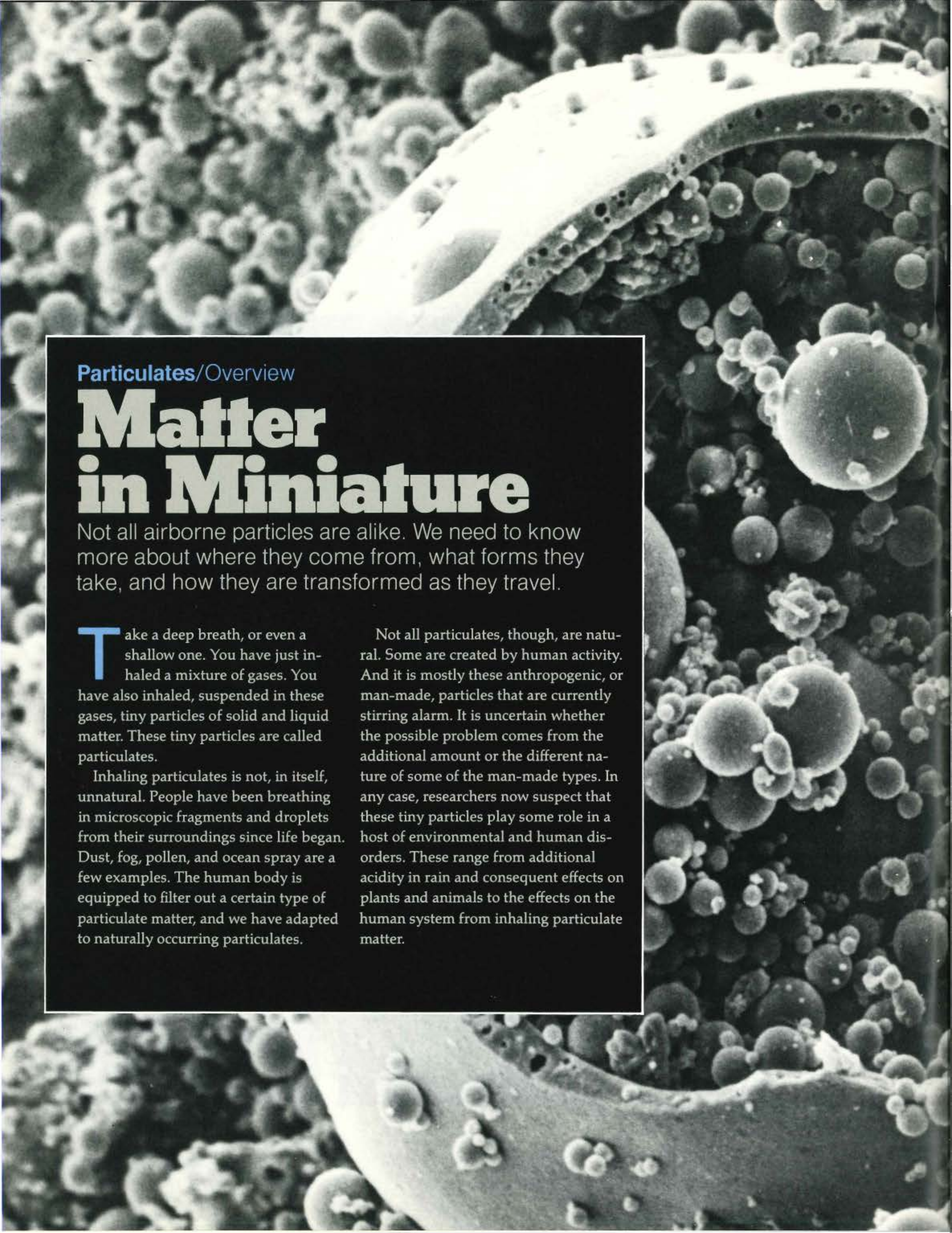
Sagan Comar Colucci Perhac McCarroll



Maulbetsch Yeager Carr Golden Baruch

Roberts

Ocken



Particulates/Overview

Matter in Miniature

Not all airborne particles are alike. We need to know more about where they come from, what forms they take, and how they are transformed as they travel.

Take a deep breath, or even a shallow one. You have just inhaled a mixture of gases. You have also inhaled, suspended in these gases, tiny particles of solid and liquid matter. These tiny particles are called particulates.

Inhaling particulates is not, in itself, unnatural. People have been breathing in microscopic fragments and droplets from their surroundings since life began. Dust, fog, pollen, and ocean spray are a few examples. The human body is equipped to filter out a certain type of particulate matter, and we have adapted to naturally occurring particulates.

Not all particulates, though, are natural. Some are created by human activity. And it is mostly these anthropogenic, or man-made, particles that are currently stirring alarm. It is uncertain whether the possible problem comes from the additional amount or the different nature of some of the man-made types. In any case, researchers now suspect that these tiny particles play some role in a host of environmental and human disorders. These range from additional acidity in rain and consequent effects on plants and animals to the effects on the human system from inhaling particulate matter.

Micrograph courtesy G. L. Fisher, M. Brummer, and B. A. Prentice, Radiobiology Laboratory, University of California at Davis

Whence the problem?

The problem of man-made particulate pollution dates back to the industrial revolution, when people first discovered they could drive machinery by using the energy released from burning wood or coal. Unfortunately, burning organic matter released not only heat energy but particles and gases as well. Over the years, industrialization grew on a steady diet of these fossil fuels, visibly increasing the levels of man-made pollutants in localities of fossil fuel use. By the turn of the century and even before, people with chest and lung disorders were being urged to leave the soot-blackened cities and seek refuge in the clean air of the countryside.

In contrast with 1900, the picture today is both better and worse. It is better because following World War II, many industries switched from using coal to using clean-burning fossil fuels, such as oil and natural gas, that release proportionately fewer visible by-products to the atmosphere. Moreover, industries recognized the need to control emissions through the development of electrostatic precipitators, giant bag filters, and other control devices.

On the debit side, though, basic socioeconomic trends signal a new need for concern. Industrialization and urbanization are still surging worldwide, which means that there will be more particulate-emitting sources than ever before—and more people, living as they do in urban/industrial areas, will be exposed to them. Areas untouched by these trends will become harder and harder to find.

Finally, the energy squeeze in the United States has forced some awkward trade-offs. The decision to phase out the use of oil and natural gas in favor of using domestic coal is already creating very substantial problems for industries, such as the electric utility industry, that must try to burn what is essentially a dirty fuel without further dirtying the atmosphere.

Factories and automobiles, like power plants, burn fossil fuels and so emit pollutants. Other types of burning, such as incineration, also add to the mass of man-made particulates in the air, as do crushing and grinding operations, such as those carried on in quarries and grain mills. That these emissions can, if uncontrolled, create health and environmental hazards has been established beyond serious dispute. But our certainty extends very little beyond this statement. The puzzle is how to deal with a threat that is still, after many years of worry and over a decade of hard research, so poorly defined.

Many questions remain. What are these tiny particles actually like, physically and chemically? How are they formed? How do they behave in the atmosphere? Which of them are really hazardous? At what pollutant levels are the natural defenses still able to cope? And beyond this safe level, how can the dangers of particulate pollution be controlled? Although most of our answers are still tentative, reviewing them can offer some perspective on the particulate control decisions that will have to be made—now and in the future, ready or not.

What are particulates like?

All that particulates have in common is that they are very small and can float, for brief or extended periods, in the air. Beyond these properties, the range of diversity is enormous.

Particulates, both natural and man-made, can range in size from about 0.005 to about 500 micrometers. (A micrometer is 1/1,000,000 of a meter.) At the upper end of that size range, they are clearly visible. Large pieces of pollen and flakes of soot fall into this end of the size range. At the other end are fine particles of submicrometer dimensions, visible only through a microscope.

Spanning an equally wide spectrum, the chemical properties of particulates range from highly active to chemically inert. The active particles are clearly capable of triggering chemical changes, both in the air and on those exposed surfaces where they happen to land. And even those that are chemically inert may act as carriers for active substances because particulates readily collect foreign matter on their exposed surfaces. This tendency to adsorb other substances can foreshadow serious health implications: a chemically inert particle inhaled into the human lung may, for example, carry a cloak of potentially harmful trace metals.

Riding in a mixture of oxygen, nitrogen, argon, carbon dioxide, and water vapor—the basic constituents of ordinary air—larger particulates behave like solid matter, regardless of whether they are solid or liquid. They react to the pull of gravity and often settle out on exposed surfaces.

Smaller, finer particulates behave more like a gas or a vapor. Because they are so lightweight, they settle very slowly, often remaining suspended in the air for days or even weeks. Further, they can change form by coagulating or by combining with other airborne matter to form more complex substances. And fine particulates provide many of the microscopic nuclei that serve as centers for atmospheric condensation processes.

The fact that airborne particulates can travel is obvious, but researchers have been surprised to discover just how far they can travel. Dust storms in the Sahara have been correlated with high atmospheric dust loadings in the Caribbean; glacial ice samples in Greenland have yielded lead particles, presumably from auto emissions in North America; and the Norwegians are concerned over industrial emissions that cross the North Sea from Great Britain and western Europe, while scientists on all sides of the North Sea hotly debate both the source and the effects of these pollutants. A case closer to home is the air pollution affecting residents of St. Louis, Missouri, when prevailing winds blow particulates across the Mississippi River from the heavy industrial concentrations of East St. Louis, Illinois. Cleaning up the air, then, can be almost impossible for one city—or even for one state or one nation—without cooperation from emitters at sometimes very distant points.

Particulates also absorb and scatter light. This is especially true of fine particles, whose diameters measure nearly the same as those of visible light waves. This light-scattering property, when multiplied by millions of particles, can produce the visual effect that we commonly describe by words such as *haze, smoke,* or *fog.* Combining the two last words, we coined the term *smog* in the 1940s to describe that peculiarly man-made murk that often clouds the air over our major cities.

Together with the air surrounding them, particulates form an aerosol—a system composed of solid and/or liquid particles suspended in a gaseous medium. Strictly speaking, the particles in a true aerosol are in perpetual suspension. In practice, however, it is common to speak of any such two-phase system as an aerosol, even if the suspension of particles is only temporary. By either definition, our atmosphere is an aerosol. It loses particles continuously, but there are always some remaining.

These are, very generally, the properties displayed by the tiny particles known as particulates. The next step is to explore their origins in somewhat greater depth, since the origin of any given particulate can be very important in determining how it will behave within the range of characteristics just outlined and how any problems it might pose may be mitigated.

Where do they come from?

In discussing origin, scientists usually draw a distinction between primary and secondary particulates.

A primary particulate is one produced at a specific point on the earth's surface —at a naturally eroding hillside, for example, or at an industrial smelter. The particle can be natural or man-made, coarse or fine, liquid or solid, from a stationary or a mobile source. The distinguishing feature is that it springs full grown from its source, whether that source is a hillside, a smelter, or the exhaust pipe of an automobile.

A secondary particulate, in contrast, is one created from the primary pollutant by a chemical reaction. We usually can't tell exactly where in the atmosphere the reaction will occur, nor do we know for sure what role catalysts play in the conversion. Sunlight, for example, clearly figures in some reactions, but others appear to take place in the dark.

What we do know is that some gases leaving the earth's surface are chemically transformed into solid or liquid particulates. For example, sulfur dioxide (SO_2) gas emitted by burning coal may be transformed into solid fragments of iron sulfate ($FeSO_4$) or tiny droplets of sulfuric acid (H_2SO_4). The distinguishing feature of a secondary particulate, whether its precursors are natural or man-made, is that it does not exist until this atmospheric transformation has taken place.

In theory, the designation primary or secondary implies nothing about the properties and behavior of the particle. In fact, however, certain correlations have emerged. Primary particles tend to be larger, on the average, than secondary ones. In addition, partly because our control technology has grown rather successful at catching the coarser particles in man-made emissions, most of the primary particles floating in the atmosphere are natural ones. The visible dust kernel might be viewed a typical particulate of primary origin.

In contrast, the secondary particulates formed in the atmosphere tend to be very fine, less than 2 micrometers in diameter. Further, their numbers have increased considerably because of human activity, and our efforts to control them have been blunted by confusion as to exactly where and how they are formed. Because they are small, they have longer residence times in the atmosphere than coarser particulates do, and they travel farther. There is also growing evidence that fine particles are potentially more hazardous since many are chemically active and are created with or carry along compounds of such elements as lead, manganese, cadmium, beryllium, thallium, chromium, arsenic, and nickel. These elements are known to be possible hazards to human health.

Particulates, then, are everywhere. They may be emitted near ground level or formed high in the atmosphere. Both man and nature contribute to their formation, and both may suffer from their effects. The next step is to explore those effects.

How can they harm us?

At low levels of concentration, particulates apparently have little or no effect on people. Sneezing, runny eyes, sore throat, and headache are the familiar effects of exposure to high levels of airborne particulates, whether they come from smog or from seasonal outbursts of pollen. The discomfort is very real. But what researchers are now looking for when they probe the health effects of particulates goes far beyond discomfort. They want to find out whether air pollution levels now existing or proscribed by regulation can cause disease or premature death.

Just one breath can scoop thousands of tiny particles out of the atmosphere and into the human respiratory tract. Those particles that are too fine to be caught by the mucous defenses in the nose and throat can shoot down into the lungs. Most are expelled by the natural mechanism of the lungs, but some may remain.

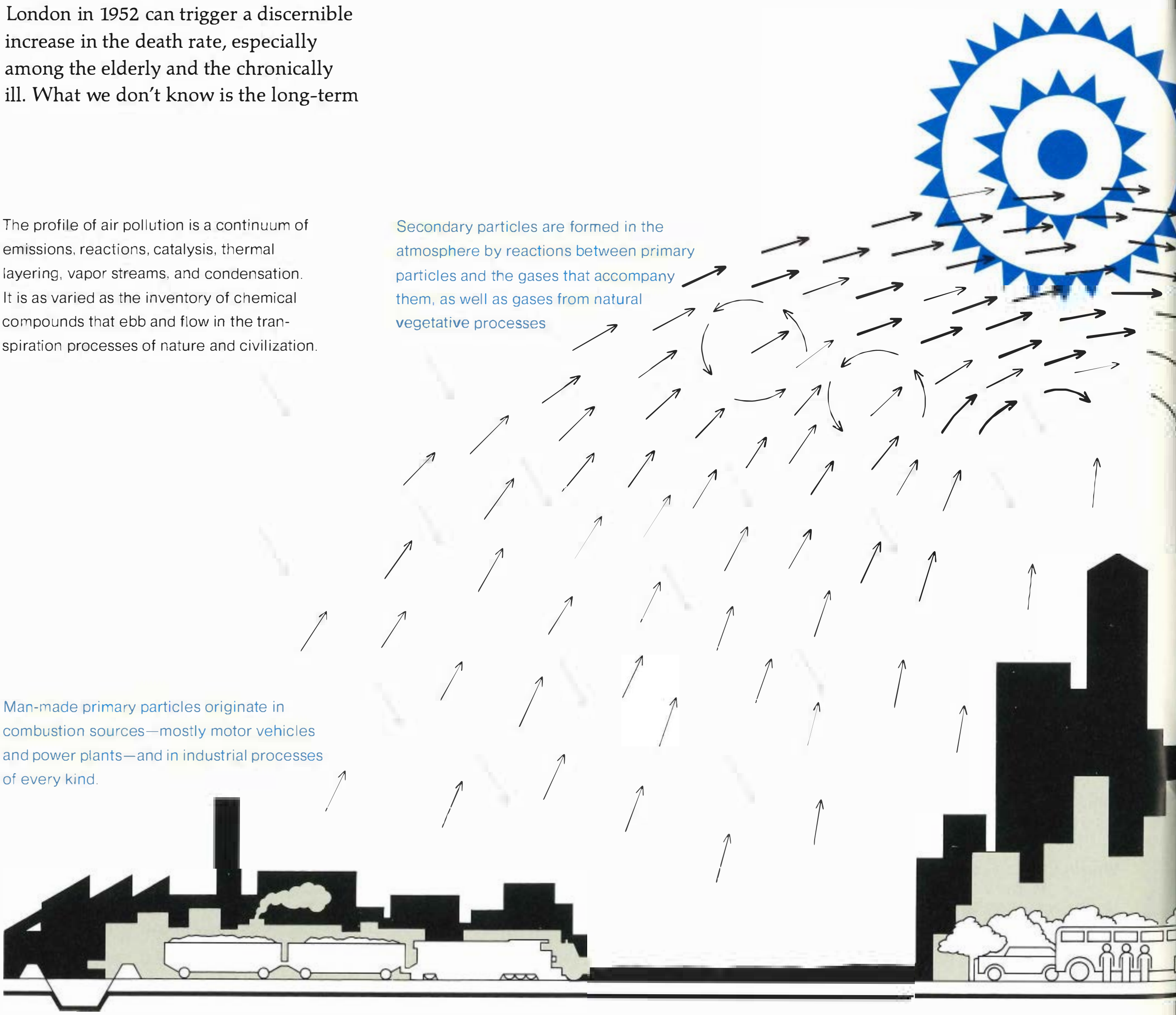
Here chemically active particles and even inert particles can produce severe irritation, leading to lung disorders such as silicosis. Particulates are also suspected of contributing to or aggravating a whole catalog of other diseases: bronchitis, asthma, emphysema, heart disease, and cancer, both in the lung and elsewhere in the body.

Trying to pin down the exact health effects of particulate matter can be frustrating indeed. After many studies and some strongly contradictory results, many critical issues still remain in dispute.

What we do know is that "killer smogs" of the sort that descended on London in 1952 can trigger a discernible increase in the death rate, especially among the elderly and the chronically ill. What we don't know is the long-term effect of lower, daily pollution levels on people who are otherwise healthy—in other words, on the majority of the population.

There are clues, however. Laboratory experiments on animals give indications of the types of effects to look for in humans. And data on industrial exposures give indications of the effects of high levels of concentration. Nailing down solid findings will be another matter, though. Laboratory animals are not people, and workers exposed to high concentrations cannot be compared directly with people breathing much lower concentrations in their daily lives.

Some low-concentration clinical exposures have been carried out on human subjects, but ethical constraints bar such studies from going beyond the induction of very subtle, short-term effects. To see



The profile of air pollution is a continuum of emissions, reactions, catalysis, thermal layering, vapor streams, and condensation. It is as varied as the inventory of chemical compounds that ebb and flow in the transpiration processes of nature and civilization.

Secondary particles are formed in the atmosphere by reactions between primary particles and the gases that accompany them, as well as gases from natural vegetative processes

Man-made primary particles originate in combustion sources—mostly motor vehicles and power plants—and in industrial processes of every kind.

if there are long-term health effects, we have had to leave the laboratory and launch epidemiological studies of the outside world.

Epidemiological studies—those that try to correlate changes in public health with changes in the level of air pollution —provide an ethical alternative, but they take time and often yield fuzzy conclusions. For a start, the task of gathering data is immense. And the population at risk (in this case, nearly everyone) is subject to the effects of a great many confounding variables.

When people in a polluted environment develop chronic lung or related disease, how can we be sure that it is due to air pollution rather than to smoking, genetic flaws, old age, exposure on the job, or any of a whole list of more subtle things, such as poor nutrition as a result of low income, disease caused by poor sanitation, and so on?

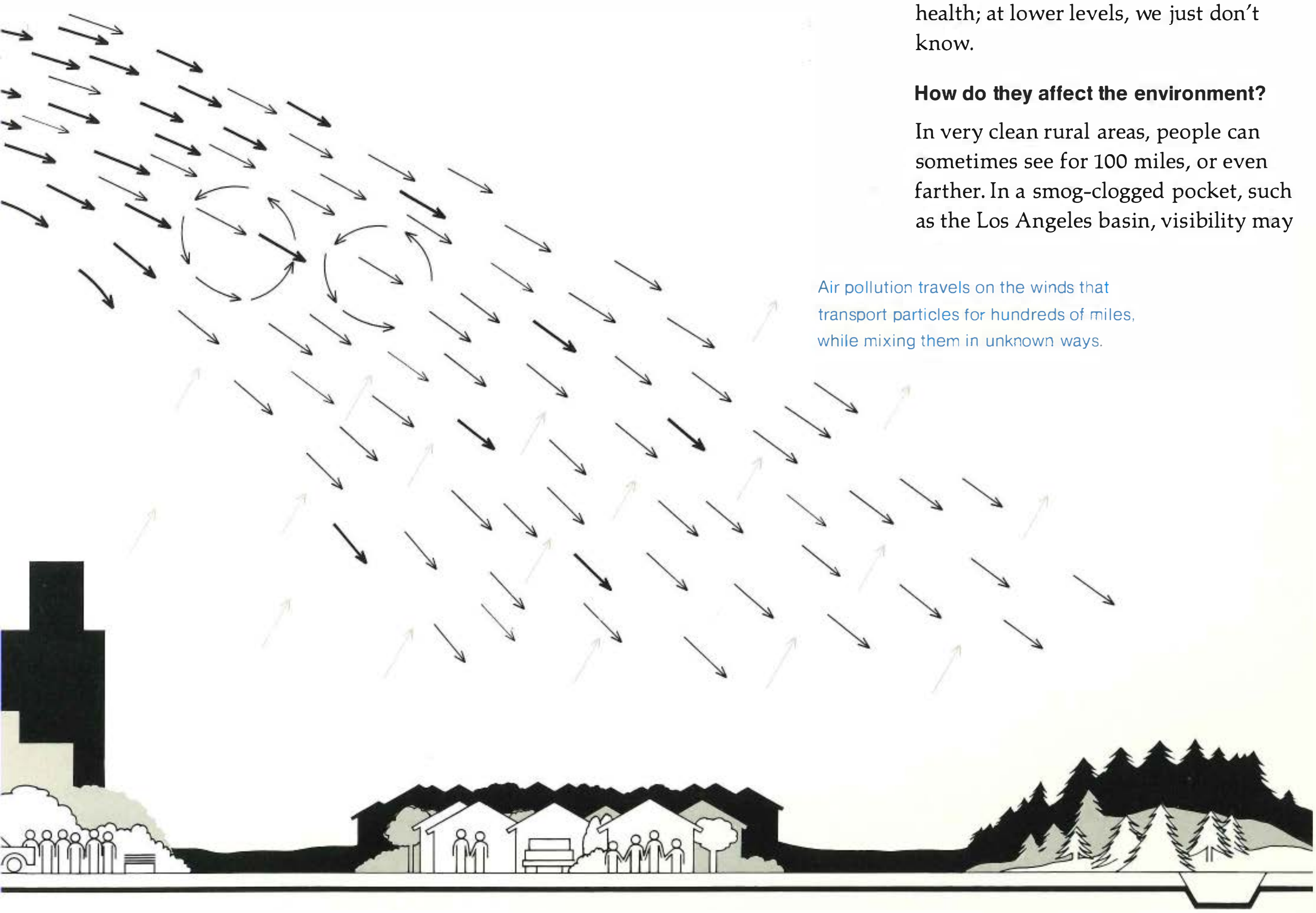
We can't draw firm conclusions until progressively narrower and better controlled studies are run. To drag out the search still further, the damage done by exposure to a toxic agent may take 30 years or more to show. Moreover, we lack adequate records on what air pollutants people have been exposed to in the short term and certainly over those 30 years or more.

It is easy to see why we are still not able to forge clear links between airborne particulate concentrations and illness in human beings. But neither can we ignore the evidence thrust on us by animal experiments, occupational exposures, human clinical studies, epidemiological surveys, and our own commonsense observations. Air pollution at high levels is clearly a threat to human health; at lower levels, we just don't know.

How do they affect the environment?

In very clean rural areas, people can sometimes see for 100 miles, or even farther. In a smog-clogged pocket, such as the Los Angeles basin, visibility may

Solar radiation—creating the photochemical phenomenon we call smog—and moisture are only two of many catalytic influences.



Air pollution travels on the winds that transport particles for hundreds of miles, while mixing them in unknown ways.

reach only a tiny fraction of that distance—perhaps only 2 or 3 miles on a bad day. High concentrations of fine-particle pollutants overhanging urban areas may help account for much of this difference.

Particulates scatter light rays that would otherwise illuminate distant objects. The resultant image is fuzzy and indistinct, with little contrast between subject and ground.

Visibility reduction is mainly an esthetic problem. City dwellers who prize their view of the skyline often discover it shrouded in brownish haze. Nor are suburban or even rural dwellers exempt. Ironically, it is the same particulate loading in the air that can spark the spectacular red sunsets admired by city and country people alike.

So-called acid rain is another phenomenon for which particulates frequently receive the blame. Such rainfall, whose acidity is believed to be increased by contact with airborne particulates, has been cited as a possible cause of forest blight and reduction in the yields of commercial crops. In addition to these allegations, which still await solid proof, it has been reasonably well established that freshwater ecosystems can be upset by an altered acid-alkaline balance in otherwise unpolluted waters, resulting in the death of the fish population. These changes are thought to stem from the deposition of acids over many seasons.

Soot-covered buildings with corroding masonry stand further witness to the assault of airborne particulates. There is evidence, too, that particulates help transmit odors. Rotting garbage, incinerators, and the tar trucks used in paving and roofing are a few sources of odor-bearing particulates.

Researchers now wonder whether particulates, if they remain suspended in the high atmosphere for long periods of time, could actually alter our climate. Because they absorb and scatter sunlight, they could act as a screen or filter, blocking out solar radiation. Loss of the sun's warmth could, in turn, reduce temperatures on the earth's surface, triggering a long-term and widespread cooling trend. However, such a trend would likely counterbalance the warming trend that some foresee as a result of increasing levels of carbon dioxide in the atmosphere.

So far, we have been looking at the health and environmental impacts of particulates as a group. But in fact, specific effects differ widely according to the nature of the agent—that is, according to the specific kind of particulate being considered.

While almost any kind of particulate in sufficient mass can have a dramatic short-term impact—say, on visibility during a dust storm—the real focus of current research is to ferret out those agents that contribute significantly to the long-term degradation of human health and the environment. And finding the true villains among thousands of possible suspects is proving to be no easy task.

Which are most hazardous?

The impact of any given particulate will depend on its chemical composition, shape, and most important, its level of concentration. Sometimes synergistic reactions occur in which a group of substances combine to produce effects that no one or two agents could produce alone. Reactions of this sort are probably commonplace in the aerosol overhanging urban/industrial areas, where the great variety of chemical emissions offers a vast array of possibilities.

Suspicion now fastens mostly on a group of chemically active substances that derive from the burning of fossil fuels, such as coal, oil, and gasoline. Leading suspects are hydrocarbons, heavy metal compounds, and the higher oxides of sulfur and nitrogen (sulfates and nitrates).

Inhalation tests with laboratory animals have shown some of these compounds to be cancer causing. For example, a hydrocarbon called benzo-alpha-pyrene is known to cause lung cancer in laboratory animals. Substantial evidence also suggests that heavy metal compounds, either in particulate form or as gases absorbed by inhaled particulates, can be similarly carcinogenic. However, the evidence of health effects for other forms of particulates is much less clear.

Sulfates and nitrates are among the most prevalent man-made particulates in the urban aerosol. There is no real evidence that they produce cancer, but some epidemiological studies have linked them with chronic bronchitis and other respiratory diseases. However, even these findings are now being disputed.

On the environmental side, sulfates and nitrates are increasingly being associated with visibility reduction and deposition of acids on the soil through rain or the gravitational settling of the particles.

How can we control them?

For optimal control of harmful particulates, we will need to know a great deal more than we know today. We are still unsure exactly how certain particulates are formed and how they are distributed in the atmosphere. Furthermore, our knowledge of their biological hazards is not yet complete enough to rule out large classes as harmless or to know what concentrations represent acceptable levels of risk. As a result, with so many unknowns, control technology has had to rely on a broad-spectrum, shotgun approach.

For example, early studies of particulate matter and the control technologies based on these studies focused on the total mass of particulates in the air. Paring down this mass with air filters became the primary aim. Trying to control particulates as a group seemed the only logical thing to do at a time when we had almost no idea which ones might do the most damage.

Since then, natural dust, which has little impact on long-term air quality, has been found to account for almost half of this mass. And other coarse particles account for most of the rest. So the emphasis on controlling mass loading now clashes with more recent work that points to fine particulates, which can slip through most filters, as the real culprits in air quality degradation.

Because of rising doubts about the adequacy of focusing on total suspended particulates (TSP) alone, researchers have proposed a new category labeled RSP. RSP stands for respirable suspended particulates. The stress here falls on those very small particles, easily inhaled, that current research is pursuing as potentially most dangerous.

Existing air quality regulations target TSP exclusively; RSP loadings have so far escaped legislation. Current laws, and the control measures mustered to meet them, have not yet caught up with the new emphasis on fine particulates.

Up to now major emphasis has been on removal of sulfur dioxide and reduction of the total mass of particles emitted. Undoubtedly future efforts will be devoted heavily to the removal of fine particulates. We see this trend emerging in the even more stringent new-source performance standards being proposed this year for particulate emissions (0.03 pound per million Btu) and plume opacity (10%). But even these will not answer the problem of the fine particulates formed in the stack and in the atmosphere.

What now?

The trend toward closer scrutiny of fine particulates appears clearly established. Promulgation of new standards for RSP seems likely in the next decade, together with concomitant shifts in control technology. Furthermore, the now prevailing belief that many of these fine particulates are formed by secondary reactions in the atmosphere has raised more thorny questions for pollution control. Why try to develop superfine filters for stack emissions if most of the fine particles are actually formed later, after the gases leave the stack? Instead, why not exert tighter control over the SO_x and NO_x emission gases from which the particles are formed or over the heavy elements emitted that may act as catalysts and themselves be potentially harmful?

For engineers and others grappling with the amorphous problem of particulate control, such frustrations are familiar. They are typical of the dilemma that comes from proceeding on an imperfect data base.

Even in the face of unknowns, though, advances are building. The question is whether they can keep up with the ballooning growth of pollution sources. Worldwide, people are burning more and more fossil fuels—driving their first automobiles, for example, and working in newly constructed factories. In the United States, this polluting trend is complicated by the switch back to the use of coal as an industrial fuel.

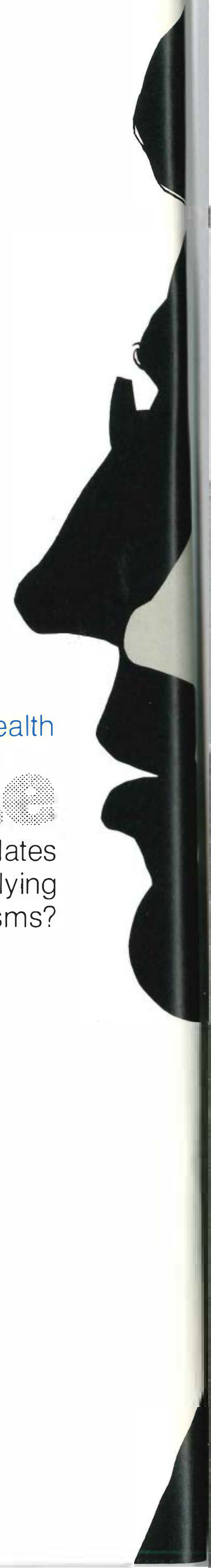
In the next century, it is likely that nuclear, solar, and other relatively clean power sources will augment fossil fuels for industrial use. Similarly, clean-running electric storage batteries may power our cars. But developing these alternative power sources will be costly. And the money that is being used to control particulate pollution today cannot be used simultaneously to fund the research that will eliminate its sources tomorrow.

Hence the tension between present needs and future objectives. The dilemma is how to protect ourselves from the uncertain effects of fossil fuel fallout without allowing excessive cleanup costs to cripple the economic machinery that can bring us cleaner power in the future. This is the puzzle that now confronts us. As a critical part of the air quality picture, it is a puzzle that power producers, regulators, health researchers, and all those responsible for the control and disposal of particulate wastes would do well to ponder. ■

Particulates/Health

Inhaling the Invisible

At what levels of concentration are particulates harmful to human health? What are the underlying chemical and biological mechanisms?



When Helmut Landsberg and Walther Anelung established the biological significance of microscopic particles in the human respiratory tract, little notice was taken.

The year was 1934 and the place was a small sanitorium in Königstein, West Germany. Landsberg, who had just earned a doctorate in geophysics from the University of Frankfurt, and Anelung, a medical doctor who owned and operated the sanitorium, determined in field tests with patients that up to 80% of the submicrometer particles in the air breathed by the test subjects—indoors and outdoors—were retained in the subjects' respiratory system. The matter inhaled included nitrogen oxides in the sanitorium's X-ray room, cigarette smoke in the dining room, dust in various locations, and automobile exhaust outdoors.

Landsberg, who went on to achieve eminence as a geophysicist and is now professor emeritus at the University of Maryland, says of that early work, "It was considered esoteric research in those days. No one was really interested then in knowing if people got sick or died from breathing these microscopic particles in the air." Landsberg's own research interests after the Königstein studies turned in the direction of climatology, and his work on the meteorological effects of airborne particles on atmospheric condensation processes became the foundation for later investigations by other scientists. Much of the present federal air pollution control legislation rests on the foundation laid down by President Truman's 1949 Air Pollution Committee, of which Landsberg was a prominent member.

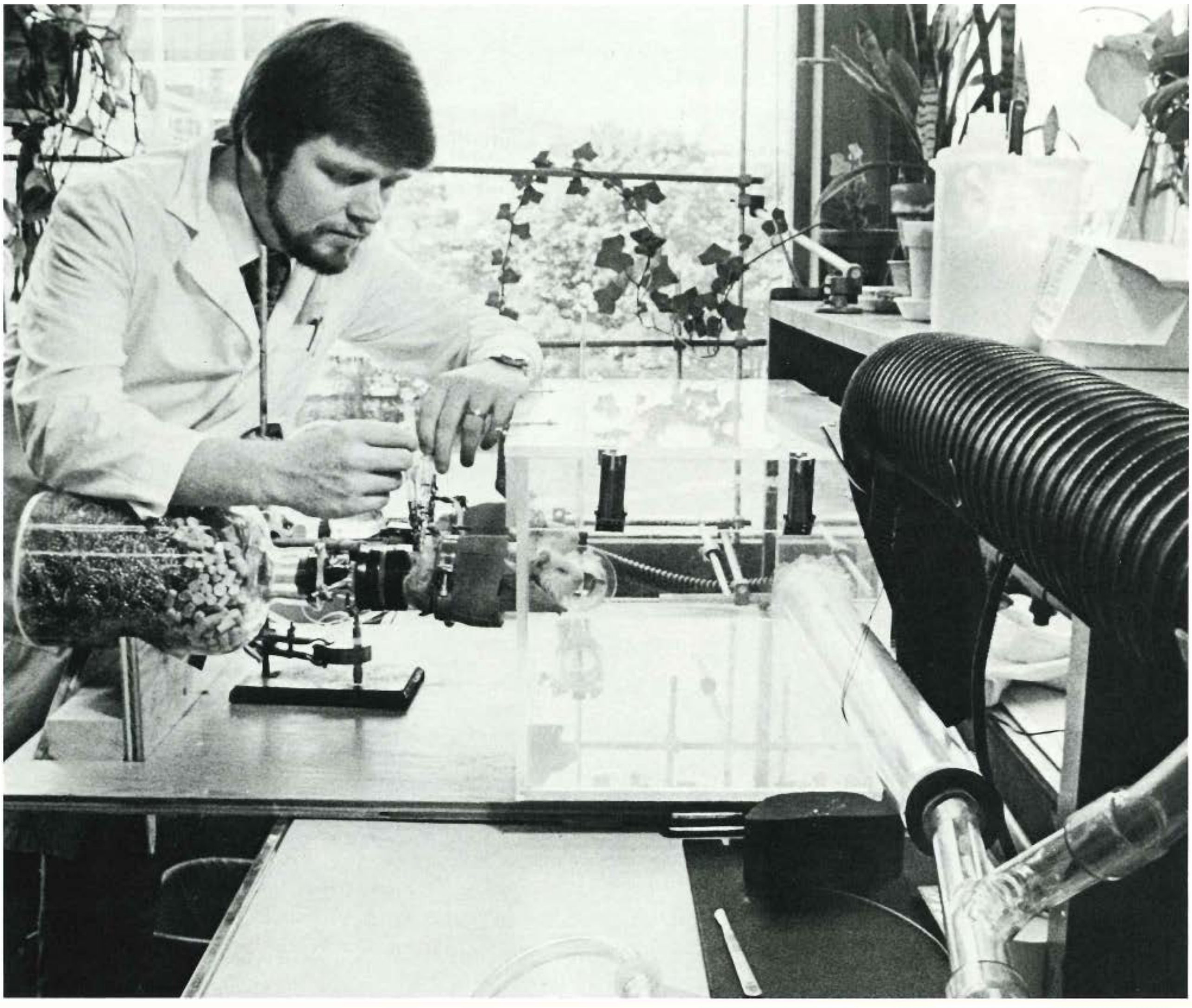
Pollution episodes

It took a succession of death-dealing episodes to call attention to the health perils carried by pollutants in the atmosphere and to prompt government action to identify and control the hazardous agents. With each of these disastrous episodes came increasing concern over the demonstrated ill-effects of severe air pollution. And, more important, action followed.

After an investigation of the 1945 smog disaster in Donora, Pennsylvania, the

An unusual aspect of the comprehensive, long-range Six Cities Study of the health effects from air pollution, being conducted by Harvard University's School of Public Health, is the use of a portable air sampler. Volunteers from the study group wear a portable monitor during their daily routine and keep a journal of their activities. The monitor collects a sample of the mass respirable particulates its wearer is exposed to. A similar monitor in the volunteer's home samples indoor air, providing data for a correlation of outdoor and indoor exposures as well as measurements of the respective exposures.

Alterations in pulmonary flow resistance and respiratory frequency are among the functions studied in the Massachusetts Institute of Technology Energy Laboratory as part of a multidisciplinary investigation of the health effects from particulates. Laboratory animals are exposed to particulates in combustion gases collected from burning coal in a model of a furnace.



U.S. Public Health Service stated that contamination of the air in industrial areas can cause serious, acute, disabling diseases. Particulates and sulfur oxides were suspected of being the harmful agents in the Donora case and in the 1952 London killer smog. But although high levels of pollution obviously affected people adversely, it was not clear what mechanism caused the ill effects. Nor was it clear at what level, if any, normal resistance could offset the effects of pollutants. It was clear, however, that pollution control was called for.

The major unresolved issue at the present time is whether or not existing ambient levels endanger public health.

Tracing the culprits

The evidence to support our ambient air quality standards has come from observation and statistical studies—epidemiological data—that have followed the disastrous smog episodes. Hospital and clinical records in New York and London, for instance, indicated that when sulfur dioxide and particulate levels were especially high, sickness and death from cardiac and respiratory disorders increased. In Japan the incidence of such diseases as chronic bronchitis, bronchial asthma, and pulmonary edema has been linked to sulfuric acid mist and suspended dust particles. In many of these studies, only indicator pollutants have been measured, leaving undetermined whether they cause ill effects or merely indicate the presence of other, causative pollutants. A National Academy of Sciences investigation, however, concluded that exposure to particulate polycyclic organic matter can result in cancer of the skin and lungs, among other afflictions.

There is increasing agreement that fine particulates (those under 2 micrometers) are the principal suspects in air pollution that is damaging to human health. These microscopic particles are especially harmful because they are able to bypass the body's respiratory filters and penetrate deep into the lungs. It has been found that more than 30% of particles under 1 micrometer that invade the pulmonary system remain there, lodging in the lung tissues.

Many chemically active and some inert particles have been found to create toxic effects. The chemically active ones may contain such toxic metals as lead, cadmium, vanadium, and nickel. Inert silica particles can cause acute physical irritation of sensitive lung tissue and lead to silicosis, among other diseases. Particulates in the lungs can also impair oxygen transfer.

What is known

The private consulting firm of Greenfield, Attaway & Tyler, Inc. (now Flow Resources Corp.) conducted for EPRI a comprehensive study of the state of knowledge of particulate matter. "There is little doubt that episodes of exceptionally high levels of air pollution may cause excess morbidity and mortality," the study report states. "However, the health effects from lower, more sustained levels of pollution are unknown. Sound scientific research has been unable to single out one pollutant or group of pollutants as a major causative variable." The report goes on to say that although suspended particulates, sulfur dioxide, and other pollutants occurring in association with sulfur dioxide appear to significantly raise mortality, and although total suspended particles seem to have a major role in the ill effects, "clear cause-and-effect relationships between specific pollutants at specific levels are lacking."

The report notes that the "evidence has often been contradictory due to the complexity of both the pollution indices and the health indices." Anthony Colucci, who was a principal investigator in the study and is now a project manager in EPRI's Health Effects Program, says that the task of establishing positive cause-and-effect relationships between pollutants, levels of occurrence, and incidence of specific diseases is "like looking for a needle in an alfalfa field." And compounding this bit of scientific detective work is what Colucci characterizes "an interpretive dilemma." He notes that there is a great deal of information on the relationship between exposure to atmospheric particulates and human health effects. "One would hope from this information," he says, "that there would emerge a coherent understanding of human health risk so that soundly based control strategies could be devised. Regrettably, this is not the case." Why not? "Principally," according to Colucci, "because of the difficulty in interpreting the reported observations of the air pollution epidemiologist and connecting them to the data base of toxicology experiments."

Colucci goes on to explain that the epidemiologist's observations are not only confounded by imprecise exposure data but also by data that are basically different from those developed by the toxicologist. For example, the epidemiologist has data correlated to total suspended particulates, while the toxicologist has screened his particulate data by physical and chemical characteristics. Under these conditions, Colucci points out, how can the response of the laboratory animal give reasonable clues to the response of humans in the real world?

A complex matter

Dr. Mary Amdur, a leading figure for nearly a generation in the study of sulfur oxides and pulmonary function, has recognized the complexity of the task of the epidemiologist in attempting to unravel the relationship between exposure to atmospheric particulates and human health effects. Said Dr. Amdur in 1969: "The inhalation toxicologist should bow before the courage of the epidemiologist who, faced with a multicomponent, highly variable exposure of a mobile population, has to 'take it like it is' when assessing the effect of urban pollution. If faced with assessing cause-and-effect relationships based on data from exposure chambers that behaved in a manner so capricious, I would have long since joined the 'back to the kitchen for women' movement."

Colucci gives another example of the problem at hand by citing from the litera-

DATA BANK FOR HEALTH EFFECTS

EPRI and members of the nonferrous smelting industry are sponsoring an air pollutant health effects data bank with Arthur D. Little, Inc. (ADL) of Cambridge, Massachusetts.

The scientific data bank includes extensive information on the effects reported in humans, animals, and plants from exposure to sulfur oxides, ozone, nitrogen oxides, lead, cadmium, arsenic, and particulates, as well as references on atmospheric chemistry, acid precipitation, and urban concentrations. The data bank is continuously updated to include the latest information from both domestic and foreign sources.

During the six years since its inception, the data bank has proved to be an effective source of information for evaluating scientific publications, preparing the scientific background for legal briefs, and analyzing toxicological studies of laboratory animals and environmental studies of humans in both industrial and urban surroundings.

The information system is available at no cost to EPRI members. A brief but appropriately detailed description of a problem, a listing of the information needed, and a comment on how the information will be used should be sent to James McCarroll, EPRI Environmental Assessment Department.

It is recommended that requests for such information be made well in advance of the time the information is needed because ADL will need time to assemble, organize, interpret, and critique the scientific literature. Reports prepared under this arrangement become available to other members of the industry and to the public.

A utility may arrange directly with ADL for similar but private use of the data bank. Under these conditions and within the contractual agreements with ADL, disposition of the resultant report is at the discretion of the utility. (Because of EPRI's tax-exempt status, in this case the utility would bear the full cost of the service.)

ture published by EPA in its CHESS (Community Health and Environmental Surveillance System) program.

"We find in the literature the terms *total suspended particulates* (TSP), *respirable suspended particles* (RSP), *suspended sulfates* (SS), and *suspended nitrates* (SN). TSP is the term applied to the particulate matter captured on the filter of a high-volume sampler, weighed and reported in micrograms per cubic meter of air drawn through the filter," he explains. "No notion of the upper or lower limit of particle size is available to translate TSP into the language of the experimentalist. Thus the term has little biological significance.

"RSP, as reported by the CHESS epidemiologist, does include the concept of particle size because this fraction of the airborne particulate is collected by using a cascade multistage impactor and cyclone samplers or equivalent particle-size discriminators. The cyclone, for example, is designed to collect no particles greater than 10 micrometers in diameter, 50% of 3-micrometer particles, and 100% of particles 2 micrometers or less. However, RSP has no toxicological significance because information on chemical species is not included in its description in the CHESS literature.

"Further confusion results," Colucci continues, "from the epidemiologist's use of the terms SS and SN. Rather than being a subcategory of RSP (in which case the notion of particle size would be included), SS and SN measurements are obtained from residue removed from the high-volume sampler used to measure TSP. Thus the portion of SS and SN that is respirable is unknown. Yet it is on the deepest portion of the pulmonary tract that SS and SN are presumed to have effects."

In search of answers

Since most electric power plants burn carbonaceous fuels and thereby produce oxides of sulfur and nitrogen—prime suspects as precursors of particulates—the electric utility industry, through EPRI, is funding an extensive program in search of Colucci's elusive needle in the alfalfa field. Current EPRI allocation of funds for particulate health effects studies amounts to $12 million, the major effort in a $16 million program for health effects research on air pollution generally. The federal government, through various agencies, is spending some $30 million on similar studies.

Under the direction of James McCarroll, M.D., former professor and chairman of the Department of Environmental Health at the University of Washington, and a nationally recognized authority on air pollution—connected respiratory diseases, EPRI has launched what McCarroll has called a multitiered program. "Each layer of understanding builds on the information gathered in the preceding stage," he explains.

The initial stage involves the compilation of a physical inventory of atmospheric pollutants—their identity and forms, effective methods for measuring and monitoring them, and how they transform in transport from their source to the populations exposed to them. This phase is intended to determine the relative contributions of specific sources to final exposure.

In the second stage, under way for some 18 months, animal toxicology studies are being conducted at three major universities, each investigating a different facet of the problem. At the Massachusetts Institute of Technology, Dr. Amdur is working with combustion engineers and physical chemists to simulate various combustion conditions in model furnaces and then expose guinea pigs to the gaseous emissions.

Timothy Crocker at the University of California at Irvine is investigating the effects of mixed and aged atmospheres (those that have undergone changes such as occur in actual atmospheric conversions) on small and large laboratory animals. Crocker is also duplicating the effects on growing, developing lungs to determine the impact of pollutants before the lungs reach maturity.

The third study involves a multidisciplinary approach in which a team of scientists at the National Primate Center at the University of California at Davis is observing the effects on primates of continuous long-term exposure to air pollutants. Biochemists are looking at the enzyme changes in the lungs of the exposed animals; pathologists are looking for any structural changes; specialists in infectious diseases are studying air pollution effects on host defense mechanisms against various respiratory infections, among other observations. All three groups are exchanging data that may illuminate their respective investigations. Toxicology studies sponsored by EPRI in other laboratories are investigating other aspects of air pollution health effects. From these studies should emerge identification of fossil fuel combustion pollutants that are potentially harmful to humans.

The third stage, begun last year, is designed to define physiological boundaries and the possible types of functional impairment that may result from exposure of human subjects—both healthy volunteers and those with various degrees of pulmonary disease—to specific air pollutants at different levels. Using specially designed human exposure chambers, these studies extend observations on experimental animals to humans.

The last stage will be a large-scale epidemiological study, drawing on the biomedical data that correlate specific effects on health of populations in the real world.

Early returns

Results have been reported from the Six Cities Epidemiologic Study of Sulfur Oxides and Particulates, which EPRI joined in funding in 1976. The largest ongoing air pollution—epidemiologic investigation in the United States, this study is a nine-year effort by the Harvard School of Public Health and originally was funded by its current cosponsor, the National Institute of Environmental Health Sciences. The study is designed to measure the levels of air pollution, especially sulfur dioxide, sulfates, and respirable particulates, and to determine the effects of levels of these pollutants on the health of adults and children. The sample population consists of some 2000 adults between 25 and 74 and 2000 grade school children. The six communities selected are Watertown, Massachusetts; Kingston-Harriman, Tennessee; the southern end of St. Louis, Missouri; Steubenville, Ohio; Topeka, Kansas; and Portage, Wisconsin.

Pollution measurements are being made by instruments at fixed locations in each city at sites representative of residential exposure. Monitoring equipment is also placed inside and just outside about 10 homes in each city to obtain the relationship between ambient and indoor pollutant levels. And unique to this study, portable personal monitors are being used. Every six days, volunteers from the health survey sample carry a transistorized personal monitor throughout the day. This monitor collects a 24-hour integrated sample of the mass respirable particulates the carrier is exposed to. A similar monitor is placed in the person's home to sample the indoor environment. To help correlate these data with their exposure, the volunteers record their activities on the sampling day.

McCarroll reports that the findings so far indicate that sulfur dioxide levels are consistently far lower indoors than outdoors. Nitrogen dioxide levels outdoors tend to relate directly to the volume of nearby automobile traffic—the higher the traffic density the higher the nitrogen dioxide concentration. Indoors, the levels are usually lower than outside, with higher nitrogen dioxide loadings apparently associated with such indoor sources as gas used for cooking or heating.

Particulates pattern

The patterns of particulates, including sulfates, vary. Outdoor levels of respirable particulates are relatively uniform across a city. However, indoor concentrations vary widely but are consistently higher than those outdoors. Higher indoor levels are usually associated with cigarette smoking. Smoking shows no association with indoor sulfur dioxide or nitrogen dioxide levels, but is strongly related to fine respirable particulates. Measurements indicate that each of the study participants is exposed to a base particulate level in the home, plus an increment directly related to the amount of smoking and inversely related to the degree of ventilation.

Respirable sulfates show a different pattern from respirable particulates. Outdoor levels are higher than indoor, particularly in winter. Sulfate levels recorded by personal monitors equate with the levels indoors in winter, where the subjects spend most of their time. In summer, when more time is spent outdoors, personal sulfate exposure appears to increase. Although sulfates are not a major constituent of cigarette smoke, exposure to smoking tends to relate to higher sulfate levels. Cigarette smoke was tested and found to have only 16 micrograms of sulfate. But paper matches, used almost exclusively by smokers in the study, contained 107 micrograms per match. So the use of paper matches is suspected of elevating the level of indoor sulfate.

In addition to gauging variations in the level of indoor and outdoor pollutants, many other measurements of health effects will be made on populations in the six cities' study. Among these are pulmonary function in children and in adults, variations in the illnesses experienced by the subjects in the six cities, such as chronic bronchitis, asthma, respiratory infections, pneumonia, and colds. The particular six cities were selected to represent a range of air pollution levels from relatively unpolluted to severely polluted, and comparisons will be made between the health of those persons exposed in the different cities and the degree and type of air pollution they are exposed to.

With data such as these flowing in from the field and the laboratory, air pollution health effects researchers—a special breed of scientist-detective—are in earnest pursuit of that needle in the alfalfa field. ■

Particulates/Regulation

Pollution in Public

During a century of changing attitudes and evolving knowledge we have redefined the pollution problem and, in turn, our legal attack on the dark side of industrial progress.

Woodcut
The Bettmann Archive

The latest federal laws on air quality force an issue that until recently, Americans have been reluctant to face. By paving the way for very stringent new rules on the siting and operation of industrial plants, the Clean Air Act Amendments of 1977 expose a key dilemma in the field of air quality legislation: How can we control the emission of harmful pollutants without squashing the growth of vital industry?

Until recent years, Americans would not have even considered a trade-off. A belching smokestack meant prosperity. Who would risk prosperity for cleaner air? Clean air was seen as an esthetic nicety—desirable, but not as desirable as a good job, a steak in the broiler, and two cars in every garage.

Today, with new evidence linking air quality to health and increased sensitivity to the esthetics of clean air, the public is taking a serious second look at air quality regulation. To many, the smokestack now stands not for prosperity but for pollution and the amorphous menace that pollution implies. The public, through its representatives in law-making bodies at every level, now seems determined to push for cleaner air, although it is doubtful that anyone, including the legislators who will be making the decisions, can peg the exact costs that such regulation could ultimately impose on the economy and the wellbeing of the nation.

To understand how we have come to this point, it is helpful to review the evolution of our attitudes toward air quality and the laws that these attitudes have created.

The black smoke era

When fuel-powered machines first began doing human work, the excitement of the revolution swept away most doubts about its consequences. Factories sprang up, raining soot on town house and tenement. But most people didn't care. A little dirt seemed a small price to pay for progress.

Decades passed, and living standards soared. Eventually, as Americans came to take the benefits of industrialization for granted, the sheer ugliness of black smoke and soot deposits began to annoy them.

St. Louis was the first city to do something about it. Well ahead of its time in 1867, that city passed a smoke ordinance. Chicago followed in 1881. The Chicago City Council declared that "the emission of dense smoke from the smokestack of any boat or locomotive or from any chimney anywhere within the city shall be . . . a public nuisance." By the end of the century, most large cities had taken similar action.

"Dense smoke" meant black smoke. To enforce their antismoke laws, city officials needed some way to single out those plumes that were dense enough to constitute a violation. An engineer named Ringelmann provided the test.

The Ringelmann smoke test rated the blackness of smoke on a scale from 0 to 5, with the darkest smoke having the highest rating. Say, for example, that a smoke inspector compared a very dark plume with his Ringelmann smoke scale and assigned a rating of 5. If his stopwatch showed that the plume remained that dark for a specified period of time—usually one or two minutes—then the emitter would be cited for a violation.

Because use of this test was widespread, the first wave of air quality requirements in the United States became known as Ringelmann laws. They were local antismoke laws, and what they actually controlled was particulates. Incomplete combustion, especially of soft coal, would release clouds of coarse carbonaceous particles. These soot particles, rising in sufficient mass, gave the smoke its dense black character.

By applying the Ringelmann test and mandating the use of electrostatic precipitators on large smokestacks to catch soot particles, most large cities were able to control severe black smoke problems by the late 1940s. Upgrading combustion efficiencies and switching from coal to cleaner-burning fuels also helped clean the atmosphere of smoke. But no sooner had this been accomplished than a new problem surfaced. A new kind of air pollution began to appear.

Enter photochemical smog

Photochemical smog—not black smoke, but a pale murk created by the reaction of chemicals and sunlight—first appeared during World War II. The wartime industrial boom had drawn more cars and more factories to the nation's cities, and one result had been the multiplication of chemical emissions in the air. This fresh brew of pollutants, more complex than the grimy billows of the black smoke era, soon became a special problem in Los Angeles.

The climate and geography of the 1200-square-mile Los Angeles basin conspired to make the area a perfect natural laboratory for the creation of photochemical smog. Bounded on three sides by mountains, the area had frequent temperature inversions, high concentrations of oxidizing agents in the atmosphere, and only very light winds. Chemical pollutants would be trapped under a lid of warm air hovering over the basin. Then, cooking in the hot sun, they would rapidly react into a visible, eye-burning haze.

At first, smog was thought to be composed strictly of gases. On closer examination, though, it became evident that smog was an aerosol containing vast numbers of solid and liquid particulates held in gaseous suspension.

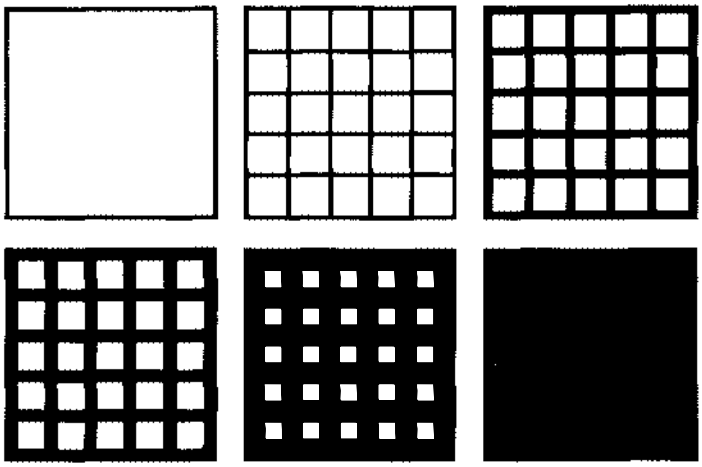
Some of these particulates came from the exhaust pipes of automobiles. Others were emitted by the smokestacks of factories and power plants combusting fossil fuels. Even burning trash in backyard incinerators added ingredients to the swirling stew of airborne pollutants.

Some types of industrial pollutants had been in the air over Los Angeles for decades, though in much lower concentrations. But their presence had been largely unnoticed. And now their numbers and levels had surpassed the critical point. Worse, synergistic reactions were occurring between suspended pollutants and the auto emissions that were beginning to blanket the basin.

By the late 1940s, Angelenos became increasingly annoyed by episodes of burning eyes and murky visibility. Still, there was no general sense of alarm. It was not until "killer smogs" struck several heavily industrialized regions that Los Angeles and the world began to understand what smog at its worst could do.

In October 1948, a prolonged smog settled over the industrial community of Donora, Pennsylvania. By the time it lifted, 20 people had died and almost 6000 had fallen ill. Almost half (43%) of Donora's residents were stricken.

The U.S. Public Health Service launched an investigation. An official later announced: "We can now say positively what couldn't be said before with



Old and new techniques for monitoring power plant stack emissions. Early smoke inspectors used Ringelmann charts: white, black, and four standard grid patterns that resolve as shades of gray when seen from a distance. Compared with smoke against a clear blue sky (for a defined time interval), they divided air pollution into six categories of severity.

Today's researchers are testing a tunable dye laser and telescope that travel by van, accompanied by their own computer and a gasoline-powered 15-kW generator. Reflections of controlled laser light bursts (at selected frequencies) are measured, permitting calculation of the amount absorbed and thereby the concentrations of SO_2, NO_2, or O_3 in the stack plume.

scientific proof—that contamination of the air in industrial areas can cause serious, acute, disabling diseases." Whether this conclusion was fully justified became and has remained a matter of sharp dispute. But the incident was critical in focusing public attention on the perils of air pollution.

The Donora investigation also influenced future air quality perspectives by singling out two major pollutants—particulates and sulfur dioxide—since these were substances obviously present and easily measured. When a similar episode struck London in 1952, leaving thousands dead, the same contaminants were implicated. Soon the people of Los Angeles and other pollution-prone cities were demanding action.

The calibrated eyeball

The Ringelmann test, devised to deal with soot, diagnosed only the darkness of the plume. It could not be used to measure the plume's opacity—that is, its ability to obscure the background and so block visibility. A sufficiently pale plume, however thick, could choke bystanders and destroy the view but still pass the Ringelmann test. Clearly, another kind of test was needed to cope with the realities of Los Angeles's photochemical smog.

To meet this challenge, the Los Angeles Air Pollution Control District, a countywide agency, mandated new standards for opacity and set about overhauling the curriculum of its special school for smoke inspectors. The Ringelmann test depended on human skill, and the opacity test would too. Only now the inspectors would have, in the words of EPRI Project Manager Stephen Baruch, "calibrated eyeballs."

At smoke-inspecting school, which Baruch attended in 1966, "they had a portable device, like a chimney on wheels, with a firebox underneath. It put out all different types of smoke. Once a month all the inspectors were tested against this metered device. They would read the smoke. . . . Their eyeballs had to be correct within a low percentage of error. Higher than that percentage and they flunked out," reminisces Baruch.

So, with stopwatches and calibrated eyeballs, Los Angeles's graduate smoke inspectors set about enforcing the county's new opacity laws. These regulations were designed to control all stationary source emissions, however pale, that could reduce visibility. In so doing, they also promoted public health by cutting down on the pollutants that people living in the basin were forced to breathe.

The opacity laws of the 1950s were the first major step in air quality legislation since passage of the early Ringelmann smoke ordinances. But as the scope of the problem widened, it became evident that even the opacity laws would not be sufficient.

Emission standards emerge

More was coming out of industrial stacks than met the eye. Not only were there clear gases, such as sulfur and nitrogen oxides, there were also particles too small to be seen. After Donora, London, and several other episodes, suspicions were hardening that these clear gases and tiny particles, invisible even to the calibrated eye of a Los Angeles smoke inspector, could be a serious health hazard.

Because it was important to know the total loading of particulates, visible or not, pouring into the atmosphere over the basin, Los Angeles county officials needed something to complement their Ringelmann and opacity laws. The answer was process weight standards.

The forerunner of today's emissions standards, Los Angeles's weight standards were specific to a given industrial process. For example, a power plant was allowed to emit, for a specified time period, so many pounds of particulates for each million Btu of fuel burned. Any emissions in excess of this amount would violate the county's process weight standards. These standards were applied to the control of both particulates and gases.

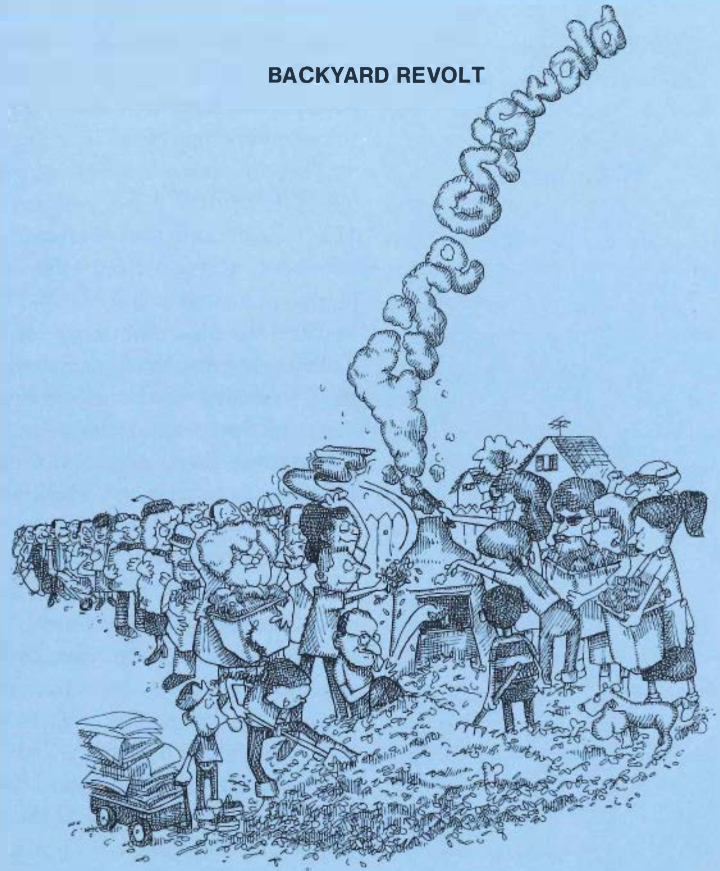
Armed with its newly enacted opacity and emissions standards, Los Angeles began cracking down on sources of air pollution. Key in this crackdown was a strict system of permits required to build or operate any new facilities that would add to the county's smog problem.

"The preconstruction review–permit process was the first of its kind in the country," says Baruch. "You needed a permit to construct, which required a review of all your plans by the Los Angeles Air Pollution Control District. Then the district sent an inspector to make sure that when you operated, you met the specifications of the permit." Failure to comply could mean a court order forcing the plant to shut down.

Going national

While Los Angeles pursued its air cleanup, other municipalities across the land watched, learned, and began to follow suit. At the same time, the federal government signaled its first commitment to the nation's growing air quality prob-

BACKYARD REVOLT



During the late 1950s, a zealous pollution control chief named S. Smith Griswold made some giant strides in coping with Los Angeles's air quality problem. But his hottest battle was not with the oil companies or the electric utilities. It was when he moved to ban citizens' use of backyard incinerators that passions really flared. The county regulators eventually won, though, shutting down the incinerators and thereby wiping out a major source of airborne particulates in the Los Angeles basin.

lem by moving in with research support and funding for state and local efforts.

The year 1955 marked the first federal air quality legislation. What this legislation did was provide federal funds—about $5 million each year for five years—to launch a research program under the auspices of the Public Health Service, an arm of the Department of Health, Education, and Welfare (HEW). In addition, it funneled technical aid to help city and state agencies train personnel and set up their own air quality control programs.

Momentum built slowly. Many members of Congress, especially those representing rural areas without serious smog problems, saw air quality spending as a frill. Still unaware of the fact that particulates and other airborne pollutants could travel and change in the atmosphere, they also saw air quality as an issue too small for federal jurisdiction. "Unlike water pollution, air pollution . . . is essentially a local problem," stated a Bureau of the Budget memo in 1955. Although the Schenk Act was passed in 1960, directing the Surgeon General to study the impact of auto exhaust on public health, the first permanent air quality legislation on a national scale had to wait until 1963.

The Clean Air Act funds research

The Clean Air Act of 1963, assisted in its slow birth by another fatal London smog in late 1962, handed enforcement powers to the federal government for the first time. They were very sparse, however. The power to set actual air quality standards and to request federal intervention in enforcing them still lay with the states. Only when a polluter in one state was affecting health or property in another state could the federal government step in and take direct action.

The main stress was on research. Following the lead of the 1960 Schenk Act, the Clean Air Act zeroed in on auto emissions as a prime source of air pollution. Soon federally funded research patterned after Los Angeles's pioneer efforts confirmed what many urban dwellers had already begun to suspect. Automobile smog was not unique to southern California. Nearly every big city in the nation had a problem.

The 1963 research mandate also triggered a push to strip the sulfur from industrial fuels. Because they tended to release sulfurous gas and particles when burned, coal and oil were the prime targets.

Perhaps most important for the future, the Clean Air Act of 1963 stressed the need for federal development of air quality criteria—that is, descriptions of the damage that individual air pollutants could do to health and property. The aim was to furnish these criteria to the states for their use in setting reasonable air quality standards.

Setting standards

The standards themselves would be prescriptive. Ambient air quality standards would apply to the outside air circulating in a city, town, or other defined area. Today, for example, the national standard for sulfur dioxide is 0.03 parts gas per million parts air, averaged over a one-year period. This standard was based on federal sulfur dioxide criteria, which described this level, plus an added margin of safety, as the threshold at which discernible damage to humans might begin to surface.

Emissions standards, in contrast, would apply to specific pollution sources. The sources could be mobile, like motor vehicles, or stationary, like industrial plants.

Underlying the standards-setting process are certain very basic questions. Primary is the question of accuracy in the criteria. Given the fact that there is much we still don't know about atmospheric pollutants and the fact that even scientists, being human, make value judgments about what is dangerous and what is not, it is reasonable to wonder exactly how precise such criteria can be.

Further questions cluster around the leap from criteria to standards. Should air quality standards be geared to protecting the average person? Or should they be strict enough to protect even those highly susceptible to damage? And in the face of uncertainty as to which pollutants and what levels are dangerous, what degree of risk should the standards reflect?

Today we are beginning to recognize the difficulty of coming to reasonable answers, and so we are still examining these questions. Back in 1963, though, the questions themselves were barely formed. National air standards didn't yet exist. The emphasis was still on research.

The research funded by the 1963 act soon turned up enough evidence of damage from auto exhaust to serve as a springboard for setting the first national standards. Some states, notably California, already had their own controls. Fearing the eventual spread of regulation on a crazy quilt, state-by-state basis, auto makers muted their opposition to the proposal of uniform emissions standards for new cars. Better, they reasoned, to build cars to a single national standard than try to comply with 50 different standards in 50 different states.

In laying down the first federal standards, the Motor Vehicle Air Pollution Control Act of 1965 echoed those already in force in California. The 1965 act also earmarked more money for research on sulfur oxides—pollutants common to fuel-burning industries in general rather than to automobiles in particular.

As the 1960s entered their second half, public anxiety about pollutants continued to mount. The solutions didn't seem to be keeping pace with the problem, which was getting bigger every year. When another fatal smog blanketed New York in November 1966, causing the premature deaths of an estimated 80 residents, the time was clearly ripe for fresh legislation bringing more rigorous controls. The agenda at HEW was clear: a regional approach, coordinated with a push for more uniform standards throughout the nation and tighter federal control.

New legislation flounders

Wrangling both inside and outside Congress marked the advent of the Air Quality Act of 1967. Especially hotly debated was the proposal to impose emissions standards—descendants of Los

Angeles's earlier process weight standards—on various industries nationwide.

By the time the air quality bill became law, the proposal for national emissions standards had been shunted aside into a two-year HEW study. Yet the Air Quality Act of 1967 did break some significant new ground. The federal government traced out air quality control regions—metropolitan areas in which one or more communities, in the same or neighboring states, shared a common pollution problem. Further, HEW was given the mandate to issue criteria and recommended control techniques for six major pollutants: sulfur oxides, total suspended particulates, hydrocarbons, carbon monoxide, photochemical oxidants, and nitrogen oxides. Then the states would be responsible for setting their own ambient air quality standards, based on the HEW criteria and subject to HEW approval.

What actually happened is that the Air Quality Act of 1967 failed to work out as planned. Since the federal government was to furnish the criteria for setting state standards, it was assumed that these state standards would come out more or less uniform. In fact, they did not. The coupling between federal criteria and state standards was never very firm, and under stress the whole procedure began to fall apart.

Because the law required public hearings in each state, those states with powerful clean air lobbies wound up with the strictest standards. Federal enforcement power was limited to exceptional situations. And the machinery for federal action, even when it could be legally brought into play, was very cumbersome.

Confusion reigned. Each state was going its own way—precisely the condition that the 1967 provision of federal criteria and interstate control regions had been designed to prevent. Meanwhile, public demands for clean air were growing louder by the minute. To make any real dent in what many people now viewed as a serious national problem, it looked as if the federal government was going to have to take a stronger hand.

Amendments strengthen the act

With the 1970 passage of the first round of amendments to the Air Quality Act, federal power finally came to the fore. Air quality jurisdiction shifted from HEW to the new Environmental Protection Agency (EPA), and there it remained. EPA became a vigorous implementer of the nation's air quality laws.

The Clean Air Act Amendments of 1970 at last mandated national—and thus uniform—ambient air quality standards. Each state became responsible to EPA for meeting the federal standards.

One way to meet the sulfur oxide standards was to pressure coal-burning industries, especially the electric utility industry, to switch to oil. This massive changeover, already begun under the Air Quality Act of 1967, was almost complete by late 1973. Then came the Arab oil embargo. Suddenly the utilities were caught in a crossfire between clean air proponents, who wanted them to continue burning oil, and energy conservationists, who now urged a switch back to coal.

To resolve the coal-versus-oil conflict, another regulatory compromise took shape. While those plants that had already converted to oil could not be ordered to reconvert if the switch would trigger air quality violations, all new plants would have to be coal-fired.

Did this mean, then, that air quality standards would be relaxed for the new coal-fired plants? By no means. In fact, the standards would grow progressively stricter.

The theory in Congress was simple. If the government passed stricter standards, industry would have no choice but to comply. Tough standards would spur control efforts. This congressional mandate, a feature of the 1970 amendments that was predictably unpopular with industry, became known as control technology forcing.

Besides the emergence of national ambient air quality standards and a new emphasis on control technology forcing, the 1970 amendments brought two other important developments. Both involved emissions standards for stationary sources.

For new facilities of certain types known to produce atmospheric pollutants, the 1970 amendments laid down new-source performance standards (NSPS). This meant that the facilities had to be engineered in such a way as to meet legal limits on the pollutants they could emit. These limits, or standards, were generally expressed in terms of pounds of pollutant allowed per million Btu of fuel burned. Steam generators, municipal incinerators, portland cement plants, nitric acid plants, and sulfuric acid plants were named in the 1970 regulations.

In addition, EPA was authorized to set standards for stationary sources' emission of any hazardous substances not already covered by the ambient air quality standards. *Hazardous* was defined to mean any substance that "may cause or contribute to an increase in mortality or any increase in serious irreversible or incapacitating reversible illness." Tagged as hazardous under this provision were mercury, asbestos, and beryllium.

The Clean Air Act Amendments of 1970 represented the first federal air quality regulations, except those for auto exhaust, that had any real teeth. After 15 years devoted mostly to funding research and offering guidelines, the federal government finally mandated firm standards and began rigorous enforcement.

Perspectives shift

Just as the fresh zeal in federal air quality supervision began to take hold, a further twist occurred. Data began to emerge from the St. Louis Regional Air Pollution Studies (RAPS) that forced researchers and regulators during the early 1970s to redefine their view of the nation's air pollution problem.

What these studies did was establish the importance of secondary particulates. By simultaneous monitoring of stack emissions and the plume downwind, scientists were able to show that particulates travel and undergo changes while airborne. Most striking, downwind air samples revealed the presence of new particulates that simply had not been there when the plume left the stack. Pioneer studies as early as the 1950s had pointed to the existence of secondary particulates, but RAPS and other work now left no doubt as to their presence and activity on a massive scale.

Once it became established that particulates could actually be created in the atmosphere—most likely from stack gases such as SO_x and NO_x—existing regulations seemed inadequate. Congressional reaction was to push for stiffer controls of both total suspended particulates and gases suspected of being their precursors.

Tougher amendments follow

The newest federal air quality laws, the Clean Air Act Amendments of 1977, reflect this altered perspective. The move once again is to force control technology by ratcheting down the allowable levels of SO_2, NO_2, and total suspended particulates in the atmosphere.

Part of the push has come in the form of a proposed tightening of new-source performance standards for these three target pollutants. For new plants that will burn fossil fuels, mainly coal, EPA is contemplating cuts to the following levels:

▫ For SO_2, 85% removal from fuel (before or after combustion) or emissions lower than 0.2 pound per million Btu

▫ For NO_2, 65% removal from soft coal and an emissions limit of 0.6 pound per million Btu

▫ For particulates, 99% removal from stack gases, an emissions limit of 0.03 pound per million Btu, and a visual limit of no more than 10% opacity

Whether such tough standards can currently be met, even with the best control efforts, is open to serious doubt. As pointed out in the April 1978 *EPRI Journal* (p. 49), "Current demonstrated experience does not support control levels more stringent than 0.06 pound per million Btu" for particulate matter. Furthermore, the costs of bringing particulate removal efficiency to 99% could be very high.

Building new coal-fired industrial plants to the proposed standards will be very difficult. Perhaps even more difficult, though, will be the prior step—finding sites for the plants that are legally acceptable.

The 1977 amendments place very stringent limitations on where potential polluters may build. In clean air areas (defined as those where pollutant concentrations do not exceed ambient standards), the aim is prevention of significant deterioration (PSD). In other words, the builder must show that the new facility would not, to a specified degree, degrade local air quality.

In dirty (nonattainment) areas, the new rules are even stricter. A potential polluter must actually improve local air quality. For example, if a new plant is engineered to release five tons of pollutants daily, the polluter must devise some way to remove more than that amount from the local atmosphere each day. While it is not impossible to satisfy this requirement—say, by buying out another polluter that emits six tons a day and closing down his operation—compliance may be very, very costly.

In the effort to cut down further on particulates and their precursors, the 1977 amendments pose major problems for control technology and plant siting. On top of this, questions are once again emerging about the whole direction of our air quality effort. Are we really regulating the right things? What point is there in launching a herculean effort to clean 99% of the particulates out of the plume if the most harm comes from the fine particulate fraction that gets away?

Today's issue: regulating fine particulates

Current controversy centers on those very fine particulates (less than 2 micrometers) that no control technology has yet succeeded in eliminating. Particles of this size are prime culprits in visibility degradation. Furthermore, being very small, they can slip easily into the human lung. What's worse, they tend to settle there. And worst of all, many of them carry or contain potentially toxic substances, such as trace metals.

New research underlining the toxicity of fine particulates has naturally led to demands for their control. And the mandate for EPA regulation of such toxic substances already exists, in both the 1970 and the 1977 amendments. In the latter, EPA has been handed the power to lay down standards for heretofore unregulated pollutants that "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health." With the findings of health effects at high levels and the tendency to extrapolate to low levels, coupled with the public demand for avoidance of any possible risk, regulatory action on fine particulates seems only a matter of time.

Two major approaches for fine-particulate regulation are now emerging from a pack of possibilities. One approach is simply to tighten the screws still further on total particulate loadings—to mandate particulate cleanup levels to, say, 99.99%, along with even stricter SO_2 and NO_2 standards, since essentially all secondary particulates are in the fine category. The other approach is to zero in specifically on fine particulates as a separate and distinct type of pollutant. This tack could mean official EPA listing of fine particulates as hazardous agents, with subsequent promulgation of separate fine-particulate standards.

And there are still other options. Regulations could shift more toward the achievement of ambient conditions than direct emissions control. Or the cost of further pollution control could be perceived as not worth the reduction in the risk of effects from pollution.

Whatever the route chosen, months and even years of haggling can be expected. The move to regulate fine particulates, already under way, will probably hew to the historical pattern in air quality legislation: New knowledge yields a new definition of the problem, which in turn —eventually—yields proposed new solutions in legal form. ■

Particulates/Control

Clearing the Air

Controls on new power plants

Air pollution control at the power plant stack has two separate targets: gases and particulates. The emphasis in control technology has varied between them in response to environmental priorities. These, in turn, have flowed from our growing understanding of the mechanisms of air pollution. Local, state, and federal regulation has expressed that understanding in the form of stack emission limitations.

The first control efforts were directed at soot and fly ash because they were unsightly in the air, cutting visibility, and because they soiled whatever they touched: clothes, home furnishings, buildings, and the landscape itself. More efficient, cleaner-burning fuel-air mixtures came first. Then came special apparatus in the flue gas ducts—cyclones and electrostatic precipitators. Together they capture 99% or more of the total suspended particulate matter in fly ash. Fly ash is about 80% of all combustion ash. The other 20% is bottom ash and economizer ash, both of which fall out naturally from the boiler and combustion gas ductwork without special equipment to intercept them.

Precipitators, the dominant control device today, are most effective in removing the larger, coarser particles and achieve an efficiency level of 99.9% for particles with diameters 3 micrometers and larger. (Collection efficiencies are higher for large-size fractions than for

rapping more than 99% of the ash from coal. The tiniest particles still pose a costly R&D problem.

total suspended particulates, and efficiencies for small-size fractions are lower.) Whatever escapes, then, measured in mass or in numerical quantity, is mostly smaller than 3 micrometers.

Concern for gases

The second historical emphasis in emission controls was on gases, notably sulfur dioxide and nitrogen oxides, because they were thought to be health hazards in their primary (emitted) form, as measured in ground level concentrations in the ambient air. This thinking is now changing to acknowledge that these gases are instrumental in atmospheric chemical transformations to secondary particles.

Control of nitrogen oxides emission is primarily located in the region of the burner and involves continual refinement of combustion conditions and chemical reactions.

With respect to sulfur dioxide two means of control have been employed. The most direct is the chemical scrubber, which uses lime or limestone in a water slurry to trap sulfur by chemical reaction, forming a waste sludge that is ponded for dewatering and disposal.

Less direct control is afforded by the use of very tall stacks to discharge sulfur dioxide (and nitrogen oxides) well above ground level so that natural dispersion reduces the measurable concentrations below statutory limits. Because of what we are coming to know about air pollution chemistry, tall stacks as a regulatory compliance strategy (for they are not truly an emission control) are now of importance only as a stopgap.

Returning to particulates

Today, the emphasis of stack control has shifted back to particulate matter. As the pendulum has swung, the concern has narrowed to address the fraction of fine particles earlier allowed to escape. There are at least five reasons for this focus.

□ Particles less than 2 micrometers are respirable to a degree that coarser ones are not. Even if chemically inert, they are a physical irritant to lung tissue.

□ Because of their greater surface area relative to their size or mass, fine particles offer a large reactive or adsorptive capacity for capturing other elements by chemical or photochemical means in the atmosphere or by coalescence or condensation.

□ Fine particles are increasingly being recognized as the principal carriers of trace metals in coal, and many are toxic—lead, cadmium, manganese, chromium, thallium, beryllium, nickel, and arsenic.

□ The particle size range 0.1–1.0 micrometer matches the wavelength of visible light, and such particles are thereby most effective in scattering or absorbing sunlight, causing opacity of the stack exhaust plume and generally lower visibility.

□ Doubling the coal consumption of electric utilities from 450 million to some 880 million tons annually in the next dozen years means a significant increase in the potential atmospheric loading of fine particles.

One solution

Although fine particulates pose a number of problems, they are all amenable to one solution—more efficient removal from the flue gas stream. Thus, given an emission standard to be met, the all-important task is to design, build (or improve), and operate mechanisms that can do the job. A close second is the task of measuring control performance. And the third task is staying ahead of the game.

Air pollution control engineers are fond of indexing their accomplishments in terms of penetration, that is, the fraction of particulate matter that escapes despite controls. Today, for a device that is 90% efficient (and this is routinely attained) 10% of the total particulate mass in the flue gas stream penetrates to the atmosphere. When the efficiency is hiked to 95%, the penetration is reduced to only 5%. From the standpoint of the surrounding community, emissions are thus cut by 50%—no mean accomplishment.

But at today's nominal level of 95% particulate control, single percentage improvements in efficiency (and the corresponding cuts in penetration) come hard and are costly. Scientists and engineers are even working on tenth-of-percent improvements, and they are looking for both absolute economy and a rational measurement of the benefits achieved.

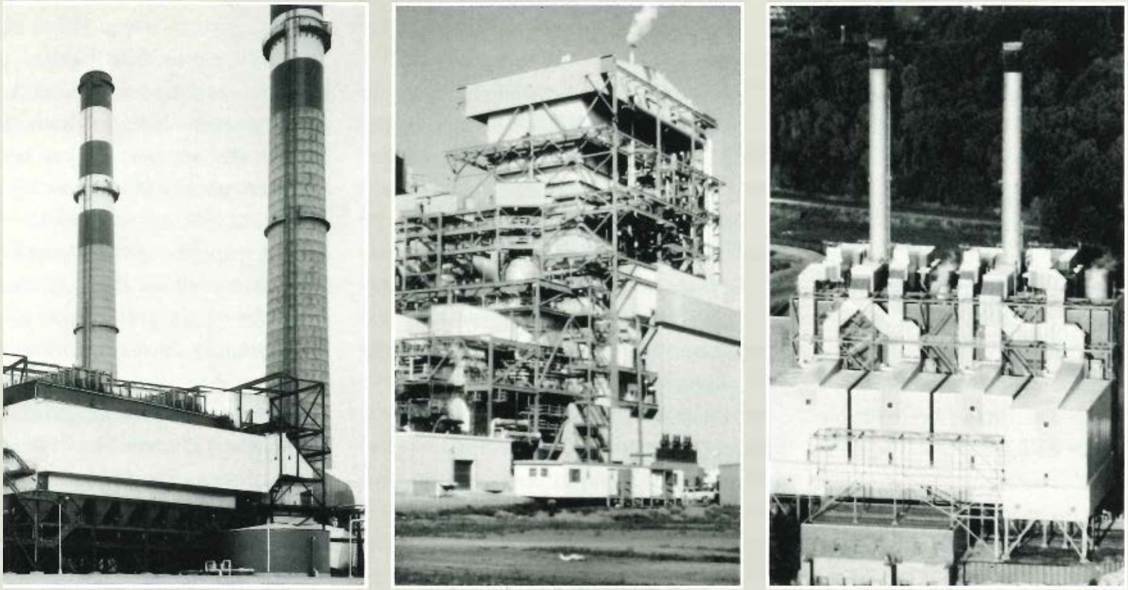
Ultimately there may be a dollar value assigned to improvements in human health, crop and fishery yields, weather and visibility restoration. But today the only measure is one of comparative performance: How much more particulate does a new or improved control consistently and reliably trap? How much more than its predecessor does it cost?

Controls in a new plant today represent 3–4% of the total cost of power generation, and it is estimated that the cost of owning and operating a precipitator to cut penetration in half would be at least 20% greater. In terms of overall efficiency, this improvement would probably be as little as 1%.

The nature of fly ash

Fly ash from coal combustion covers a wide range of particle sizes that originate in several ways. Purely mechanical processes, such as pulverizing, account for particles from several micrometers in diameter up to 100 micrometers or more. Incomplete combustion yields particles in the range of 0.1–1.0 micrometer. Some fuel components vaporize and then condense in the flue, forming particles in this same size range. And there is ionization, producing particles that range from molecular clusters as small as 0.005 micrometer up to so-called condensation nuclei of perhaps 0.01 micrometer. In contrast to all these, a natural dust kernel is about 500 micrometers, and the diameter of a human hair is about 100 micrometers.

Uncontrolled fly ash emissions are characterized by a mass median diameter of 8–30 micrometers. Conventional cyclones, scrubbers, and precipitators reduce this size range to 0.5–2.0 micrometers. Thus it is fine particles that are



Cavernous ductwork and its framing mark the paths of power plant flue gas and the equipment needed to remove tons of fly ash every hour. Electrostatic precipitators (left) between a 700-MW plant and its twin stacks contain 2800 collector plates to capture highly resistive fly ash from low-sulfur coal combustion. Wet scrubbers (center) at a 700-MW power station feature extensive steel support for the vessels and piping of venturis and alkaline sprays that remove both particulates and sulfur dioxide from flue gas. Baghouses (right) added to a power plant are scaled to the different gas flow volumes from its three 25-MW and one 40-MW coal-fired units. Even this modest installation involves more than 3300 separate fabric filter bags.

POWER PLANT EMISSIONS IN PERSPECTIVE

As frequently characterized, the electric utilities are third in the nation (behind automobiles and heavy industry) among readily definable sources of air pollution. Indeed, fossil-fueled power plants are acknowledged to produce 24% of annual particulate emissions, 65% of the sulfur oxides, and 29% of the nitrogen oxides. Of this, about two-thirds come from coal-fired plants. And on a weight basis, the particulate residue from coal far exceeds that from oil: 80–120 pounds of emissions per 1000 pounds of coal, compared with less than 2 pounds of emissions from an equivalent amount of oil.

the target of advanced emission controls.

The structure of fly ash particles can also be characterized. Among the largest are hollow spheres of 20–60 micrometers in diameter. Despite their gross dimensions, they are significant in fine-particle control for two reasons. Some are empty and therefore extraordinarily light for their size, thus having aerodynamic properties of much smaller particles. They tend to bounce off collection surfaces and continue out the stack. Other large, hollow particles, however, contain smaller ones inside, perhaps 10–200 solid particles. Some estimates suggest that 20–40% of all fly ash particles in the 5–10-micrometer range are encapsulated and thus captured by large-particle control devices. The remaining category of large fly ash particles is solid spheres smaller than 5–10 micrometers.

Particle size has a direct bearing on trace metal transport. Because of its geologic origin, coal contains traces of nearly every element. Most of them remain in bottom ash. But some are found in the fly ash fraction, where the concentrations of several elements, heavy metals among them, are greater on the fine particles. The mechanism of this enrichment is not conclusively known; it may result from evaporation and subsequent condensation. It is important to learn if the concentrations exceed those on natural atmospheric particles.

Other than fly ash, flue gas streams include a small fraction of polycyclic organic material (POM) in particulate form. POM is known to include carcinogens, but the quantity traceable to power plant emissions is judged to be less than 1% of the total from all sources.

Dimensions of the control problem

The magnitude of the emission control problem can be seen by another set of dimensions, the flue gas duct itself and the volume of the exhaust stream passing through it. For a 1000-MW coal-fired plant, the ductwork approaching a scrubber or precipitator measures some 84 square meters (900 square feet) in area. In a typical case, the gas flow through this ductwork may be 1887 cubic meters per second (4 million actual cubic feet per minute), at a velocity of 18 meters per second (60 feet per second). (Actual cubic measure denotes volume at a stated temperature.)

This volume can be translated into mass loading. A convenient working figure is 40 tons of fly ash every hour for a 1000-MW plant that burns 500 tons of coal per hour (with an ash content of 10%). On an annual basis, with some discount for plant availability, the control target is easily larger than 300,000 tons.

Three basic control technologies deal with fly ash in volume: electrostatic precipitators, aqueous scrubbers, and fabric filters. A fourth, centrifugal cyclones (which whirl the gas to cast out particles by centrifugal force), does a credible job on large fly ash particles but is not economically amenable to improvement in dealing with the fine fraction.

Putting a charge to fly ash

The electrostatic precipitator (ESP) came to the forefront shortly after World War I in the first effective attack on fly ash. It is thus well known and has been reduced to familiar practice, satisfactory reliability, and relatively low capital and operating cost. Its overall performance is excellent, typically 99% in terms of the total mass of fly ash. And its own energy consumption is characterized in terms of a small pressure drop from inlet to outlet (typically only half an inch of water).

An installed ESP consists of narrow vertical passages in the duct, with slender wires or rods between the suspended plates that form the passages. A high-voltage field is established between wires and plates, and a charge is imparted to the fly ash particles, causing them to flow to the plates and adhere by electrostatic attraction.

ESPs today are sectionalized, having as many as 14 separate fields in series with progressively lesser strengths to effectively charge and collect successively smaller volumes and smaller sizes of particulate. The accumulated dust layer on the plates is periodically shaken loose by cam-actuated hammers, or rappers, that vibrate the plates, and the dust falls into hoppers for disposal.

The technology is conceptually simple, the apparatus is relatively compact (considering its task and its competitors), and the flue gas stream remains dry, which minimizes corrosion problems downstream and yields a buoyant plume of minimal opacity for whatever fine-particulate fraction still contained at the stack exit.

Opacity, of course, is a specific issue of air pollution control, and it is a function of the concentration of light-scattering particles in the size range of visible wavelengths. Under today's emission standard for new power sources (0.045 kilogram, or 0.1 pound, of particulate mass per million Btu of fuel heat content), a plume opacity of 20% is a reasonable correlation. Less certain is the relationship between the 0.014-kilogram (0.03-pound) limit and 10% opacity of tighter emission standards now proposed.

Precipitators thus become much less efficient and much more expensive in dealing with ever-finer particulate matter. Their efficiency also depends on the ash and sulfur content of coal. The latter has especially motivated major developments in precipitator design and operation, because sulfur dioxide control concerns have turned attention to low-sulfur coal reserves.

But another key factor in ESP performance is the relative conductivity or resistivity of the fly ash. Low resistivity is desirable, but low-sulfur coals characteristically yield a high-resistivity ash. Dealing with it requires stronger ESP fields, larger collection plate area for a given gas flow, and more violent rapping because high-resistivity dust also sticks tighter.

Nearly every ESP design parameter has thus come up for research and further development. Sticky dusts build up thicker and sooner; thicker layers effectively reduce the field intensity and lower collection efficiency.

One response to these phenomena has been to reposition ESPs upstream, to the hot side of air preheaters, because ash resistivity is lower by two orders of magnitude at the higher temperatures. Another response is to impart a higher electrostatic charge. The EPRI-sponsored high-intensity ionizer does just that, by a factor of 3–5. A third approach is the use of conditioning agents in the flue gas stream to reduce resistivity. However, there are several problems with the last approach: cost, uniformity of particle distribution, and potential fouling of surfaces.

EPA and EPRI research today seeks advances that will tailor ESP performance toward the removal of fine particles by agglomeration before collection, by duct geometries that will produce more uniform gas flow across the entire ESP frontal area, and by more effective rapping and dust removal. For example, the kinetics of collector plates 9 meters (30 feet) high are complex and their vibratory patterns more so, yet ash must be jarred loose sufficiently to fall for collection, and not so hard as to be caught up again in the flue gas stream (reentrainment).

Scrubbing particles

Scrubbers involve more variety of configuration than ESPs, but they are well named because they all employ a liquid (mainly water) to wash particles out of the flue gas stream. Additionally, of course, by the introduction of lime or other chemically reactive compounds, they are used to extract sulfur dioxide.

Two common scrubbers for particulate removal are the venturi type and the moving-bed type. In the former, venturi restrictions accelerate the gas stream so that it atomizes the water. The different velocities of gas particles and water droplets provide many opportunities for impacts (head-on collisions) and interceptions (tangential ones) by which particulates are captured in the droplets. The moving-bed scrubber promotes mixing and impaction in a turbulent three-phase medium, a bed of glass or plastic spheres, as well as water and gas.

A more recent technology than ESPs, scrubbers have the potential advantage of being suitable for both gaseous and particulate emission control. Also, their efficiency is independent of coal ash composition. However, they may require a pressure drop of 8–10 inches, as well as a large water flow rate, for good particulate removal. The last fact leads to a number of problems: the water supply itself, waste water pollution control, an enlarged volume of wet waste (sludge), entrainment of mist in the flue gas, and numerous opportunities for scaling, plugging, and corrosion.

Although scrubber efficiency generally exceeds 99% for particulates larger than 2–3 micrometers, it falls off drastically for fine particulates (to less than 20%) and is susceptible to improvement only at great energy cost and greater pressure drop. There is, in fact, an inherent incompatibility of objectives in optimizing scrubbers: efficient gas removal is fostered by a long residence time (the period of contact between liquid and gas particles), while efficient particulate removal is fostered by high relative velocities and, therefore, a short residence time—virtually the moment of impact.

Baghouse: the cutting edge

The cutting edge of utility particulate control is adaptation, development, and scaleup of the fabric filter. Its configuration is well described by the name, baghouse, given to the multicompartmented installation that contains thousands of bags, each perhaps 305 millimeters (1 foot) in diameter and 9 meters (30 feet) long. Typically, the bags are suspended above flanged holes in the compartment floor. Flue gas enters the bottom of the bags, passes out through their walls into the compartment itself, and flows on to the flue duct.

Fabric filters could not have been considered for utility use until the advent of synthetic fibers that can withstand the thermal and chemical environment of flue gas ducts. Today there are a number of materials, mainly glass fiber, that can be woven or felted in a number of ways. Most of these materials are eminently efficient throughout the particulate size spectrum but differ in their lifetimes under operating conditions and also under the physical stress of the techniques used to clean them from time to time.

Three means are conventionally used in various industries to remove dust from fabric filters. The common ones are a reverse air flow and a technique that combines reverse flow with a gentle shaking of the bag at its point of suspension in the baghouse. The third is that of pulsed reverse air flow. This is a much more severe process, which shortens bag life.

EPRI has sponsored comparative research studies of ESPs and bag filters under specific conditions: a 500-MW design using four different coals, with variations in power output, collection areas (the measure of ESP capacity), and air-to-cloth ratios (the measure of fabric filter capacity). At the current particulate emission standard of 0.045 kilogram (0.1 pound) per million Btu, the levelized annual cost of the fabric filter is almost economically competitive in controlling the dust from three of the four coals. At the lower emission level of 0.023 kilogram, or 0.05 pound (the currently proposed EPA standard for new plants is 0.014 kilogram, or 0.03 pound), the fabric filter is more economical for three of the four coals.

When these theoretical results are extrapolated to deal with the flue gas volume of a 1000-MW coal-fired plant, the fabric filter always appears as the economic choice because increases in baghouse capacity are less costly than those in ESPs.

Interestingly, fabric filter cost, by any measure and for any plant capacity, is constant for all values of emission standard. Performance efficiency is a function of the filter fabric and virtually independent of coal or ash character. In fact, filter efficiency improves as the dust layer first builds up on a clean bag.

Limited and atypical utility use of fabric filters on a small scale has produced efficiency figures of 99.8% removal of total particulate mass, and better than 99% for those particles larger than 0.1 micrometer. In one test, efficiencies reached 99.9% for particles larger than 0.36 micrometer.

Despite these impressive figures, fabric filters are not being adopted and designed into many power plants today. The principal reason is the lack of widespread experience and the consequent absence of thorough cost and reliability data. Another is the excessive pressure drop, approximately eight times that of an ESP. Also, operation and maintenance requirements are not yet well defined—for example, the frequency of bag breakage and replacement, and possible corrosion problems arising from the use of high-sulfur coal.

The influence of instruments

If the problems of controlling particulates are difficult, it can fairly be said that the problems of measuring control performance are fierce. Instruments must perform their functions in the high-temperature, -pressure, and -chemical environment of a combustion flue gas stream. But what is worse, the instruments themselves (their materials and configuration) influence the behavior of the particles being monitored, thus altering their size distribution, concentration, and even their chemical composition.

Monitoring instruments capture particles by the same physical mechanisms featured in ESPs, scrubbers, and fabric filters: impact, interception, and diffusion, primarily. Each is best suited to a different particle size range.

Impactors (and cyclones, impingers, and centrifuges) depend on inertia, a use-

The Emissions Control and Test Facility at Denver, Colorado, symbolizes EPRI's integrated approach to air quality control. Several complementary R&D efforts are being pursued with the common objective of developing more effective hardware to fit between a coal-fired utility boiler and its exhaust stack.

Built alongside the Arapahoe station of Public Service Co. of Colorado, the test facility went into full operation late last year, drawing as much as 33 m^3/s (70,000 ft^3/min) of flue gas through its three sets of ductwork. Today, a 24-m^3/s (50,000-ft^3/min) stream permits experimentation with commercial-scale electrostatic precipitators; a 4.7-m^3/s (10,000-ft^3/min) stream is being fitted for subscale and diagnostic work with small arrays of high-intensity ionizers and precipitator sections; and the remaining 4.7-m^3/s (10,000-ft^3/min) stream is being prepared for tests of a small gravel-bed module and an electrostatically augmented fabric filter. A year from now, a fourth stream rated at 18.9 m^3/s (40,000 ft^3/min) will be ready to begin work with conventional fabric filters.

The difficulty in setting priorities and the sequence of test programs was summarized in the *Journal's* interpretive report on the Clean Air Act Amendments of 1977 published last April. The following comments are drawn from the section on particulates (p. 48).

"Based on extensive EPRI field test results, the proposed [by EPA] reduction in the particulate New Source Performance Standard to 0.03 lb/MBtu and 10% opacity will be technically and economically beyond the commercial state of the art for electrostatic precipitation. . . . However, technology improvements in development could, if successful, permit this control capability by the early 1980s. . . . The probable immediate result . . . will therefore be a shift to fabric filters (baghouses). Although removal efficiency test results have been encouraging, at the present time baghouses are only being used on four small, atypical utility generation facilities. . . . [A] reliable commercial design base for immediate, large-scale application over the range of commercial utility boiler and fuel conditions does not exist and will not for at least three years."

In short, the fabric filter reveals inherent performance capability but is not routinely available, while the precipitator is widely available and reliable but falls short of the performance efficiency required to meet tighter emission limits on a routine basis. Which avenue to pursue first?

For two reasons, improvements in precipitators have first call on the test facility capabilities. One is the existing utility investment in precipitators and the consequent incentive to upgrade their efficiency. The other is the new technology of the high-intensity ionizer, a novel device that employs an array of venturi orifices (arranged like a diffuser plate) to speed flue gas through the intense charging field of each orifice. The result is higher electrostatic charges on the particles (3–5 times), greatly enhancing the efficiency of particle collection on the plates of a conventional precipitator.

A further development to be evaluated at Arapahoe is the fine-particulate agglomerator. Because of the inherent inefficiency of precipitators for fine-particle collection, this device will use the enhanced charge produced by the ionizer to agglomerate the fine particles before they reach the collection plates.

The ionizer and the agglomerator are both physically compact for retrofit installation ahead of existing equipment. They offer the promise of reduced size (and therefore cost) for the new precipitators needed to treat any given flue gas volume.

While ionizer and precipitator test programs occupy two of the flue gas streams at Arapahoe, the third is about to test a gravel-bed module for high-temperature gas cleanup. The mechanisms and kinetics of the module are analogous to those of a scrubber: thoroughly mixing the particle-laden flue gas with a medium offering extensive surface area for capturing particles by impaction.

Next year, this evaluation will be succeeded by subscale tests of an electrostatically augmented fabric filter. Here electrostatic phenomena are used to condition the character of the filter dust layer as it builds up, making it more uniform. It also makes the layer fluffy so that its labyrinthine passages offer more surface area for particle capture, while permitting clean gas to get through with minimal pressure drop.

The future scope of fabric filter tests is still being worked out. In general, research will seek to optimize filter performance in terms of the trade-offs in air-to-cloth ratio, cleaning techniques, and bag geometry.

In essence, the Emissions Control and Test Facility is a test bed for both improved and entirely new concepts in particulate removal. Its instrumentation and management afford opportunity for thorough and consistent evaluations and the gradual accumulation of a data base that is authentic in correlating emission standards with emission control performance.

ful property in particles larger than about 0.3 micrometer. The gas flow is constrained to a curve in passing the collection surface, and inertia causes particles to cross the streamlines of flow and hit or land on the impactor surface. The tendency of particles to bounce makes for an unclear boundary between particle sizes collected on impactors that have been tailored to specific sizes.

Interceptors are arranged geometrically to collect lighter, smaller particles that do not cross streamlines. The mechanism is more nearly that of friction, stopping a tangentially passing particle.

Diffusion takes advantage of electrical conditions that can be established and are known to favor the attraction of one or another particle size or range. This monitoring method is useful for so-called ultrafine material less than 0.5 micrometer in size.

The differences among these mechanisms of sample collection explain in part a dip in the efficiency of ESPs for capturing particles in the 0.05–2.0 micrometer range. Larger particles intercept many flux lines in the ESP field and accept a strong charge, attracting them to the plates; ultrafine particles are governed by the diffusion-charging behavior of a gas. But neither electric mechanism works consistently well for the particle sizes in between.

Measurement of collected sample concentrations and distributions takes advantage of many physical properties and phenomena: gravimetric, optical (light scattering, mainly), chemical, and electrical. A distinct problem is in correlating theoretical and empirical values, or in explaining and compensating for them otherwise. One measurement technique, for example, requires that the sample be diluted in order to count the sampled particles by the difference between emitted and received light intensities across the sample chamber. Corrections must then be made to compensate for the dilution.

Sample-size distribution may be influenced by particles already collected, as when a filter's holes become partially plugged and retain smaller particles than intended. Also, there may be secondary particle formation on the sample probe or monitoring surface that distorts the profile of particle-size distribution in the flue gas.

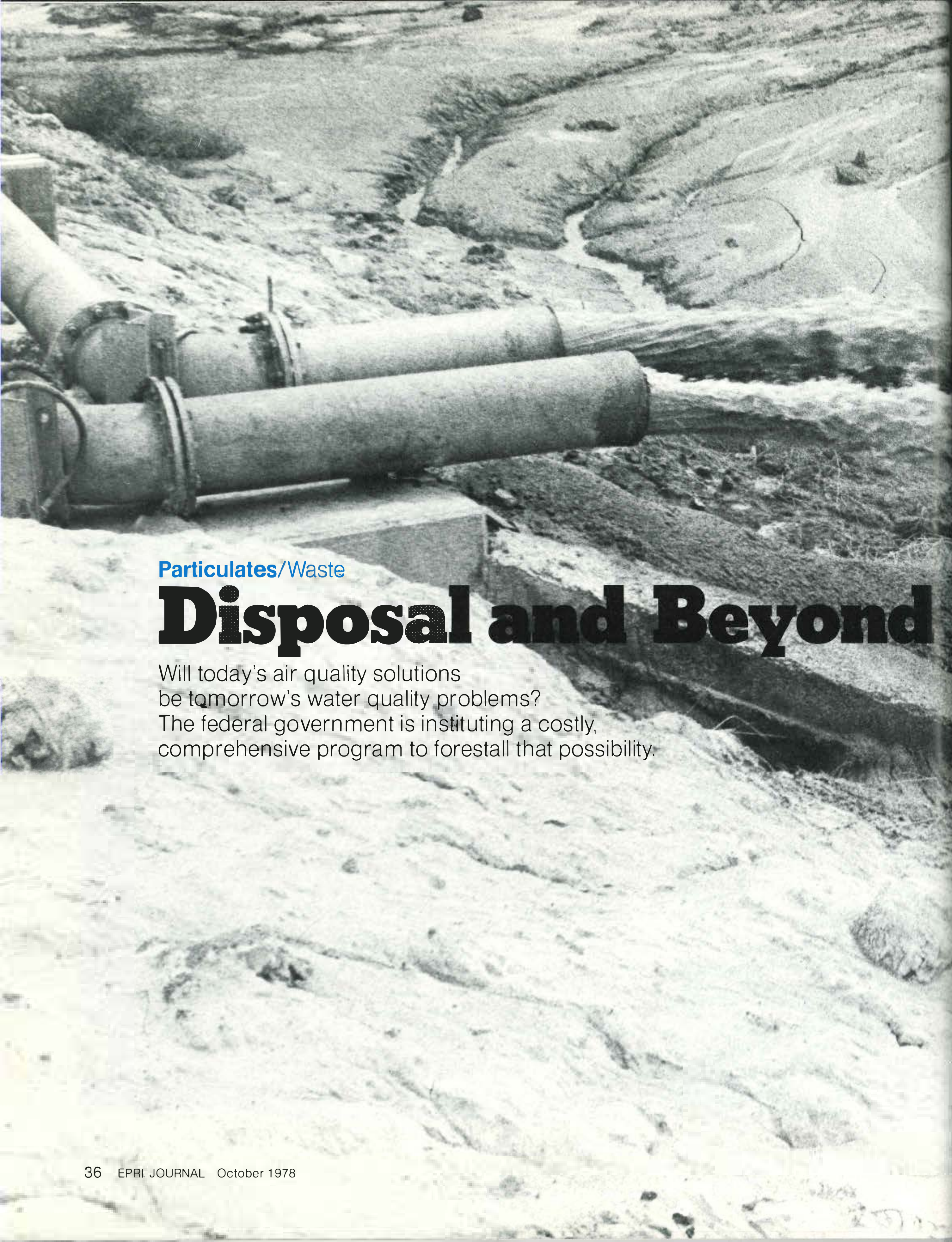
In sum, each instrument for particle sampling or size and concentration analysis has its limitations in applicability, reliability, and reproducibility of results.

Forcing the technology

From this qualitative survey of particulate emission control and instrumentation technology, it is apparent that air pollution control itself is still new. Evolving scientific knowledge, translated into regulatory standards, is forcing the technology today. Many of the nation's designated 200-plus Air Quality Control Regions are not yet meeting all the ambient standards laid down in 1971. Cost-motivated reluctance by one or another factory or industry isn't the only reason. Another is the complex and infinitely varied chemical and particulate composition of the aerosols over different communities. Statutory controls may be effective in one case but far off the mark in another. Equally significant is the formative nature of fine-particulate control technology itself.

Wherever their sources (in the case of primary particles) and whatever the mechanisms of formation (in the case of secondary particles), the fine fraction of total suspended particulates has come to dominate the scene.

From the standpoint of a community or region whose populace breathes and functions in ambient air, emission controls are a single entity. They must address the gaseous precursors of secondary particles as well as the primary particles that originate in power plants. Today the pendulum of stack emission control swings toward primary particulates from coal. But because of the major role of gaseous sulfur dioxide and nitrogen oxides in the formation of secondary particles, it is foreseeable that the pendulum eventually will again swing the other way. ■



Particulates/Waste

Disposal and Beyond

Will today's air quality solutions
be tomorrow's water quality problems?
The federal government is instituting a costly,
comprehensive program to forestall that possibility.

Electric utilities have spent billions for filters, electrostatic precipitators, and scrubbers to clean particulates and chemicals out of flue gases at fossil-fueled power plants. The products of air pollution control, fly ash and scrubber sludge—as well as bottom ash and wastes from other plant operations—are disposed of in pits, ponds, and landfills at rates of about $2 a ton.

Those modest prices may soon climb skyward. Under the Resource Conservation and Recovery Act of 1976 (RCRA), the EPA has drafted tough new regulations for the treatment, storage, and disposal of hazardous solid wastes, including a series of chemical and biological tests for determining hazard to human health or the environment. RCRA defines solid waste as "any garbage, refuse, sludge from an . . . air pollution control facility . . . including solid, liquid, semisolid, or contained gaseous material. . . ." Any waste not discharged under a Section 402 NPDES permit is considered a solid waste. Metal-cleaning waste would be a solid waste when disposed of in landfills and an effluent when discharged under NPDES requirements.

There is industry concern that power plant wastes may be classified as hazardous under these tests; if the regulations and the tests become final early next year, the cost of disposing of any hazardous utility solid waste might reach $90 a ton. For an industry that churns out 60 million tons of waste a year, the implications are in the multibillion-dollar range. As Kurt Yeager, director of EPRI's Fossil Fuel Power Plants Department, explains, if all utility wastes are declared hazardous, disposal costs under draft regulations could nearly equal utility fuel costs.

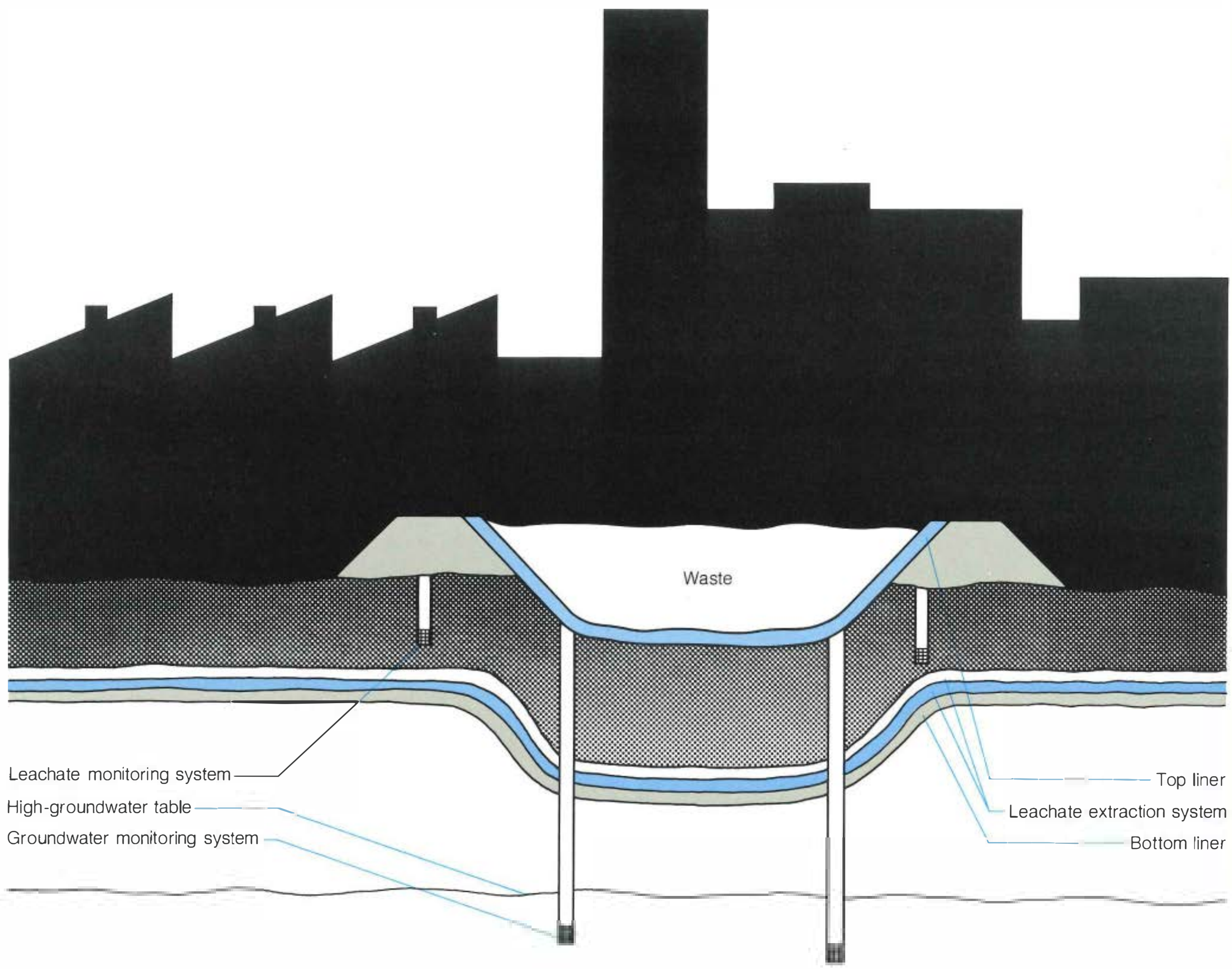
Contamination fears

Utility industry wastes are mixtures of trace elements and other compounds that are potentially hazardous. According to Tony Colucci, project manager in the Health Effects Program, these wastes may contain arsenic, mercury, selenium, sulfur oxides, nitrogen oxides, hydrocarbons, and more. If the wastes are disposed of in a haphazard manner, there is a possibility that harmful amounts of these components may leach into the groundwater or mingle with surface water during floods or spills. In short, while utilities are cleaning up the air by using accepted air pollution control procedures they may inadvertently endanger the water supply. The results of any contamination could take years to become apparent.

However, there are concerns that draft tests (issued March 24, 1978) may not be appropriate. "Some among the scientific community question whether the proposed tests are a reliable indicator of hazardousness," says Ralph Perhac, manager of the Physical Factors Program.

Burden of proof

Under draft EPA regulations, the individual waste generator (in this case, the utility) is responsible for determining if the waste it produces is hazardous. A sample must be declared hazardous if it gives a positive result in just one of a number of tests for toxicity, corrosiveness, radioactivity, reactiveness, ignitability, or infectiousness.



To test for toxicity, for example, a utility must first obtain an elutriate, or extract, by applying a specific toxicant extraction procedure (TEP) to a representative waste sample. The elutriate may not exceed the specified concentration of any compound on the EPA's special chemical list, nor may it exceed applicable thresholds in EPA's criteria for human health water quality or aquatic environment water quality. Tests for mutagenic activity and bioaccumulation potential are among additional tests required.

The tests are not inexpensive. The cost of running one waste sample through this battery of toxicity tests can be anywhere from $10,000 to $15,000, according to Perhac. Furthermore, a plant may need to run a number of samples to make a fair report.

Test results depend on a variety of circumstances. Fly ash constituents, for instance, differ according to type of fuel used, method of combustion, and the point in the boiler from which the sample is obtained.

The industry is concerned that certain power plant wastes may be identified as hazardous by draft criteria. An EPRI data study done by Fred C. Hart Associates, Inc., indicates that ash, scrubber sludge, metal cleaning wastes, boiler blowdown, and other power plant wastes might approach or exceed certain of the draft criteria, specifically in the areas of toxicity, radioactivity, or corrosiveness, and therefore be considered hazardous. The waste streams with the greatest hazard potential were judged to be ashes and scrubber sludges.

Comparisons of waste data with draft criteria were made, using the maximum concentrations found for all potentially hazardous waste constituents; therefore, results represent worst-case conditions. Furthermore, the data used for comparison with the toxic criteria were based on samples taken from raw waste streams and not based on an elutriate obtained by the TEP, as specified in draft criteria.

"These conclusions are not meant to suggest that most fossil-fueled power plants, or even a typical plant, generate hazardous wastes," the report cautions. "They indicate merely that several waste streams at some power plants may contain concentrations of corrosive, radioactive, or toxic pollutants high enough to be deemed hazardous according to draft criteria."

Under proposed EPA regulations, wastes deemed hazardous to human health or the environment will be disposed of in carefully constructed landfill or ponding systems. This proposed pond model uses two low-permeability liners to prevent wastes from leaching into the groundwater A leachate monitoring system between the two liners alerts operators to any top-liner failure. Should a leak occur, the operator must be able to pump out the offending leachate. Below the second liner, a groundwater monitoring system acts as further assurance that leachates are being safely contained. Landfill systems proposed by EPA also call for liners and monitors.

The draft regulations strive to protect the surface water, too. All surface runoff from active portions of hazardous waste facilities must be collected and confined to a point source before discharge. Structures capable of diverting all the surface runoff from a severe storm from the active portions of the facility must also be constructed and maintained.

Surprising news

The news that ordinary power plant wastes might be categorized as hazardous apparently came as a surprise to many utilities. Coal ash, for instance, has been around—and disposed of—for centuries, and has many by-product uses, according to Dean Golden, project manager for solids by-product and hazardous waste disposal. He characterized the industry's realization of the situation as a "gradual but rude awakening" caused by emerging legislative and regulatory actions having major technical and economic impact on the utility industry.

As Perhac points out, there remain questions in the scientific community on the validity of the draft tests. Besides concern about what the tests actually indicate, there is the problem of reproducibility. "Many of the hazardousness criteria involve trace elements in parts per billion," says Perhac. "In this range, chemical analysis is almost as much an art as a science. There is a strong human element involved."

Another possible point of contention is what constitutes a representative sample of ash. "Different samples of ash from the same plant have different compositions," says Perhac. This could create confusion for those who will administer the tests.

There is some possibility that EPA may alter the proposed draft before the regulations become final. Accordingly, Edison Electric Institute (EEI), a national association of investor-owned utilities, has organized the Utility Solid Waste Activities Group (USWAG). Thirty-two utilities have already joined the group, according to Christopher Hughes, EEI's environmental projects manager. On the basis of applied research and data collection, the group will independently assess the validity of the proposed tests, and may ultimately suggest better ones.

Under regulations proposed in July, a utility will have 90 days after final criteria go into effect to identify and report any hazardous waste activity. Failure to report on time can result in civil and/or criminal penalties of up to $25,000 a day for each day of violation.

If a utility declares a waste nonhazardous and that waste is later proved hazardous, according to Golden, the penalty is a steep one: a fine of $25,000 a day, retroactive to the effective date of regulations. Utilities should be warned that RCRA contains a citizen suit provision that allows a member of the public to sue to enforce compliance with the statute.

A close watch

Under RCRA mandate, EPA will closely regulate the generation, transport, treatment, storage, and disposal of any waste determined hazardous. The states will help implement and enforce the regulations. The goal: to be certain the waste is contained. Golden estimates the cost of this zero-risk disposal will be about $90 a ton. He bases his figures on a 1976 EPA study of the hazardous waste management industry. The study estimated the disposal cost for hazardous waste to be between $88 and $90 a ton.

Draft regulations issued March 24, 1978, include strict rules on hazardous waste facility siting. These facilities may not be located in wetlands (with a few exceptions) or in areas where they could be inundated by a 100-year flood (one with a 1-in-100 chance of occurring in any year). Unfortunately, power plants are frequently sited near water to facilitate equipment cooling, and waste disposal facilities are usually sited near power plants to minimize disposal costs.

Facilities will not be allowed in critical habitat areas or near active fault zones. They must be a sufficient distance from public roads and residences so the public health is not endangered.

In addition to siting requirements, EPA has drafted other hazardous waste facility specifications. Landfills and ponds located over usable aquifers must be arranged so as to prevent direct contact between the waste and the surface water or groundwater. For landfills EPA suggests 3 meters (10 feet) of soil with a permeability of less than or equal to 1×10^{-7} centimeters per second. Groundwater and leachate monitoring systems will be required for all ponds and landfills that have the potential for discharge into usable aquifers.

Gates, guards, and warnings

According to draft regulations, unauthorized entry by people or domestic animals must be prevented by barriers, secured or manned gates, and warning signs on the facility perimeter.

The draft regulations also call for contingency plans for hazardous waste facilities. These plans would minimize damage to human health or to the environment in the event of accidental discharge. Copies of the plans would go to local police, fire departments, and hospitals.

Facility closure, long-term care, and personnel-training requirements are also part of the picture. For instance, draft closure plans for hazardous waste facilities require that all operating equipment must be disposed of or decontaminated by removal of waste residues. Arrangements must be made for future groundwater and surface water monitoring at disposal sites; the facility must provide the necessary monitoring equipment. The facility must be secured so that the waste cannot be contacted by people or by animals. The owner or operator of the facility must file information with the proper authorities, indicating what waste has been buried on the site.

Extensive bookkeeping

An integral part of RCRA is the extensive bookkeeping for hazardous wastes. Permits are required for owners and operators of waste storage, treatment, and disposal facilities. Strict record keeping is ordered. A utility, for instance, must record details on what and how much waste has been produced, as well as on its disposition.

RCRA also orders a comprehensive "cradle-to-grave" manifest (shipping document) system, which will track hazardous wastes from the point of generation to their ultimate disposition.

In a sense, RCRA echoes other recent federal legislation, specifically, the Toxic Substances Control Act of 1976 (TSCA). Under TSCA, EPA has promulgated inventory reporting regulations for chemical substances, including ash and sludge, manufactured for a commercial purpose.

Proposed RCRA measures are a decided contrast to the way most utilities now dispose of wastes. Ponds are usually unlined, unless there is a state requirement for that precaution, according to Paul Emler Jr., chairman of the policy committee of EEI's USWAG, and senior environmental advisor at Allegheny Power Service Corporation. "Probably less than half the states have very stringent groundwater requirements to the point that liners would be required."

As a rule, older landfills are not designed to prevent leaching; newer landfills generally have a leachate collection system. Emler also said that if fly ash and scrubber sludge are declared hazardous, it's extremely unlikely that any present disposal facility would pass muster with the draft EPA regulations.

Nonhazardous guidelines

Even if a waste is found to be nonhazardous, power plant waste disposal prices will go up—to about $10 a ton, according to Golden. Under RCRA, the individual states have the responsibility of establishing nonhazardous solid waste management programs. Federal guidelines will help the states develop plans, which will receive EPA approval. Without federal approval, a state will not receive funding for its solid waste program.

One minimum requirement for approval is the closing or upgrading of open dumps. These will be replaced by sanitary landfills—those that pose "no reasonable probability of adverse effects on health or the environment." Rules proposed February 6, 1978, will generally prohibit the siting of facilities in environmentally sensitive areas, such as wetlands and floodplains. Before a new site may be located or an existing site expanded in a sensitive area, the facility must clearly demonstrate that no feasible alternatives exist and that no significant adverse impact on the environment or public health will occur. A "clear demonstration" will entail the complete and accurate assessment of hydrogeologic, engineering, technological, environmental, economic, and other pertinent factors. These regulations encourage but do not require the installation of monitoring systems.

EPA is undertaking an inventory of disposal sites (the utility industry, not the only one affected by the new regulations, is expected to be inventoried in 1979), and anything less than a sanitary landfill will be given five years to come up to standards.

Industry response

If power plant wastes are judged hazardous, the utilities face a costly and time-consuming cleanup. There are, however, ways the industry could mitigate RCRA's impact.

Process changes might reduce the amount of waste produced. As part of an EPRI solid waste disposal program, for example, an increased emphasis is now being placed on the development of regenerative scrubber systems. Throw-away scrubber systems (those that produce sludge or other potentially leachable by-products) are the favored technology today for economic reasons. However, the more expensive regenerative systems, which produce marketable sulfuric acid or elemental sulfur, may prove to be the better choice in light of RCRA.

Utilities might also make use of the country's hazardous waste management industry for disposal of their wastes. This growing industry of about 95 firms operates some 110 disposal sites, according to Golden. EPRI is planning a study to determine whether this sector is capable of absorbing a large influx of utility waste, at least until utilities can site, design, and construct their own facilities.

Resource recovery, another goal of RCRA, might well result from tough new regulations. "Instead of spending $90 to dispose of a ton of hazardous waste," says Golden, "a utility would be encouraged to pay up to the same amount to develop that waste as a resource. For instance, it might be practical for utilities to recover valuable materials, such as aluminum, from fly ash under these economic conditions."

However, some existing ways of disposing of untreated power plant waste may vanish if this waste is determined hazardous. About 13% of the fly ash produced by electric utilities is now used—untreated—in civil engineering projects such as road building, according to John Faber, executive director of the National Ash Association. Should fly ash be determined toxic, corrosive, or radioactive, "We're in trouble," Faber says. The association is trying to convince EPA of the economic importance of ash recovery.

Impact uncertain

The overall impact of RCRA remains uncertain at this time. Over the coming months—even years—the EPA will draft, propose, receive comment on, and promulgate the multitude of bits and pieces that will constitute the law. The regulations have yet to be finalized and enforced; the electric utility industry is in the process of coping with the portions of the regulations now in evidence. Still, one certainty emerges: the days of $2-a-ton waste disposal are rapidly drawing to a close. ■

EPRI'S SOLID WASTE DISPOSAL PROGRAM

In response to utility industry needs, EPRI is preparing a major interdepartmental solid waste disposal program. This research and development effort will combine the resources of the Water Quality Control and Heat Rejection Program of the Fossil Fuel Power Plants Department and the Biomedical Studies, Ecological Effects, Health Effects, and Physical Factors programs of the Environmental Assessment Department. The new program will assist the industry in reducing the cost of achieving RCRA intent. The proposed program, which will be in the multimillion-dollar range, has five main objectives.

□ Define the physical and chemical nature of solid wastes. EPRI efforts will include evaluating EPA test procedures and determining the reproducibility of test results. EPRI will also look into fuel composition, sample variability, surface physics and chemistry, leachate chemistry, and transport phenomena.

□ Develop an economic and environmentally sensitive method for assessing the hazard potential of utility wastes. This will include health effects and biomedical studies, with studies on trace element toxicity and an assessment of the Ames mutagenic assay.

□ Develop resource recovery processes and utilization systems. EPRI will develop ways to remove hazardous constituents from waste and will evaluate the economics of hazardous waste treatment. FGD sludges and advanced system residues will also be studied. A handbook for using fly ash as structural fill will be developed, and the use of fly ash to enhance methane production will be evaluated.

□ Develop safe solid waste disposal systems. EPRI will study FGD sludge and ash disposal and will develop sludge and ash disposal handbooks. Disposal site studies are proposed, including groundwater modeling of leachates, an assessment of the environmental effects of current disposal systems, and a study of the effectiveness of various liners. Ocean and deep mine disposal options will be explored, together with disposal methods for advanced system wastes, such as coal liquefaction and gasification wastes.

□ Respond to socioeconomic concerns facing the industry. EPRI will assess the economic impact of RCRA on the utility industry, as well as the applicability of RCRA hazardous waste regulations to the industry. The capability of the hazardous waste management industry to absorb amounts of utility wastes will be evaluated, and the economics of FGD throw-away systems versus regenerative systems will be reevaluated.

Science and Technology—Gone Far Enough?

Cure for cancer. World hunger. Energy shortages. Have science and technology gone far enough? Certainly no one would deny that many of the fruits of science and technology have brought great benefits to the human race. Consider polio vaccine and other health care advances. Light, heat, and power for the home. New irrigation techniques. Indoor plumbing. Sanitation. These results of scientific endeavor have elevated the standard of living of entire populations in the industrialized world above what was dreamed about centuries ago.

In recent years, however, increasingly vocal segments of the public have raised questions about current and future directions for scientific probing and technological innovation. Concerns have been voiced about ethical limits, social impacts, and the human prospect for progress and survival.

The natural environment versus the human-made environment. Soft versus hard. Growth versus no-growth. Quality versus quantity. Dispersed versus centralized. The debates rage on.

Centennial of Light

The year 1979 offers the international scientific community and the public a unique opportunity to examine these issues and to take stock of where science and technology have been in the past century and where they are going in the future. October 1979 marks the 100th anniversary of Thomas Alva Edison's invention of the first practical incandescent lamp—an invention that began the electric age and the transformation of modern life. In commemoration of this milestone, industries and groups tracing their heritage to Edison have launched a year-long Centennial of Light celebration that will thrust into the limelight the concepts of innovation, invention, science, and technology.

As one of the official events of the centennial year, EPRI will join with the Thomas Alva Edison Foundation (a nonprofit organization dedicated to the advancement of science and engineering education) in sponsoring an international symposium, "Science, Technology, and the Human Prospect," April 1–4, 1979, in San Francisco, California.

"The Edison Centennial Symposium will be an international forum for exploring the impact that scientific discovery and technological innovation have had on society," said Chauncey Starr, symposium chairman and vice chairman of EPRI. "The program is planned so that participants may constructively address concerns raised about directions for science and technology. We hope to provide a clearer perspective for layman and expert alike on where we have been, where we are now, and where we are going in the future."

The symposium will bring together some 1000 leaders from the international science policy community, industry, government, research institutes, the media, and universities, including students who will inherit a world shaped by critical decisions made today. Participants will join in plenary sessions for 10 major addresses to be delivered by speakers representing science ethics, public opinion, and social impact. Seven workshops will focus on specific disciplines, such as food, health, and communications, giving participants an opportunity to formulate concrete recommendations for change in these areas. Two special sessions will explore the social impact of electricity and the resolutions of controversies in science and technology. A number of special events are also being planned.

Symposium highlights

Among the major issues the symposium participants will address are:

▫ How scientific discovery and technological innovation affect society's self-image and attitudes toward the physical environment. Evolution, for example, has changed views on religion. Labor-saving appliances in the home and other factors have dramatically altered self-concepts of women. The industrial revolution spurred socialism and may have contributed to current prevailing notions that society (government) should provide for basic human needs. What implications for future changes in self-concepts lie in today's innovations and discoveries?

▫ Ethical limits to scientific inquiry—one of the major science controversies of contemporary times. To what extent should we engage in genetic engineering? In bacteriological warfare? Survival dependence on life-support systems? Who makes these decisions? Addressing this general topic will be Alasdair MacIntyre, professor of philosophy and political science at Boston University. MacIntyre has extensively researched the problems of medical ethics and the philosophy of medicine. He is a consultant to the National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research.

▫ Energy and civilization. How have new power sources—from harnessed animals to steam engines and electric dynamos—altered social, political, and intellectual life? Is the most civilized society the one that uses the greatest amount of energy per capita? These questions form the basis of an address by George Basalla, a leading science historian who has written extensively about the social implications of science and technology. Associate professor of the history of science and technology at the University of Delaware, Basalla is the author of articles and a forthcoming book on images of scientists in pop culture (TV, comic books, movies).

□ Creativity. What factors give rise to creative individuals and creative societies? The age of the individual invention has given way to an era of scientific teamwork in large industrial laboratories. Which is more conducive to creativity that will benefit mankind? In the transition, has basic research been deemphasized to the detriment of innovation? One of the speakers addressing this topic will be Simon Ramo, vice chairman of the board, cofounder, and chairman of the Executive Committee of TRW, Inc. A leading spokesman for research and development, Ramo is a pioneer in microwaves, high-frequency radio, and the electron microscope. He is also an adviser to several government organizations. Ramo's address to the symposium will be "Technological Innovations."

□ Public reactions. There was a time in the golden age of invention when such figures as Edison were accorded the adulation of folk heroes. What happened to change this attitude to the disenchantment and suspicion prevalent today? Jean-Jacques Salomon, head of the Science Policy Division of the Organization for Economic Cooperation and Development in Paris, France, will address this general topic.

□ The human factor. How have science and technology affected the everyday lives, hopes, and dreams of the people? Have they brought adequate health care, education, leisure, material comfort? Speaking on this subject will be Eric Hoffer, longshoreman on the Pacific Coast, former migratory field laborer and gold miner, and prolific author.

□ Economic productivity. Looking at both developed and developing countries, how does economic productivity result from scientific advances? How can scientific and technological developments promote economic productivity? Addressing this subject from the viewpoint of developed countries will be Edwin Mansfield of the Department of Economics at the University of Pennsylvania. From the point of view of developing countries, the speaker will be Sumitro Djojohadikusumo, Minister of State for Research, Indonesia.

In addition to the speeches, workshops, and special sessions, the symposium will include a number of special events. A multimedia, audiovisual spectacular will open the symposium, providing an impressionistic review of the course of technology and society during the last century. Exhibits from the Smithsonian Institution and from Pacific Gas and Electric Company will display memorabilia of Edison and other facets of the period. EPRI will distribute a special issue of the *EPRI Journal* that will focus on the evolution of organized R&D. San Francisco Bay Area businesses and organizations will host a reception on the evening preceding the symposium at the Exploratorium in San Francisco's Palace of Fine Arts.

Questions about registration for the symposium should be directed to the conference managers, Government Institutes, Inc., 4733 Bethesda Ave., N.W., Washington, DC 20014 (301) 656-1090.

CENTENNIAL OF LIGHT 1879–1979
Calendar of Major Events

February 9–12	International Edison Birthday Celebration, Part I Disneyworld, Orlando, Florida Sponsored by the Thomas Alva Edison Foundation and the Edison Electric Institute Selected science students and educators will attend technical lectures by leading scientists and engineers, visit industries, and explore the scientific and technological marvels of Disneyworld.
February 23–March 1	International Edison Birthday Celebration, Part II Munich, Germany Sponsored by Thomas Alva Edison Foundation and Siemens Corporation Students from the Munich Technical University, the University of Munich, and other countries will attend technical lectures and visit industries.
April 1–4	Edison Centennial Symposium: "Science, Technology, and the Human Prospect" San Francisco, California Sponsored by the Electric Power Research Institute and the Thomas Alva Edison Foundation
October 21	Reenactment of Lighting the Original Bulb Greenfield Village, Dearborn, Michigan Sponsored by Thomas Alva Edison Foundation, the Henry Ford Museum, and Greenfield Village (The Edison Electric Institute) Officials will reenact the invention of the electric light, using Edison's original equipment in his Menlo Park laboratory transported by Henry Ford to Greenfield Village.
December 31	Reenactment of the First Street of Light Greenfield Village, Dearborn, Michigan Sponsored by the Henry Ford Museum and Greenfield Village (The Edison Electric Institute) Reenactment of the first electric lighting of a public street—the same buildings and houses first lighted by Edison for public display on New Year's Eve, 1879.

EDISON CENTENNIAL SYMPOSIUM
"SCIENCE, TECHNOLOGY, AND THE HUMAN PROSPECT"
San Francisco, California, April 1–4, 1979
(Preliminary Program)

Sunday, April 1	Reception at Exploratorium, Palace of Fine Arts	
Monday, April 2	Opening of Plenary Session	
	Remarks and introduction of speakers by the Honorary Chairman, Centennial of Light	Robert Smith, Chairman, Public Service Electric & Gas Company, New Jersey
	Remarks by Symposium Chairman	Chauncey Starr, Vice Chairman, EPRI
	Address: "Energy and Civilization"	George Basalla, Associate Professor, History of Science and Technology, University of Delaware
	Address: "Science and the Concepts of Man"	(Speaker to be announced)
	Luncheon	
	Address: "Ethical Limits to Scientific Inquiry"	Alasdair MacIntyre, Professor, Philosophy and Political Science, Boston University
	Special Session: "Does the Past Have a Future?: Trends and Issues in the History of Electric Power"	Thomas Hughes, Professor, History and Sociology of Science, University of Pennsylvania
	Workshop Sessions	
	Medicine and Public Health	Chairperson: (to be announced)
	Food and Agriculture	Chairperson: (to be announced)
	Urban Development	Chairperson: John Eberhard, Consultant, Architecture and Urban Planning
	Communications	Chairperson: (to be announced)
	Energy	Chairperson: Wolf Hafele, Deputy Director, International Institute for Applied Systems Analysis, Austria
	Human Population and Ecology	Chairperson: F. Kenneth Hare, Institute for Environmental Studies, University of Toronto
	Humanistic Aspects of Science and Technology	Chairperson: (to be announced)
Tuesday, April 3	Plenary Session	
	Address: "Patterns of Creativity in Science"	(Speaker to be announced)
	Address: "Technological Innovations"	Simon Ramo, Vice Chairman of the Board, TRW, Inc.
	Address: "Public Reactions to Science and Technology"	Jean-Jacques Salomon, Head, Science Policy Division, Organization for Economic Cooperation and Development
	Special Session: "Resolution of Science and Technology Controversies"	Arthur Kantrowitz, Chairman of the Board, Avco Everett Research Laboratory, Inc.
	Continuation of Workshop Sessions (statement of accomplishments, current and anticipated problems, and recommendations for action)	
	Reception	
	Banquet	
	Address: "Science, Technology, and the Human Factor"	Eric Hoffer, Philosopher and Author
Wednesday, April 4	Plenary Session	
	Address: "Science, Technology, and Economic Growth"	Edwin Mansfield, Professor, Economics, University of Pennsylvania
	Address: "Technology and Global Economic Development"	Sumitro Djojohadikusumo, Minister of State for Research, Indonesia
	Address: "Science, Technology, and Social Achievements"	(Speaker to be announced)

Film Series Spotlights Coal

The first of EPRI's technical films for nontechnical audiences is ready for release. *The Electric Story: Coal* is a 19-minute film that explores the technology and trade-offs of generating electricity with coal.

As the film is aimed primarily at high school and service club audiences, it is designed to entertain as well as educate. For example, an animated character opens walls in a power plant to show the basic process of turning coal into electric power, and simple working models illustrate the principles of electrostatic precipitators, filter bags, and scrubbers.

The coal film and the others in the series are based on the premise that if members of the public are honestly informed about the key technical problems the industry faces, they will be better able to make informed political and economic decisions.

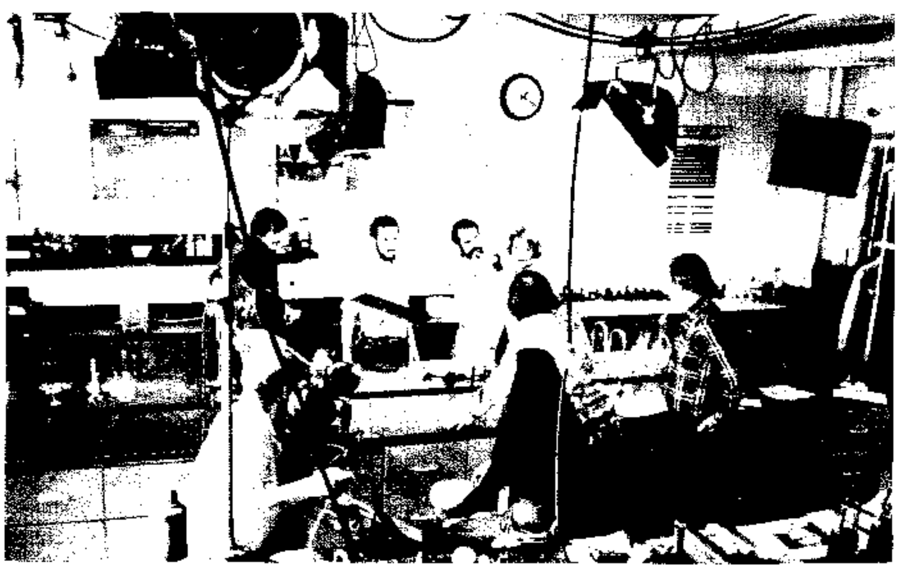
The concept for the film series was developed after consultation with member utilities, industry associates, and educators. The consensus was to produce a series of films that could help explain complex technical ideas, such as how to use coal without fouling the environment. Script content was checked by EPRI and industry representatives before and during production.

Because many of those who will see the films have little background in science, it was decided to present the information in story form. Slide versions of proposed film scripts were produced and shown to high school classes and to a group of industry communications experts. The result of their comments and reactions is a script about a journalist and a photographer who are assigned a major story on coal. The viewer learns about coal technology as the film characters learn.

The Electric Story: Coal documents the efforts of the utility industry to find less expensive ways to make electricity from coal without harming the environment. The characters in the film review the various approaches to clean fuels, fluidized-bed combustion, and the three primary stack-gas control methods. Strong statements about the need for conservation are made during the film and at the conclusion.

Over the next four years, a dozen films will be produced on important technical issues. Two films on solar energy are scheduled for early 1979 release. One covers solar heating and the other deals with methods of producing electricity from the sun. The subjects for the first three films were selected by polling public information officers of EPRI member utilities. Later films will cover such topics as load management, fusion, system reliability, the breeder, geothermal energy, and distribution.

The Electric Story: Coal is available to EPRI members for $125 a copy; the price to nonmembers is $250. Preview copies are available from the Research Reports Center.



Film crew and actors prepare to shoot a laboratory sequence in EPRI's new film, *The Electric Story: Coal*. Working models of precipitators, bag filters, and wet scrubbers were built to help the actors explain coal technology.

At the Institute

Board Authorizes Research

The EPRI Board of Directors has authorized the design and construction of a pilot plant that uses a new type of water-conserving cooling system that may reduce the cost of dry-cooling systems for power plants by as much as 50%. The $8.4 million plant, slated for construction during 1979, will be located at the Pacific Gas and Electric Co. (PG&E) Kern facility in Bakersfield, California. It will use evaporated and condensed ammonia rather than water as the coolant.

The project was one of 115 new and ongoing research and development projects approved by the Board at its regular quarterly meeting, held August 4 in Denver. In addition, the Board approved a 1979 budget of $234 million, which is an increase of $48 million over estimated 1978 expenditures.

Also in the area of fossil fuel research, the Board authorized nearly $6 million to design and construct the nation's first facility to test new coal-cleaning technologies. Construction of the facility is expected to begin in mid-1979 on a utility site to be selected this fall. Specifically, the facility will allow relatively easy testing of many different fully integrated coal-cleaning processes. It is hoped that data from the facility will help utilities meet air emission requirements for coal-fired power plants while improving boiler reliability.

In electrical systems research, the Board authorized a key project to develop and test a multiple-function meter for measuring electricity use at customers' premises. This electronic meter is a potential replacement for the conventional induction watthour meter presently installed in millions of homes and businesses throughout the country.

The so-called smart meter will contain programmable logic that will help utilities control electricity loads automatically. Among other functions, the meter will measure how much energy is used per hour, how many hours it is used and at what time of day, and the total energy consumption.

In other actions, Barton W. Shackelford, executive vice president of PG&E, was appointed to the Board, succeeding John F. Bonner, PG&E president and chief executive officer.

The Board also appointed Virgil H. Herriott, general manager of Sioux Valley Empire Electric Association, to the EPRI Research Advisory Committee.

Electric Field Effects Seminar

Results of EPRI-sponsored research on the effects of electric fields and influence of these effects on the design of high-voltage alternating-current power lines were presented during a recent seminar in Albany, New York.

The seminar, attended by 120 representatives from U.S. and foreign utilities, consulting firms, universities, manufacturing companies, and public service commissions, featured results of research conducted at Project UHV, a research center operated by General Electric Co.

The Project UHV staff conducted the seminar, using as its text *Electrostatic and Electromagnetic Effects of Ultrahigh-Voltage Transmission Lines,* the final report for EPRI Project 566, which is part of an extensive research program being conducted by EPRI's Electrical Systems Division. The staff discussed methods and techniques that were developed to measure electric fields and their effects, to measure spark discharge currents induced in humans and in objects, and to reduce electric fields at ground level. In addition, staff members discussed data collected on the effects of electric fields, including effects on humans. As part of the seminar, participants traveled to Project UHV in nearby Pittsfield, Massachusetts, where they took part in test demonstrations.

Seminar speakers included representatives from EPRI's Environmental Assessment Department and the DOE Division of Electric Energy Systems.

Energy Experts Visit EPRI

A group of senior officials and energy experts from around the world visited EPRI recently as part of the Multiregional Project on Energy Research and Development, sponsored by the U.S. International Communication Agency. The project is designed to provide senior officials and experts from other countries with an overview of energy R&D programs in the United States and to facilitate international discussion of R&D issues within the group and with American counterparts. Pictured is EPRI Senior Planning Engineer Wayne Seden giving an overview of the Institute's R&D program. Seden also provided a description of the planning factors and the estimates that form the basis for EPRI's R&D plan. In addition, presentations were given by Frank Rahn, technical assistant to the director of the Nuclear Power Division, and Richard Zeren, manager, Program Integration and Evaluation, Fossil Fuel and Advanced Systems Division.

Fuel Cell Developments

New developments in fuel cell technology were shared at the third annual National Fuel Cell Seminar recently held in San Francisco and attended by some 300 representatives of U.S. and foreign manufacturers, research and development organizations, and utilities. Seminar activities were planned by representatives of the National Fuel Cell Coordinating Group: from left, Arnold Fickett of EPRI, Dr. James Huff of the U.S. Department of Defense, Dr. J. Stuart Fordyce of NASA, Gary Voelker of DOE, and Vincent Fiore of the Gas Research Institute. Gary Johnson of the Environmental Protection Agency is not pictured.

UHV Lines Purpose of Soviet Visit

A group of Soviet scientists visited EPRI recently to discuss research on possible health and ecological effects of ultrahigh-voltage power lines. The scientists were accompanied by two representatives from Bonneville Power Administration, who coordinated the visit, and two interpreters. The visit was part of the U.S.–USSR science exchange program.

Project Highlights

Utility Insulator Strength Increased

By using improved formulas and processing methods, two firms under contract to EPRI have developed insulator porcelains that have more than twice the strength of those used in the manufacture of insulators today, reports EPRI Transmission Department Director Robert Perry.

McGraw-Edison Co. more than doubled the strength of a standard silica electrical porcelain by reducing the porosity to make the material more compact and by controlling the growth of the interlocking crystals during firing. The results are similar to those obtained when chopped glass fibers are put in resins to make fiberglass.

Gould Inc. more than doubled the strength of high-alumina porcelains (typically used for heavy-duty insulators), mainly by increasing the amount of aluminum oxide used as a filler material but also by removing coarse quartz and lignite impurities and by improving methods of mixing, forming, and firing.

The improved insulator porcelains will offer utilities higher reliability and more flexibility in designing electrical systems. Use of either fewer high-strength units or smaller, lighter units will reduce utilities' overall insulation costs.

The improved materials are not yet commercially available. Manufacturers of insulator porcelains, however, will soon be purchasing equipment needed to produce the improved materials, and the new porcelains should be on the market within the next two years.

EPRI reports, *Extremely High Strength Porcelain* (EL-722) and *Improvement of Electrical Porcelain Insulators* (EL-721-SY), completed by McGraw-Edison and Gould, respectively, can be obtained from Research Reports Center.

EPRI Setting Up Software Center

To ensure that the programs EPRI develops for the utility industry are complete, usable, and maintained, EPRI is establishing the Electrical Power Software Center under RP1284. The center, to be managed for EPRI by Technology Development Corporation (TDC), will distribute programs, program packages, and data libraries. It will also update programs, incorporate new concepts suggested by EPRI research, and correct bugs as they are discovered. In addition, the center will help users install programs.

TDC has been operating such a center for EPRI's Nuclear Power Division for almost a year. The center is now being expanded to take care of programs from both the Nuclear Power and Electrical Systems divisions, which have been more involved than other EPRI divisions with the development of computer codes. It is anticipated that the center will serve users worldwide.

On request and for a small fee, the center will make and send tapes of programs, user's manuals, and instructions for making systems operational. Also included will be examples against which the user can compare results to verify that systems are working correctly. The programs from the center will generally be provided in a machine-specific form, according to the user's request; thus, if a user has access to a CDC 7600 computer, the tapes he receives will have been compiled and checked for use on that machine. If a user requires extensive support from the center in understanding the use and operation of a program, a consulting fee may be charged.

Initially, the center will handle about a dozen large programs, and several more will probably be added as they become available from ongoing projects later this year.

It should be emphasized that the center is not intended to be a library of all software programs developed in the industry. Rather its purpose is to maintain and ensure the usefulness of the programs developed by EPRI for the industry.

For more information about the new center, contact Leroy Krider at TDC, (415) 734-5500; John Lamont at EPRI (Electrical Systems), (415) 855-2293; or Burt Zolotar at EPRI (Nuclear Power), (415) 855-2092.

EPRI Negotiates 57 Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Fossil Fuel and Advanced Systems Division				
RP536-3	Feasibility of Stacking Gypsum Produced in Flue Gas Desulfurization	2 years	130.0	Southern Company Services, Inc. *T. Morasky*
RP553-2	Solar Heating and Cooling of Buildings: Requirements Definition and Impact Analysis, Phase 3	18 months	390.3	The Aerospace Corp. *J. Beck*
RP625-2	Design of Refractories for Resistance to High-Temperature Erosion/ Corrosion	8 months	80.0	Westinghouse Electric Corp. *J. Stringer*
RP779-18	Exploratory Studies in Catalytic Coal Liquefaction	5 months	100.0	Mobil Research and Development Corp. *W. Rovesti*
RP835-3	Operational Aspects of Ammonia-Based NO_x Control Technology	19 months	401.5	Stearns-Roger, Inc. *D. Giovanni*
RP979-8	Design of Alloys for Resistance to High-Temperature Erosion/ Corrosion in Fluidized-Bed Combustors and Gasifiers	14 months	125.0	Battelle, Columbus Laboratories *J. Stringer*
RP979-9	Preliminary Engineering Work for Pressurized Fluidized-Bed Combustor Corrosion/ Erosion Test	5 months	330.9	National Coal Board (England) *J. Stringer*
RP982-11	Scrubber-Generated Particulate	9 months	20.8	TRW, Inc. *R. Rhudy*
RP982-12	Coolwater Unit No. 2 Coal Conversion—Phase 2 Study	6 months	96.0	Stearns-Roger, Inc. *D. Giovanni*
RP1084-1	Impact of Customer Load Management Technologies on Utility Load Shapes	1 year	149.0	Systems Control, Inc. *T. Yau*
RP1084-2	Modeling of Multiple Energy Storage Systems in Production Costing Simulation	6 months	51.5	Energy Management Associates, Inc. *T. Yau*
RP1086-4	Electrolytic Hydrogen Market Potential	7 months	73.9	The Futures Group *B. Mehta*
RP1094-3	Power System Equipment Module Test	9 months	229.5	Colley Engineers & Constructors, Inc. *G. Underhill*
RP1181-1	Porous Dike Intake Structure	2 months	220.0	New England Power Service Co. *J. Maulbetsch*
RP1192-1	Assessment of Distributed Photovoltaic Electric Power System	2 years	537.2	JBF Scientific Corp. *E. DeMeo*
RP1195-4	Laboratory Confirmation of Correlations Between Rock Core and Brine and Between Construction Material and Brine	18 months	32.2	Stanford University *V. Roberts*
RP1198-4	Comparative Hazard Investigation for Zinc-Bromine Battery	9 months	68.7	Factory Mutual Research Corp. *J. Birk*
RP1200-3	Stability of Kocite Electrocatalysts in Phosphoric Acid Cathodes	1 year	119.0	UOP, Inc. *E. Gillis*
RP1255-2	Municipal Solid Waste as a Utility Fuel	7 months	9.9	Combustion Processes, Inc. *C. McGowin*
RP1256-1	Pilot Development of Catalytic NO_x Processes	1 year	44.7	Stearns-Roger, Inc. *N. Shah*
RP1258-1	TVA Absorption/Steam-Stripping Pilot Plant	3 months	12.1	Tennessee Valley Authority *S. Dalton*
RP1259-1	Trace Element Removal Characteristics of Particulate Control Devices	11 months	391.2	Meteorology Research, Inc. *M. McElroy*
RP1260-2	Water Management in Advanced Coal Conversion Systems	5 months	30.0	Water Purification Associates *J. Maulbetsch*
RP1263-3	Disposal of PCB Materials	11 months	20.0	Tennessee Valley Authority *D. Golden*
RP1269-1	Solar Heating and Cooling Simulation Programs	18 months	199.2	Arthur D. Little, Inc. *G. Purcell*
Nuclear Power Division				
RP503-4	Sensor Time Response Verification	3 months	13.6	Industrial Design & Engineering Associates *D. Cain*
RP964-2	Vibration Tests at Indian Point-1 Nuclear Power Plant	17 months	74.9	Consolidated Edison Company of New York, Inc. *C. Chan*
RP1125-2	Transfer of Technical Data and Recordings Describing Defects in Samples of Steam Generator Tubing	5 months	11.5	Battelle, Pacific Northwest Laboratory *G. Dau*
RP1167-2	Chemistry of Corrosion-Producing Salts	3 months	25.0	Babcock & Wilcox Co. *T. Passell*
RP1237-1	Estimation Techniques for Elastic-Plastic Fracture	18 months	317.7	General Electric Co. *T. Marston*
RP1240-1	Analysis of Irradiated Pressure Vessels in Material Data	2 years	98.1	Fracture Control Corp. *K. Stahlkopf*

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1253-1	Breeder Reactor Fuel Cycle	30 months	42.9	Westinghouse Electric Corp. *M. Lapides*
RP1284-2	Electric Power Software Center	1 year	286.3	Technology Development Corp. *B. Zolotar*
RP1321-1	Feasibility Study of the Potential Application of the Endochronic Theory	2 months	6.0	Systems, Science & Software *R. Oehlberg*
RP1332-1	Mechanisms of Environmental Cracking in Systems Peculiar to the Power Generation Industry	2 years	189.8	General Electric Co. *R. Smith*

Electrical Systems Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1204-1	Arc By-Products in Gas-Insulated Equipment	10 months	116.8	Gould Inc. *V. Tahiliani*
RP1206-1	DC Line Insulators	2 years	307.0	Sediver, Inc. *R. Kennon*
RP1206-2	DC Line Insulators	26 months	275.7	Lindsey Industries Inc. *R. Kennon*
RP1277-1	Transmission Line Wind-Loading Research	2 months	30.0	Meteorology Research, Inc. *P. Landers*
RP1279-1	Transmission/Distribution Line-Stringing Tensioner	18 months	133.7	Morgan Power Apparatus Corp. *P. Landers*
RP1281-1	Field Evaluation of New Outdoor Insulators	1 year	238.3	Lindsey Industries Inc. *E. Perry*
RP1282-1	Bipolar DC Transmission Research Above ±600 kV at Project UHV	6 months	534.2	General Electric Co. *R. Kennon*
RP1285-3	Detection of High-Impedance Faults on Distribution Circuits	16 months	225.6	Texas A&M Research Foundation *W. Shula*
RP1352-1	Probability-Based Design of Wood Transmission Structures	3 years	496.1	Colorado State University *P Landers*
RP1356-1	Distribution Reliability and Risk Analysis	18 months	374.2	Westinghouse Electric Corp. *W. Shula*
RP1359-2	Evaluation of the Electrical Environment in High-Voltage Substations	1 year	269.6	Texas A&M Research Foundation *S. Nilsson*

Energy Analysis and Environment Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP434-23	Electric Utility Rate Design Study	6 months	33.4	Putnam, Hayes & Bartlett, Inc. *R. Malko*
RP1050-1	Comparative Evaluation of Models of Energy Utilization and Studies of Conservation Technologies	3 years	549.9	University of Arizona Engineering Experiment Station *A. Lawrence*
RP1226-4	Socioeconomic Impact of Power Plant Construction	8 months	85.6	Denver Research Institute *R. Wyzga*
RP1300-1	Regional Data Base for Support of Electricity Supply Projects	9 months	81.7	Gordian Associates Inc. *J. Chamberlin*
RP1305-1	Regional Visibility: A Feasibility Study	9 months	88.7	Dames & Moore *G. Hilst*
RP1314-1	Pathogenic Amoebae in Power Plant Cooling Lakes	1 year	50.0	Union Carbide Corp. *J. McCarroll*
RP1315-1	Bioassays of Air Emissions From Fossil Fuel Power Plants	5 months	150.0	Battelle, Columbus Laboratories *J. McCarroll*
RP1316-1	Statistical Methods and Data Base for Relating Air Pollution to Human Mortality	18 months	200.0	Battelle, Pacific Northwest Laboratory *R. Wyzga*
RP1368-1	Inclusion of Cogeneration in Electric Utility Models	10 months	98.6	Resource Planning Associates, Inc. *J. Chamberlin*
RP1372-1	Selected Alternatives to Conventional Chlorination Practices for Biofouling Control	18 months	190.5	Marine Research, Inc. *J. Reynolds*
RP1376-1	Monitoring Precipitation Chemistry in the Eastern United States	22 months	445.0	Rockwell International Corp. *C. Hakkarinen*

Washington Report

EPA Has Dual Role in Particulate Control

The Environmental Protection Agency (EPA) wears two hats as the lead federal agency charged with protecting air quality through control of particulates and other power plant emissions. It acts as regulator, setting and enforcing rules to limit levels of particulates in the atmosphere, and as researcher, funding and managing programs to better understand and control these emissions.

In its work on particulates, as well as in other major areas, EPA is making a major effort to integrate its two roles and to expand long-term anticipatory research.

"From its inception EPA recognized the need to balance near-term research objectives in support of regulatory programs with a longer-term program to stimulate advances in environmental sciences," Administrator Douglas M. Costle told the House Subcommittee on the Environment and the Atmosphere on July 19, 1978. "We have been driven, however, by legislation to support short-term regulatory deadlines."

Costle went on to say that he felt the agency had erred by short-changing long-term research in the past and that he intended to see the situation rectified in the future.

In support of this objective, the agency formed five pilot research committees to review programs and recommend research strategies in specific areas, one of which was particulates. In September, EPA's Office of Research and Development (ORD) circulated internally a report from the particulate research committee intended as the top planning document in this area. The report lays out a research strategy aimed toward allowing particle standards to be set that "protect the public health, but are not necessarily restrictive." The research plan will be part of a larger EPA report scheduled to go to Congress this October.

The research plan focuses on inhalable particles (IP), which the committee defines by size as particles 15 micrometers or less. EPA's current approach is to regulate particulate levels by a measure of mass referred to as total suspended particles (TSP). Current regulations limit particulate emissions from new coal-fired electric boilers to 0.045 kilogram (0.1 pound) per million Btu, regardless of particle size. Proposed new-source performance standards would reduce this allowable volume further to 0.014 kilogram (0.03 pound) per million Btu.

EPA is required by law, however, to revise its criteria document for setting ambient air particulate standards by December 31, 1980. The orientation of its particulate research toward the inhaled particle size fraction rather than total suspended particles may foreshadow a change in regulatory approach as well.

In fact, Roger Cortesi, director of ORD's Criteria Development and Special Studies Division (and also chairman of the particulate research committee) explains that EPA is currently evaluating whether the TSP approach should give way to a standard based on "the size particles that we think are actually getting into the human lung and causing the observed health effect."

Cortesi's colleague in EPA's regulatory section, Jim Weigold, Assistant Director, Strategies and Air Standards Division, confirms that the agency is looking in this direction, but emphasizes that officials are carefully assessing the data first.

"If, after the assessment, we find that inhalable particles do indeed cause the harm, then we may go to an inhalable particle standard by 1980," he said.

Defining the exact size of harmful inhalable particles is a matter of controversy. Cortesi's committee settled on 15 micrometers and below. They feel that bigger particles are screened from the respiratory system by bodily defense mechanisms in the throat and nose.

Cortesi concedes that some researchers may think 15 micrometers is too high, but he explains that the size takes into account mouth breathers, such as asthmatics and people running or exercising vigorously.

Weigold admits that many health experts are focusing on fine particles (2 or 3 micrometers and below) but says that at this time, no one has enough knowledge to say that particles in the 2–15-micrometer range do not cause problems. Therefore, he is confident that if the TSP approach to regulating particulates is changed in 1980, it will be in the direction of inhalable particles, not fine particles.

The research strategy described by the Cortesi committee report on inhalable particulates outlines six major programs.

□ Monitoring Particles in the Atmosphere aims to enhance knowledge of what particles there are in the air, at what levels, and where. The program involves establishment of a 300-site network where particles will be measured in two size fractions: 2.5–15 micrometers and 2.5 micrometers and below. The major measuring instrument in this program is called a dichotomous sampler, which is capable of taking measurements in these two size ranges.

"We are collecting data on particles in both size ranges to be prepared if further down the line we feel that we don't have to worry about those in the 2.5–15-micrometer range," Cortesi explains. The program also involves evaluation of other sampling techniques and compliance test methods.

□ Characterization of Effects focuses on both health and visibility effects of particulates. The health program, conducted at EPA's Health Effects Research Laboratory at Research Triangle Park in North Carolina, has three main thrusts: an animal toxicology program to develop data on chronic effects from exposure to particulates; clinical studies on humans to examine acute (short-term) effects on both normal and stressed (with heat, exercise) persons; and epidemiological studies that Cortesi refers to as "our only source of real-world and chronic human data." The Cortesi report recommends that EPA resources be added to the six-cities' health effects study, a project also being supported by EPRI.

□ Characterization of Sources of Particles involves researchers observing emission sources—for example, steel mills, power plants—and attempting to characterize particles emitted in terms of size and chemical composition. "We want to be able to say 'this particle is coming from a steel mill' or 'this one is emitted by a power plant,'" Cortesi explains. Emissions are being characterized from residential sources, internal and external combustion, electric generation sources, commercial/institutional sources, and industrial sources.

□ Relation of Pollution Sources to Ambient Particles Levels basically looks at the relationship between primary particulates that are emitted directly from the source and secondary ones formed after emission. The work involves laboratory and chamber measurements, field observations, and modeling to study how secondary particles, such as sulfates and nitrates, are formed; how they react with various weather and land conditions; how they are dispersed; and how they are transported. Work in this area corresponds to such EPRI research as the Sulfate Regional Experiment (SURE), which involves air and ground monitoring of sulfate and sulfur dioxide levels in the northeastern United States. EPA has a program dubbed STATE (Sulfur Transport and Transformation in the Environment), which focuses on an area bounded by the Mississippi River, Appalachian Mountains, Great Lakes, and southern border of Tennessee.

□ Development of Measurement Techniques is a program of instrumentation R&D. Perhaps the greatest need not now being addressed in this program, Cortesi comments, is to develop a routine, reliable, and relatively cheap compliance enforcement instrument that inspectors can "stick into the stack" to make sure standards for fine particulates are being met. Cortesi's research committee recommends that work be begun in this direction.

□ Fine-Particle Control Technology Development is the last of the six areas defined by the research report. As particulate regulations become stricter (99% removal from solid fuel and 70% from liquid fuels proposed by new-source performance standards), this program becomes more crucial.

Much of this work is being done under the direction of Frank Princiotta, director of ORD's Energy Process Division. Princiotta's division includes not only particulate research but also work on other emissions control technology. At this writing, the division stands to lose a slice of its technology work in response to a mandate from the Office of Management and Budget that EPA and DOE trade $14 million of FY79 projects. Current thinking is that EPA will give up a portion of its control technology in the sulfur oxide, extraction, and conservation areas in return for part of DOE's health and ecological research. Most of the particulate work, Princiotta explained, will not be affected by the trade.

Princiotta's division is concerned with developing technology to control primary particulates—those emitted directly from the stack. "We're trying to develop effective, inexpensive controls for particulates from coal combustion sources," he explains. This includes improving existing technology (electrostatic precipitators, baghouses, wet scrubbers) and developing new concepts.

For the utility industry, Princiotta sees improvements to existing technologies as the path for the next 10–20 years.

"My own personal feeling is that we're essentially going to see variations of our current three technologies. It takes a long time for a new technology to get from a bench-scale operation to commercial use."

In seeking such improvements, EPA and EPRI are working on separate programs, but keeping closely in touch, Princiotta remarks. He sees EPRI's high-intensity ionizer as a promising approach to improving the efficiency of electrostatic precipitators, especially with low-sulfur western coals that produce high-resistivity fly ash. "I think that might be a good way . . . around the problem," he says.

EPA has traditionally not become involved with big hardware projects, but piggybacks on existing control technology installations around the country. Many of these facilities are utility owned. One fabric filtration facility that EPA is evaluating, for example, is at Southwestern Public Service Company in Amarillo, Texas. Princiotta explains that through programs such as these, EPA cooperates extensively with industry in implementing its programs.

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FOSSIL PLANT PERFORMANCE AND RELIABILITY

Large fossil-fueled steam power plants constitute a major portion of the baseload capacity in this country but have the poorest availability records. Statistics show that the reliability of these large machines is not improving but rather continues to deteriorate. Because of ever-increasing environmental restrictions, which will require more encumbering front- and back-end equipment, this deterioration of reliability is expected to continue. EPRI has dedicated resources to the overall improvement of reliability and performance of both new and existing fossil-fueled steam power plants.

Causes of major losses in plant availability have been examined through the use of Edison Electric Institute (EEI) statistics, and the resultant conclusions have been supplemented through meetings with utility industry representatives. The Fossil Plant Performance and Reliability Program deals with five separate but interrelated areas—turbine generators, steam generators, plant auxiliaries, plant chemistry, and integrated plant.

Figure 1, which is based on the EEI statistical sample of large fossil units rated 400 MW and above, shows that the operating availability of the plants has decreased more than 6% between 1966 and 1976. In addition, the figure shows the trend extended for operating availability as well as for equivalent availability (which includes partial outages) for these large units. Lower availability forces individual utilities to increase the production of electric energy by older, more costly units. Lower availability also creates higher reserve requirements to accommodate customer load demands. The equivalent availability for those fossil units in the EEI sample rated higher than 600 MW has been as low as 65% in recent years. A preliminary analysis to quantify the cost of this low availability in a typical system produces a value of approximately $1 million for each 1% of lost availability in a single 800-MW coal-fueled unit. The value is predicated on an average fuel cost replacement differential of 12 mills/kWh and a capacity charge of 50 cents/kW-wk.

There are 258 units rated higher than 400 MW in the 1976 EEI statistical sample. Many of these units are oil- or gas-fueled and produce a lower fuel cost replacement differential than coal-fired units. A reasonable estimate puts the value of a 1% loss of availability for an 800-MW oil unit at about $250,000. This is predicated on a differential production cost of 3 mills/kWh. On these bases, the combined value of a 1% loss of availability in those EEI sample units that are rated higher than 400 MW is between $50 million and $200 million per year. The equivalent availability of all units in the EEI sample during 1976 was 82.1%, whereas these larger units had a comparable average of less than 70%. This 12% cost difference in loss of availability is valued between $600 million and $2.4 billion for the year 1976.

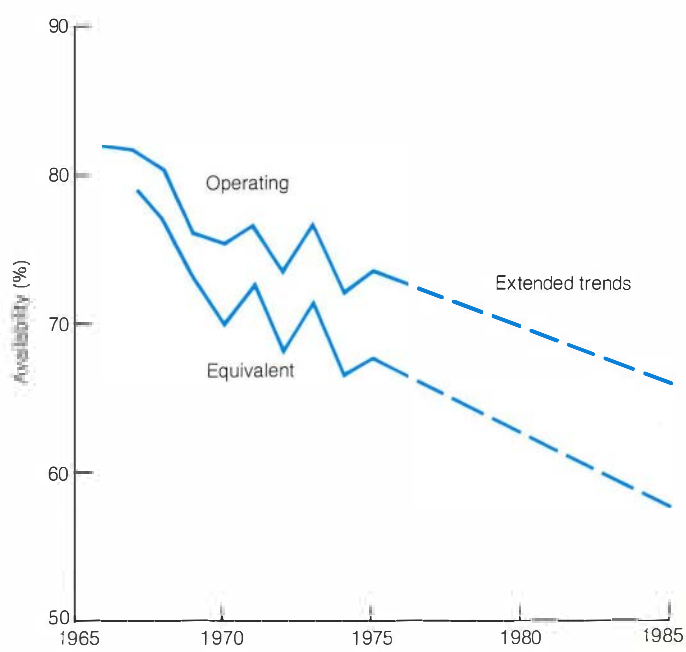


Figure 1 Actual operating and equivalent availability of units rated 400 MW and higher, with extended trends of these factors. Equivalent availability is operating availability that includes partial outages.

Performance values are a little easier to quantify. For the year 1976, a 1% efficiency gain would have reduced utility operating costs by more than $160 million. Average efficiency for the utility industry in 1976 was 31.9% (10,383 Btu/kWh); the most efficient unit during that period was rated at 37.3% (8872 Btu/kWh). Experience indicates that the average yearly efficiency of a particular unit depends to some degree on its exhibited equivalent availability during the period of computation. Efficiency design for baseload units is such that performance falls rather fast at loads of less than maximum capacity. Also, an excessive number of startups of these large units tends to decrease average efficiency.

Fossil plants, especially coal-fired plants, will continue to be a major source of new capacity through the year 2000. With the increasing licensing difficulties and cost of the nuclear option, coal plants will continue to be an attractive option to the utility industry, even with more stringent environmental standards. Figure 2 indicates the potential growth of each technology available to the utility industry through the year 2020. Note that according to this projection, power production from coal plants will continue to expand through 2000, when it is expected to account for approximately 45% of the total (compared with 40% now).

The Fossil Plant Performance and Reliability Program assumes that design is responsible for 30% of the total number of outages and that operation and maintenance activities account for 20% and 10%, respectively. Most of the rest are scheduled outages for overhauls. This breakdown of responsibility is important because it must be recognized that improving equipment will not solve the entire reliability problem. These assumptions incorporate available data and the experience of many utilities. The breakdown could be representative of all existing large fossil units taken collectively.

Within the category of design responsibility, the reasons for the greatest reliability losses in large fossil plants were found to be:

- Turbine blade failures
- Turbine generator bearing failures
- Generator failures
- Boiler tube failures
- Fouling and slagging of boiler heat transfer surfaces
- Control system inadequacy
- Condenser leakage and failures
- Coal pulverizer failures
- Failures of fans
- Boiler feed pump failures

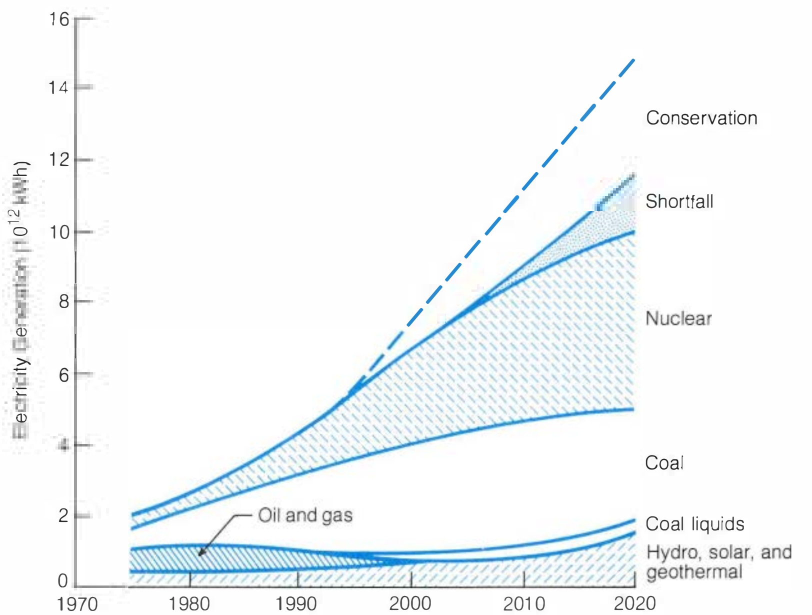


Figure 2 EPRI projections of power production growth show the continuing U.S. requirement for additional fossil plants.

Turbine generators

According to the EEI statistical information for larger units, turbine generators exhibit an availability loss of approximately 19%. EPRI's minimum near-term improvement goal is to reduce this to 16.35% over the next five years. In the five years after that, the turbine generator subprogram should pay back between $300 million and $1.25 billion to the utility industry. The program has identified failures of blades, bearings (and lube systems), generators, and control systems as the major causes of lost availability. This subprogram has nine active projects, and eight additional projects are planned for the near future.

Seven EPRI projects address the most important category, which is blade failures. Most blade failures have been found to result from one of three factors:

- Solid-particle erosion
- Water induction
- Stress corrosion/corrosion fatigue

Solid-particle erosion is presently believed to be the direct result of boiler tube and steam-piping exfoliation, and the steam generator and plant chemistry subprogram is actively concerned with this problem.

Water that is induced into steam turbines through extraction lines is a primary cause of both minor and major damage to turbine blades. Westinghouse Electric Corp., in conjunction with Boston Edison Co. and EPRI, is testing a system for detecting water induction in an operating unit (RP637). This project should lead to identification of the operating conditions that prevail when water is likely to be induced into the turbine. The final report is expected early in 1979.

Perhaps the most serious problem is the failure of low-pressure turbine blades through a stress corrosion/corrosion fatigue mechanism. Small amounts of impurities borne in the steam system condense and deposit in the latter stages of the low-pressure turbine. The deposition builds to a point at which corrosion is initiated in the stressed areas of the blades and other turbine components. The corrosion, usually in the form of pitting on the material surfaces, initiates cracks in these highly stressed areas, and fatigue failures follow. It has been estimated through the use of several industry surveys that at least 10% of the nation's fossil units are affected by this phenomenon.

Because of the severity of the problem, two approaches have been taken—examination of the mechanisms that cause corrosion-related failures and the development of replacement materials and protective coatings to eliminate the effects of corrosion.

The first approach is being used in three projects. One of these addresses efficiency degradation and blade erosion in the low-pressure steam turbines due to the presence of moisture in steam (RP735). The project is a study of water droplet formation, size distribution, and growth rates under simulated turbine-operating conditions. Nonsteady expansion waves are used to produce the desired steam conditions. When the condensation phenomenon has been defined quantitatively, it will be possible to design turbines that are more efficient and reliable.

Because of the nature of the testing device, EPRI has directed General Electric Co. to conduct condensation tests using actual boiler steam. This will provide necessary information on the condensation of metallic and nonmetallic substances that have been found to play an active role in initiating blade corrosion in the latter stages of low-pressure turbines. These efforts, scheduled for completion in 1979, will provide guidance for the future design of turbines and blades, as well as recommendations for operating existing units to increase efficiency and prevent corrosion.

Another project (RP1407) is designed to provide a detailed understanding of the interaction between spontaneous steam condensation and pressure shock waves in steam nozzle flow, and to show that pressure disturbances outside the nozzle can produce flow instabilities that create cyclic forces on the flow passages. Such a periodic flow instability would play an important role in the final failure mode of turbine components. It might well be the cause of high-cycle fatigue failures and of cyclic stress, which is a factor in the initiation of corrosion-assisted cracks. Westinghouse is the contractor in this two-year project.

In the third project, Rochester Institute of Technology will develop data on blade-root vibration damping in a form compatible with fatigue and dynamic stress calculation techniques and will present the generic results in a format that can be used by utilities and manufacturers in the design and specification of steam turbines. Because L − 1 blade failures are most often associated with a fatigue mode, this project will provide information not currently available on blade-root damping.

Because it may not be possible to eliminate the mechanisms responsible for stress corrosion/corrosion fatigue in low-pressure turbine blades, the second research approach is aimed at lessening their effects by providing material resistance to the corrosive turbine environment. Two projects take this approach.

In the first (RP1264), titanium alloy blades will be substituted for steel in two L − 1 rows of an operating steam turbine at Commonwealth Edison Co.'s Kincaid Station to determine whether titanium alloys in impure steam suffer less corrosion and fatigue than do present materials. The project will provide additional data for solving a generic problem of fossil turbines. Commonwealth Edison and Westinghouse's Steam Turbine Division are the contractors and cosponsors.

In the second project (RP1408), low-pressure turbine coatings will be evaluated in laboratory tests on specimens exposed to turbine environments to demonstrate the best coatings in actual components. A successful coating, applied in those areas of blades, blade roots, and shrouds where corrosion pitting is initiated, would provide a protective barrier and eliminate failures of these components. This three-year project will be conducted by Westinghouse and Southern California Edison Co.

Bearing and generator failures are being studied through root-failure cause analysis in an attempt to define areas in which research and development can have the greatest impact (RP1265). Control system problems, especially in cyclic unit operation, are the subject of a joint project (RP911) by Westinghouse, Babcock & Wilcox Co., and Commonwealth Edison (*EPRI Journal*, October 1977, pp. 51–52).

Steam generators

Loss of availability in steam generators is about 15% for large fossil units. With a near-term goal of improving availability by 2.09%, this subprogram is expected to pay back between $235 million and $1 billion to the utility industry in the five-year period 1982–1986. Tube failures, fouling, slagging, and control system inadequacies have been identified as the major sources of unreliability for steam generators. The subprogram has six projects under way and eight planned for the near future.

Tube failures in the water-wall sections, economizers, and superheat portions of the boiler are estimated to account for approximately half of total boiler availability losses. Immediate causes include failures of tubes at the transition welds of dissimilar metals, embrittlement, erosion, and corrosion. Current efforts include cause analysis of the root failures in several plants known to have severe boiler curtailments because of tube failures. This analysis will determine the R&D priorities for the most severe causes of boiler pressure part failures. Battelle, Columbus Laboratories is interviewing plant personnel, reviewing log records, and analyzing material samples for the plants selected. This process, including final analysis, should be completed early in 1979 (RP1077).

Boiler tube fouling and excessive slag formation from the burning of pulverized coal are a major cause of boiler capacity losses. In a long-range study, Brigham Young University is using a small laboratory combustor to investigate what effect the mixing of fuel and air has on the kinetic processes in pulverized-coal combustors. With this combustor, instrumentation and software can be used to measure gas and particle mixing rates, gas composition in the furnace, coal burnout, char composition and distribution, local pollutant properties, temperature profiles, and ash-slag properties. The initial report is now in circulation, with the follow-on work to be completed early in 1979 (RP364).

In the shorter range, Battelle-Columbus is investigating the influence of minerals on fireside fouling and slagging of boilers. This project, to be completed late this year, should correlate the mineral matter both qualitatively and quantitatively with the slagging and fouling properties of the individual coals. Field tests of five utility boilers and coal/ash laboratory analyses of coal samples have been completed, and the analysis of data is under way (RP736).

Plant auxiliaries

Fossil plant auxiliaries are responsible for an availability loss of 8%. EPRI's near-term improvement goal is to reduce this loss by 2%, which should pay back between $215 million and $900 million to the utility industry over the following five-year period. The R&D priorities of this subprogram are the equipment improvement of water systems, fuel-ash systems, and air-gas systems. There is only 1 active project dealing with plant auxiliaries; however, 12 additional projects are planned for the near future.

This subprogram recently issued a final report on feed pump outages, which summarizes more than 3000 pump failures. Recommendations for further R&D efforts are under consideration. EPRI and the EEI Prime Movers Committee are formulating design recommendations for improved pump reliability on the basis of this report (FP754).

Analysis of the causes of failures in coal pulverizers is under way (RP1265-1). It is expected that this effort will determine the highest priorities for generic problems in coal mills, as has been accomplished for the boiler feed pumps.

Vibration analysis through computer simulation should provide the basis for predicting the vibratory behavior of any system that consists essentially of a rotating mass carried on a shaft with bearings, a supporting structure, and a subsoil. Excessive fan vibration has resulted in machinery damage and full and partial curtailments of unit load. The model developed in this project can be applied to the correction of existing vibration problems and to the design of new equipment (RP984).

Plant chemistry

Outages associated with plant chemistry are included in the statistics for the three preceding subprograms. The near-term objective for plant chemistry is to reduce overall plant availability loss by 0.9% between 1978 and 1982, with a resultant industry payback of $100 million to $400 million between 1982 and 1986. This subprogram also deals with plant metallurgical deficiencies. Eight projects are under way, and six more are planned for the near future.

Of specific interest in this subprogram is the ongoing work of Foster Wheeler Energy Corp., which has developed a pressurized chromate treatment for the internal surfaces of superheat and reheat tubes. This process treatment has proved effective, on a laboratory scale, in inhibiting the rapid growth and ultimate spalling of oxides in the steam environment. Follow-on work includes the cleaning and treatment of exfoliated boiler tubes and the investigation of processes that allow the chemical cleaning and treatment of pendant boiler tubes. The successful completion of this project should help eliminate the cause of solid-particle erosion of high-pressure and intermediate-pressure turbine blades (RP644).

Integrated plant

It is expected that the integrated plant subprogram will pay a higher return to the utility industry than other subprograms in the Fossil Plant Performance and Reliability Program. The goal is a 1.7% improvement in plant availability over the next five years, which should pay back $190 million to $800 million between 1982 and 1986. The subprogram deals with recommendations on design, operation, and maintenance practices as well as overall plant performance. Thus this area involves a transfer of technology between the actual projects and the implementation of the program's R&D output. In addition, this subprogram is responsible for providing the statistical data on causes of failures in fossil plant components. There are 5 active projects and 14 near-future projects designated for this subprogram.

Efforts in this subprogram now include the formulation and validation of dynamic and steady-state computer models of an individual fossil unit. The dynamic model will provide the utility industry with dynamic-stability information on the composite system for control design. The steady-state model will provide an accurate troubleshooting tool for existing units. This model tool will also be useful in optimizing cycle design and monitoring the performance of existing units. These models should be available for general use early in 1981 (RP1184).

Acoustic emission monitoring continues at New England Power Co.'s Brayton Point plant. Imminent failure of a boiler feed pump was predicted from data collected by the utility and the Atomics International Division of Rockwell International Corp. Efforts in this area are being coordinated with Canadian utilities (RP734).

Reversing the downward trend

EPRI's Fossil Plant Performance and Reliability Program provides guidance for the utility industry in an area under scrutiny by all levels of government. Accomplishment of the objectives of individual projects will provide the technology to reverse the downward trend in availability of large fossil units. The program will pay back at least $12 billion to the utility industry over the next 20 years. This program is important in keeping with the national goals of efficient energy use and reduced dependence on oil and gas, because it promotes higher availability of more efficient baseload equipment and reduces the need for oil- and gas-fueled peaking units. *Program Manager: David Poole*

OPEN-CYCLE MHD

Recent progress in the national magnetohydrodynamics (MHD) power generation program includes milestones in the development of the MHD channel, superconducting magnet, inverter, coal combustor, and preheater. EPRI has made advances that are relevant to national achievements in inverter development, systems analysis, and the electrodynamics of slag layers in the MHD channel.

National MHD development

The national MHD development program is moving into a new phase, which will concentrate on integrating the major MHD components into a unified operating system. The central facility for this development phase is the Component Development and Integration Facility (CDIF), which is under construction in Butte, Montana, under the auspices of DOE. The test facility is designed to study the operation of an integrated MHD power system composed of coal combustor, channel, superconducting magnet, and dc/ac conversion equipment at a 50-MW (th) input level (approximately 2½ times larger than any existing U.S. MHD facility).

The move into the integration phase of development has been supported by significant progress in the engineering development of individual components. Major milestones have been achieved in most of the MHD subsystems during the past year. These achievements include:

- 250 hours of cycled operation of the electrode walls of the generator, with a scheduled shutdown of the test
- Satisfactory performance of a 5-T saddle-coil superconducting magnet in an MHD generator test
- Dc/ac conversion of the output of an MHD generator, using a forced-commutated inverter
- 95% slag removal in a high-temperature, two-stage coal combustor
- 900 hours of operation of a high-temperature, regenerative heat exchanger simulating a direct-fired (i.e., MHD exhaust) condition

The 250-hour electrode-wall test was conducted by Avco Everett Research Laboratory, Inc., under the sponsorship of DOE. This milestone is particularly encouraging for the national program because it was conducted under simulated coal-fired conditions, with electrical stresses on the channel approaching levels typical of a commercial generator. In the previous U.S. channel duration record, 95 hours in 1976, it was demonstrated that electrochemical erosion of the anode wall was the most serious life-limiting problem for the MHD channel. This problem was to a large extent controlled in the recent test by cladding the anodes with platinum, an oxidation-resistant material. A comparison of the anode recession in the 95-hour and 250-hour tests is given in Figure 3.

The current testing of the 5-T superconducting magnet is part of the U.S.–USSR cooperative program. The magnet, built by Argonne National Laboratory for DOE, is the largest superconducting magnet of the type (saddle-coil) appropriate for MHD applications. Its 34-MJ stored energy is almost an order of magnitude greater than that of existing superconducting magnets of the saddle-coil type. In June, the magnet was operated with an MHD generator at the Soviet U-25B facility. The duration of the test was several hours, and the performance of the magnet was completely satisfactory.

An inverter milestone was achieved as part of a joint EPRI–DOE development program for MHD power-conditioning and control circuitry. The test, which represents the first extended operation of a forced-commutated inverter on an MHD generator, was of five hours' duration and achieved a maximum power level of 80 kW. A more complete description of this test is included in the following project summaries.

The last two milestones, in the areas of coal combustors and direct-fired preheaters, were accomplished at Pittsburgh Energy Research Center (PERC) and Fluidyne Engineering Corp., respectively, as part of DOE-sponsored programs. The PERC combustor is a small-scale (5-MW [th]), atmospheric pressure, two-stage combustor, which should be scalable to larger sizes and higher pressures. The large degree of slag removal demonstrated (95%) will greatly improve the operating environment for the downstream potassium seed and heat recovery equipment in the MHD cycle.

EPRI projects

The EPRI contribution to the national MHD program has three primary objectives:

- Development of a key MHD subsystem

- Identification of economically competitive power plant configurations that satisfy utility requirements on reliability and performance and that may have reduced development times

- Contribution to the knowledge of MHD phenomena, which are important to the overall system but which are not the main focus of national and foreign research programs

The first objective, development of a key MHD subsystem, is the primary goal of a joint EPRI–DOE project for engineering the power-conditioning and control equipment in the MHD portion of the power cycle. This work is in progress at the Avco Everett Research Laboratory (RP642). The responsibility for this work has been divided into a DOE segment on consolidation circuitry (i.e., the circuitry required to combine the low-current outputs of many electrodes to a common potential) and an EPRI segment on inverters and controls.

The EPRI-sponsored portion of this project is designed to study the performance of

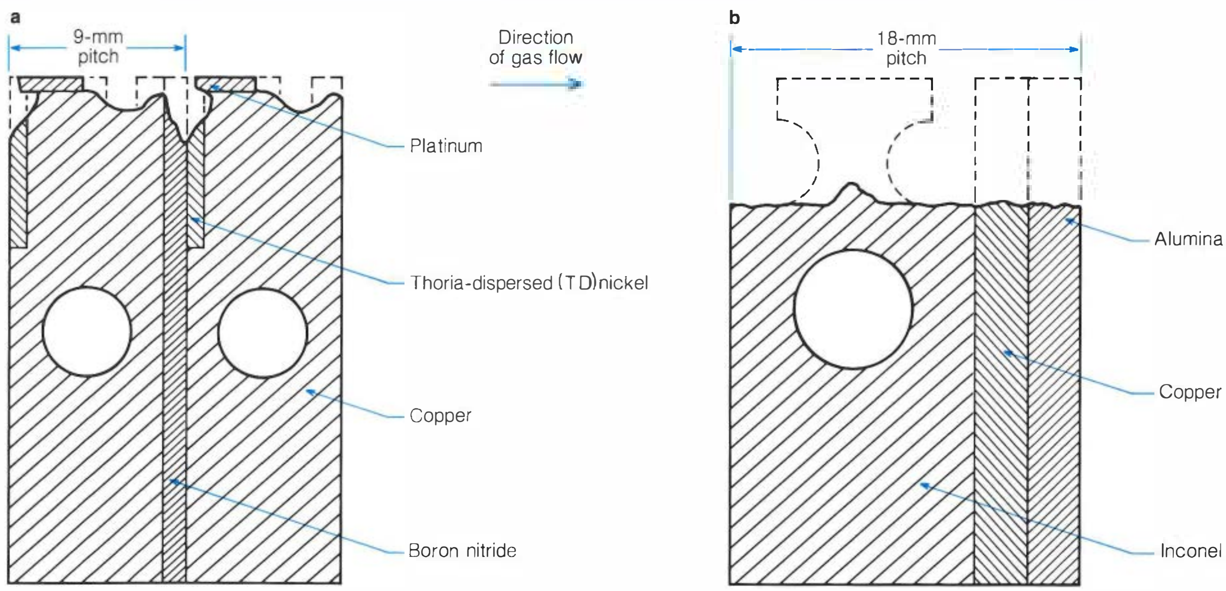


Figure 3 In tests of the electrode walls on the Avco Mark VI MHD generator, the degree of anode recession caused by electrochemical attack was much less after 250 hours of power generation with platinum-clad anodes (**a**, March 1978) than after 95 hours of power generation with anodes that were not clad (**b**, February 1976).

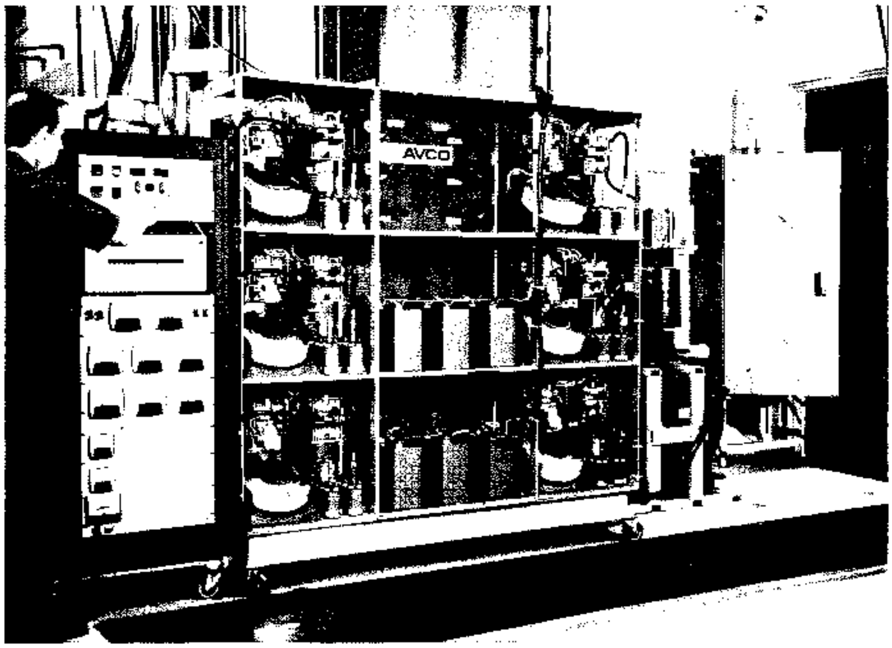
both forced- and line-commutated inverters in experimental operation on an MHD generator and to define their operating characteristics on the power grid. A three-phase, forced-commutated inverter (Figure 4) has been designed, fabricated, and tested as part of this project. This unit is composed of two bridges operated in series and has a total dc load voltage and current capacity of 2500 V and 100 A. Pulse-width modulation is used to control the dc voltage level, and the output of the two bridges is combined to produce a 12-pulse wave, which is free of all harmonics below the eleventh.

In June, the forced-commutated inverter was operated on the MHD generator for the first time. Operation was derated to 80 kW for the initial test. Performance of the inverter was normal during the six-hour test.

Four line-commutated inverters, each of 90-kVA capacity, have been procured by Avco for testing with the consolidation circuitry. This testing was planned to begin in the second half of 1978.

A second phase of the EPRI segment of the Avco work will involve the design of an inverter system for the CDIF. For this phase, consultants from manufacturing divisions of General Electric and Westinghouse will be employed to aid in the design of a system that will ultimately be of commercial interest to both manufacturers and utilities.

Figure 4 As part of a joint EPRI–DOE project at the Avco Everett Research Laboratory to develop power-conditioning and control equipment for the MHD generator, this forced-commutated inverter was developed. Testing of the inverter on the Avco Mark VI MHD generator was started this June.



The identification of MHD power plant configurations that are acceptable to the utility industry and that have potentially shorter development periods is recognized within EPRI as an essential task in support of the national development program. The potentially high efficiency of the MHD cycle will lose some of its attractiveness if the overall system does not satisfy utility expectations for reliability or if the system operating characteristics do not integrate well into the utility system.

The effort to define acceptable MHD plant configuration has two parts—operational analysis and system analysis. The interrelation between these two tasks and the way they jointly achieve the goal of defining preferred plant designs are shown in Figure 5. The operational analysis, being performed by Westinghouse (RP639), is intended to define realistic goals for availability, performance, and costs, leading to an MHD power-generating system that will compete favorably with alternative technologies. The methodology employs a Westinghouse computer model that not only provides an economically optimal expansion plan for a utility that meets the system's load growth requirements but also simulates the planning-decision process of the utility. The MHD system and the alternative candidates are defined by capital, operating and maintenance, and fuel costs, as well as by operating characteristics.

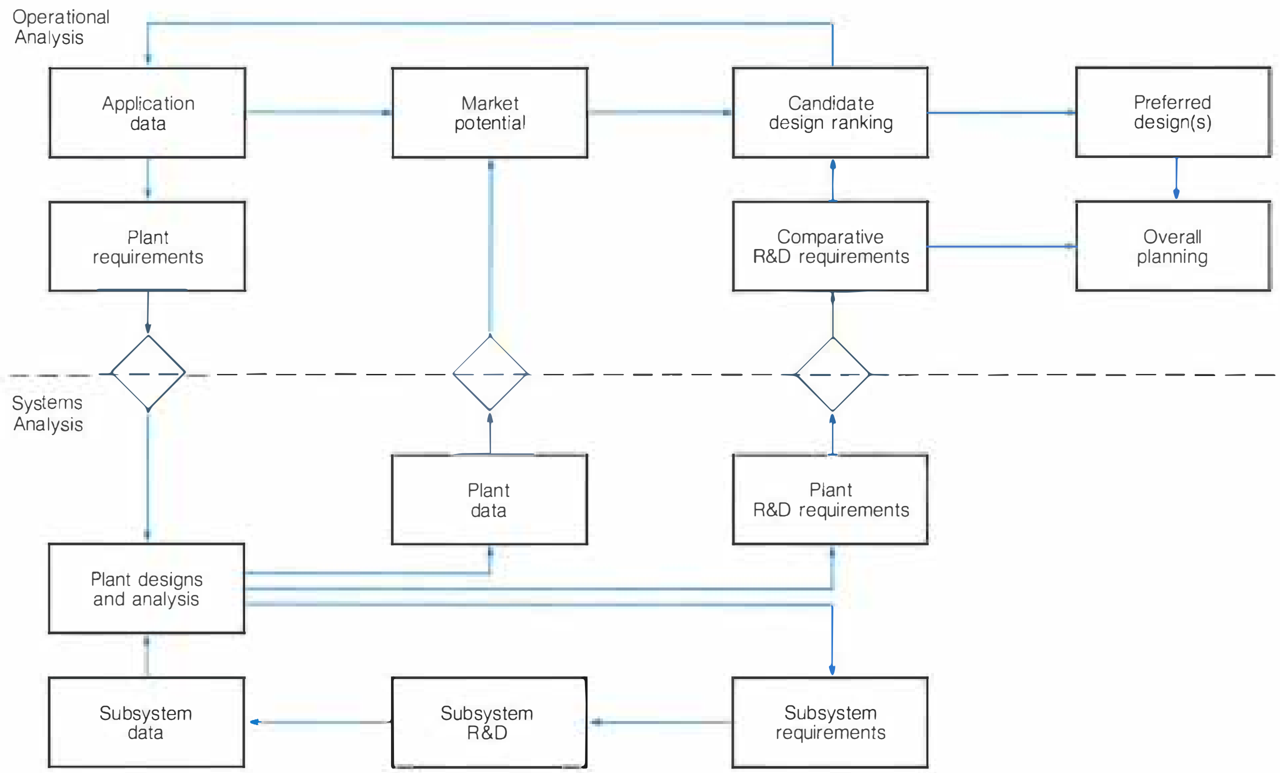
The results for the operational analysis indicated that MHD is most applicable to baseload operation and that (partially as a result of its baseload application) the incorporation of MHD into the utility system is strongly influenced by its availability, initially assumed to be 74%. An additional conclusion is that acceptance of MHD is only slightly affected by improvements in its already high heat rate, which has an assumed value of 7066 Btu/kWh.

The systems analysis complements the operational analysis by providing information on performance, cost, operating characteristics, maintenance requirements, and R&D requirements for specific plant designs. Westinghouse (RP640-1) and STD Research Corp. (RP640-2) are studying plant configurations that incorporate modifications designed to improve plant reliability and reduce development time. These modifications include multiple MHD channels of proportionately smaller size (replacing a single large channel) and oxygen enrichment to attain high-combustion temperatures (replacing high-temperature air preheaters). Both of these changes will cause a degradation in the plant heat rate, so an assessment of the viability of the new configurations will require additional operational analysis.

EPRI is also sponsoring research into specific problems in the MHD system. The slag layer, which develops on the walls of the channel as a result of slag carrying over from the coal combustor, is one such problem. It is generally accepted that the slag layer, which interfaces with the hot combustion products and colder electrodes, has a significant effect on both the electrical performance and the durability of the channel. These problems are being addressed at Stanford University, where the electrical conduction through the slag layer is being studied (RP468). Factors that control whether current conduction through the slag layer is by arcs or by diffuse transport are being determined.

An important conclusion of this work has been that diffuse current transport is being impeded by polarization of the slag layer (i.e., segregation of the ionic conducting species). Work is being directed toward elimination of this polarization effect, thereby allowing diffuse current transport. If diffuse transport can be achieved, it will be possible to assess the impact this has on channel performance and durability. *Project Manager: Andrew Lowenstein*

Figure 5 Flowchart showing the interaction of the operational and systems analyses in formulating preferred designs for MHD power plants.



R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

NUCLEAR DATA DEVELOPMENT

EPRI has continued to support a series of nuclear data projects that will help to develop the national reference library Evaluated Nuclear Data File (ENDF/B) to a level where it can become an adequate standard for thermal reactor analysis. Major effort has been directed toward determining the sensitivities of thermal reactor calculations to different types of nuclear data and toward improving the data types of greatest importance. The fifth version of ENDF/B, scheduled to be released by the end of 1978, is expected to improve on earlier versions in the area of thermal reactor applications.

Nuclear data constitute the basic input for calculations in reactor design, safety analysis, and fuel-cycle optimization. Uncertainties in such calculations, whether due to inadequacy of nuclear data or to approximations in the theoretical models of reactors, must be covered by the imposition of costly margins of safety. In order to reduce data-related uncertainties and to better understand uncertainties in calculative models, EPRI has continued to support the development of ENDF/B, which can be used as a standard source for all reactor-related nuclear data. To achieve this objective, EPRI has cooperated closely with the government agencies responsible for the development of ENDF/B. Previous versions of this library were developed primarily for fast reactor and defense-related areas. EPRI's present contributions constitute an attempt to upgrade the library for utility applications by:

- Determining the types of data that have the greatest impact on LWR analysis (nuclear data sensitivities)
- Supporting new evaluations and measurements for data types of greatest importance
- Testing the thermal reactor benchmark calculations in the present data files (ENDF/B-IV), using very rigorous analytic methods
- Providing guidance on the effect that data modifications proposed for ENDF/B-V will have on thermal benchmark calculations

Determination of nuclear data sensitivities

A nuclear data reference library must contain an extremely large number of data sets, even if consideration is restricted to materials found in an operating LWR. In order to make efficient use of limited funding, it is necessary to determine the most important types of data for a specific set of criteria. A computer system capable of determining the impact of variations in nuclear data on LWR fuel-cycle cost (TPS76-644) was developed at Rensselaer Polytechnic Institute (RPI). The sensitivity of the fuel-cycle cost depends on assumptions about the back end of the fuel cycle. Cross-section uncertainties become considerably more costly if reprocessing and plutonium recycle are not allowed. The cost sensitivity is also influenced by the manner in which information from benchmark experiments is used in the calculative model—for example, by cross-section adjustment or use of bias factors. A detailed study of the sensitivity of the fuel-cycle cost to nuclear data under such assumptions is being carried out at RPI (RP975-4).

The sensitivity of a calculated parameter to a set of nuclear data (such as a thermal neutron fission probability or cross section) is only partly indicative of that data set's importance. A calculation that does not depend very strongly on a particular cross section may nevertheless contain substantial uncertainties if that cross section is poorly known. A systematic methodology developed at Oak Ridge National Laboratory (ORNL) for estimating and using the uncertainties inherent in nuclear data was applied to the study of the propagation of uncertainties in the analysis of LWR benchmark experiments (RP612 and RP975-3).

To provide an overview of the status of nuclear data, including major problem areas and outstanding discrepancies, a seminar was held at the Brookhaven National Laboratory (BNL) National Nuclear Data Center (RP975-1). The seminar also provided a review of the status of integral experiments used as benchmarks for data validation and of industrial experience with nuclear data in LWR analysis.

Support for new evaluations and measurements

Results from the RPI sensitivity studies justified the support given by EPRI to the review and evaluation of thermal cross sections of the fissile nuclei ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu at Battelle, Pacific Northwest Laboratories (BNWL) (RP512 and RP707-1). Other fission-related properties, such as energy spectra and in particular the total number of neutrons produced in fission, were shown to be extremely important. Since the information on the number of neutrons produced in fission for all the fissile elements depends heavily on the properties of ^{252}Cf (which is used as a standard), the need to provide better information on this material will be addressed in future research, even though ^{252}Cf does not enter directly into the design and operation of LWRs (RP707).

Information on other heavy actinide nuclides, including various isotopes of neptunium, plutonium, americium, and curium as well as isotopes of higher atomic weight, has been assembled and formulated for ENDF/B-V by Savannah River Laboratory on the basis of extensive experience in the production of these isotopes (RP451 and RP707-2). BNL is revising the ENDF/B-IV data relating to the isotopes ^{234}U and ^{236}U because the data are considered to be out-of-date and inaccurate (RP975-1). Structural and control materials contribute to a lesser extent to calculative uncertainties. However, the ENDF/B-IV files for zirconium and hafnium, which were missing, were provided by Science Applications, Inc. (RP343), and the gadolinium isotope files, which were considered inadequate, were upgraded through work carried out by BNL (RP708).

Only two direct data measurement projects have been supported by EPRI. Both were carried out at RPI (RP511). The first measurement was an attempt to resolve a long-standing discrepancy between measured and calculated neutron capture rates in the resonance range of ^{238}U. Using a method of neutron transmission and self-indication recommended in the proceedings of an EPRI-sponsored seminar (RP220) on the ^{238}U capture problem, RPI determined in detail the shape of the neutron cross sections in the vicinity of the lowest (and most important) few resonances of ^{238}U. The measurements were carried out at three temperatures: 77 K (the temperature of liquid nitrogen), 293 K (room temperature), and 873 K. The results indicated a need to reduce the ENDF/B-IV resonance widths. Such a reduction is in the right direction for the resolution of the discrepancy.

The objective of the second measurement was a more accurate determination of the capture and total cross sections of ^{232}Th in the thermal energy range. Large uncertainties in the cross sections of this material were pointed out in a BNWL study of the temperature coefficients of reactivity in high-temperature graphite reactor lattices (RP353). Reduction of the uncertainties is also necessary for more-accurate evaluations of the usefulness of thorium as an alternative LWR fuel. It should be noted that EPRI support of nuclear data measurements, though limited, has encouraged a number of DOE laboratories to extend their measurement programs to include data of interest to EPRI.

Testing of ENDF/B-IV

The adequacy of a nuclear data base can be determined from the analysis of benchmark experiments that are relatively simple to interpret. The analysis methods must be accurate enough not to introduce appreciable calculative uncertainties. The set of benchmark experiments used for testing the ENDF/B libraries prior to EPRI's involvement consisted of critical spheres containing homogeneous solutions of uranium nitrate or plutonium nitrate, water-moderated uranium metal critical lattices, and heavy-water-moderated natural uranium exponential lattices.

EPRI has provided additional benchmarks consisting of water-moderated uranium oxide and mixed-oxide (uranium-plutonium) critical lattice experiments carried out at BNWL (RP348). A Stanford University study reviewed the derivation of the benchmark parameters (eigenvalues, reaction ratios, etc.) from such measured data as foil activations. The Stanford study was carried out for both the ENDF/B set of experiments (RP247) and the BNWL critical lattices (RP830). In both cases, the study resulted in substantial revision of the experimental parameters. A rigorous analysis of all benchmark experiments using ENDF/B-IV data was carried out by BNL (RP220, RP708, and RP975-1). In addition, the BNWL critical lattices were analyzed in a joint EPRI-Stanford in-house study. The primary tool of analysis in the BNL projects has been the RECAP code, a full-range, point-energy Monte Carlo code developed under the government's naval reactors program. RECAP, although somewhat limited in flexibility, provided the most accurate analytic representation available. SAM-CE, an alternative Monte Carlo program with a more flexible geometry capability, was developed by Mathematical Applications Group, Inc., for future testing of nuclear data and for benchmarking of such design codes as EPRI–CELL and EPRI–CPM (RP972).

Results of the analysis showed ENDF/B-IV to be fairly adequate for the uranium oxide and mixed-oxide criticals. The most stringent test of the data was provided by the tight uranium metal lattices. An overprediction of resonance captures in ^{238}U of 5–10% (depending on the hardness of the neutron spectrum) was found to cause the eigenvalues for these lattices to be underpredicted by over 1%. The only other significant discrepancy seemed to be an underprediction of captures in ^{240}Pu observed in the analysis of plutonium systems. Both of these isotopes are undergoing major revisions for ENDF/B-V.

The extensive ENDF/B-IV data for fission-product nuclides were processed into a more convenient form for LWR isotopics analysis and tested by Los Alamos Scientific Laboratory (RP453 and RP975-2). Test results indicate excellent agreement for the total buildup of capture rates, which is due to the accumulation of fission-product nuclides. However, a discrepancy seems to be present in the partition of these capture rates among epithermal and thermal energies. The resolution of this apparent discrepancy is hampered by lack of adequate benchmark information.

Guidance for ENDF/B-V

One of the major criticisms from utilities interested in using ENDF/B data in thermal reactor applications was that a two-year development cycle did not allow adequate time for testing the library against LWR benchmarks. At EPRI's suggestion, the preparation time for ENDF/B-V was extended to four years, and the procedures were modified to allow for preliminary testing of a new version prior to its release, and for the utilization of test results in the development of the next version.

In order to provide additional guidance during the developmental stages, EPRI contracted with ORNL to produce sensitivity profiles for two selected LWR benchmark experiments—water-moderated uranium metal lattice (RP612) and mixed-oxide lattice (RP975-3). Sensitivity profiles, when combined with proposed data modifications, will give a quick estimate of the impact of such modifications on various selected benchmark parameters.

The development of a national multipurpose reference file of nuclear data under the support of various sponsors that often have different interest areas is a difficult task. Progress has been complicated by the fact that modifications that constitute an improvement in one area of application have often resulted in degraded performance in others. Since all modifications are justified on the basis of direct experimental evidence, it has been necessary to understand and correct the causes of such degradations. This may have slowed the rate of progress, but it has resulted in an accurate data library.

The fifth version of the ENDF/B library is undergoing its prerelease testing. Since it is probable that the library will undergo further modification as a result of this testing, it is difficult to estimate its performance in thermal reactor benchmark experiments. However, it is safe to assume that the library will contain many improvements on earlier versions, and it is hoped that it will eventually prove useful for thermal reactor analysis. *Project Manager: Odelli Ozer*

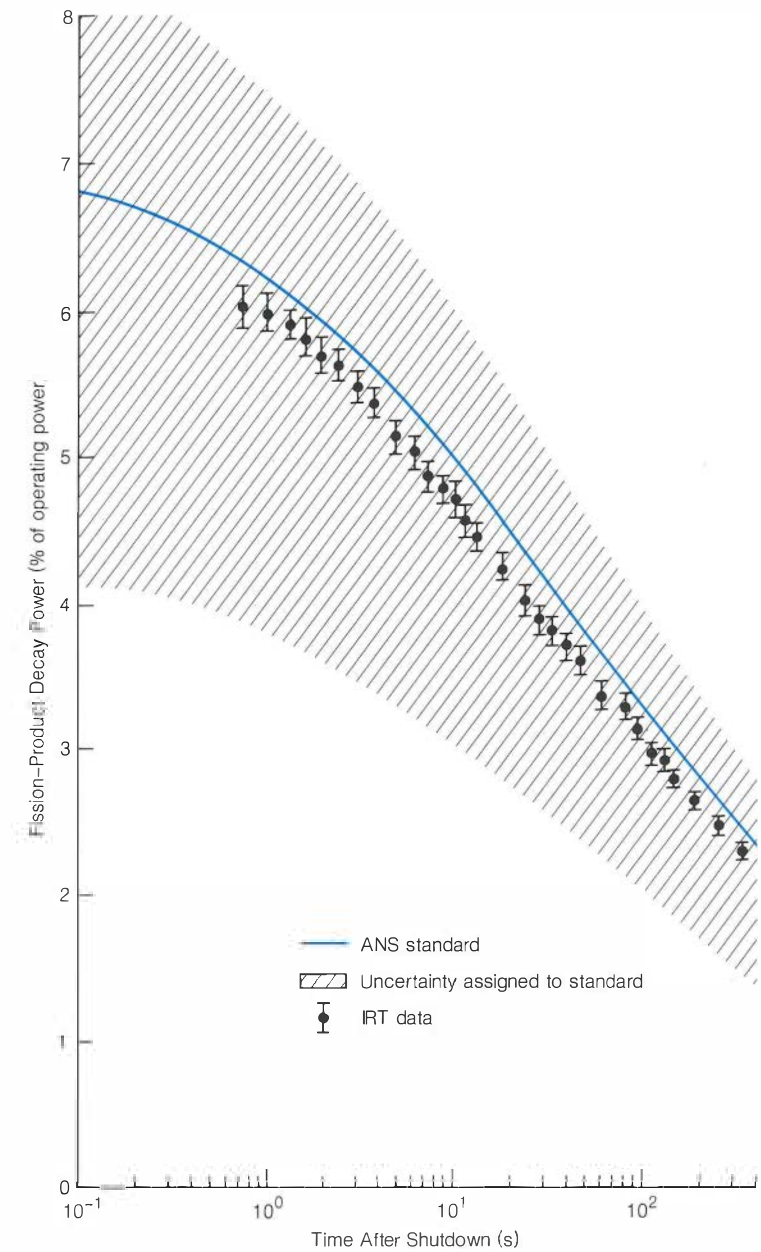
FISSION-PRODUCT DECAY HEAT

The record of commercial nuclear generation of electricity is outstanding in terms of operational safety. The bases for confidence in a given plant's behavior under abnormal conditions stem from an extensive technology, including mock-up experiments and basic physics measurements. Examples of the former are the extensive semiscale and loss-of-fluid test experiments that are under way at the Idaho National Engineering Laboratory. These experiments, sponsored by the federal government, will clarify aspects of such hypothetical occurrences as LOCAs. Data derived from such mock-ups *are supplemented by the acquisition of information from physics measurements. Such fundamental measurements have been conducted at various sites, including national laboratories. EPRI has sponsored experiments related to the mechanism underlying a postulated LOCA—the amount and rate of production of decay heat generated by fission products after the shutdown of the reactor core (RP766 and RP957).*

For safety calculations, decay heat is specified through a draft standard of the American Nuclear Society (ANS). This draft standard (ANS 5.1) makes use of extensive, detailed (summation) calculations and experimental data for its estimate of the decay heat produced and associated statistical uncertainties. Present regulatory rules specify that an additional 20% of decay heat should be added to the ANS standard. IRT Corp. and EPRI have been supporting experimental research related to these bases for the ANS standard. Figure 1 compares the ANS standard with the results from earlier IRT measurements for ^{235}U fission-product decay power. The results of these earlier experiments, funded in RP230, are prototypical of the final results to be attained from the current research projects. One area of the current research involves the measurement of ^{239}Pu decay heat (RP766). Another area involves the measurement of the components of this heat—the beta and gamma spectra from the decay of ^{239}Pu fission products (RP957). The information from this latter work can be compared in detail with corresponding calculations. Upon verification, these summation calculations can be run in certain conservative modes (using such computer codes as CINDER or ORIGEN) to satisfy standard conditions imposed by federal regulations.

The work under RP766 involves the measurement of the total decay heat from ^{239}Pu in the 1–10^5-cooling-time range following irradiation. In this research, thin metallic targets are irradiated by neutrons from a ^{252}Cf source and then transferred via a pneumatic rabbit system to the center of a 4-m^3 liquid scintillator. The scintillator produces a signal approximately proportional to the total beta and gamma energy being emitted. Beta and gamma components of the decay heat signal are differentiated via an auxiliary measurement in which iron was placed in the scintillator to absorb the beta component. With this methodology, IRT made analytic corrections to the data on the order of 10% for gamma escape from the scintillator and beta absorption in the sample.

Figure 1 In the event of a LOCA, account must be taken of the variation of fission-product decay power with time after shutdown. This figure compares the ANS standard (and its associated uncertainty) for this time-dependent power with experimental data measured by IRT Corp. in an earlier project. The results of these experiments are prototypical of the final results to be attained from the current research projects.



The normalization of these data to determine decay heat per fission depends on a calibration of energy deposition in the scintillator via a National Bureau of Standards calibrated ^{60}Co source. In addition, it is necessary to determine the fission rate in the targets during irradiation. This is accomplished in an auxiliary experiment using small samples in which fission-counting efficiency is on the order of 95–97%, thus allowing a precise determination of the fission rate. After this determination, the samples are covered to retain the fission products and are irradiated for a time corresponding to the irradiation times employed in the primary experiment. These samples are then measured in the scintillator to allow a normalization of the primary experiment. These small samples are not used in the primary experiment because their size results in an undesirably large statistical uncertainty at long cooling times.

The techniques just described, applied to previous measurement of the ^{235}U decay heat, yielded results having excellent internal consistency. For ^{239}Pu, discrepancies were found between the relative mass of the deposits (as determined by counting the 129-keV gamma rays) and the measured fission rates from the small samples. The measured signals from the scintillator were also discrepant. The number of targets utilized to date was insufficient to allow the determination of the source of the difficulty. An upcoming measurement with a larger quantity of targets should allow a satisfactory normalization.

In addition, EPRI is sponsoring a normalization effort in cooperation with ORNL. This will involve the comparison of selected fission-product gamma-ray information measured from one of the IRT samples, with corresponding data observed with an ORNL ion chamber in which the fission rate from a ^{239}Pu deposit has been determined. Corrections for differences in irradiation times will be applied on the basis of known isotopic half-lives.

The work under RP957 involves the measurement of beta and gamma spectra at various times after fission of ^{239}Pu. Comparison with spectra derived from the ENDF radioisotope library should reveal the source of discrepancies between measured and calculated decay heat for this isotope.

This project is unique in several aspects.

- Beta and gamma spectra are being measured simultaneously under identical conditions.
- The gamma spectra are being recorded with a high-resolution lithium-drifted germanium (Ge [Li]) spectrometer to allow identification of specific isotopic lines.
- Gas transmission counters are being used in both spectrometers to distinguish between beta and gamma events.

The fissile sample is attached to a polyethylene rabbit and irradiated by neutrons from a water-moderated 10-mg ^{252}Cf source. At the end of irradiation, the computer controlling the experiment moves the rabbit to the spectrometer in about 1 s, at which time counting commences. The beta particles emerging from one side pass through a Mylar window immediately adjacent to the sample and then proceed through an evacuated collimator to a second Mylar window, which defines the gas counter volume. The counting gas is high-purity methane at atmospheric pressure.

The beta particles then pass into a 3.8-cm-thick plastic scintillator viewed by a low-noise photomultiplier tube. A time coincidence is required between the gas counter and the plastic scintillator to distinguish the beta events from the undesired gamma events.

The gamma rays from the opposite side of the sample enter a collimator–gas counter system identical to the one just described. On this side a high-quality 80-cm³ Ge(Li) spectrometer is located behind the gas counter rather than the plastic scintillator. This spectrometer is operated in anticoincidence with the gas counter to reject unwanted beta events.

The signals from the two spectrometers are ultimately digitized for storage in a computer memory. The signal selector allows the computer to rapidly select beta or gamma signals for storage. The spectra not being accumulated are stored on the computer disk. When the computer has sampled the beta and gamma spectra 10 times each, the net spectra are written on magnetic tape for further processing.

After correction for gamma-ray efficiency and beta-ray energy loss, the spectra are normalized to determine the number of events per fission via an auxiliary experiment in which the fission rate from a thin ^{239}Pu sample is measured in an ion chamber irradiated by the ^{252}Cf source. When the fission rate has been determined, the target is covered (to retain fission fragments) and reirradiated. This covered sample is then counted in the spectrometer to allow normalization via selected intense gamma rays. The data are compared with spectra calculated from the ENDF library after folding in the spectrometer response functions as calculated by the electron–gamma ray transport code SANDYL. *Program Manager: Walter Eich*

ANALYSIS OF TORNADO MISSILE RISK

As part of a comprehensive program to produce a tornado-resistant design for nuclear power plants, a project was undertaken to formulate, develop, and demonstrate a probabilistic methodology for quantifying the risk of damage from tornado-borne missiles (RP616). A computer simulation code, TORMIS, has been developed that incorporates results of all EPRI tornado-related research projects. The risk, as determined from two hypothetical case studies, appears to be acceptably small.

To ensure the health and safety of the general public, NRC design criteria specify that safety-related nuclear systems be protected from tornado-borne missiles traveling at maximum credible velocities. NRC Standard Review Plans also specify that if the probability of impact by such a missile on a critical area of the plant is less than about 10^{-7} per year, it need not be considered as a design basis event.

Attempts to quantify the effects of tornado-borne missiles on the safe operation of nuclear power plants have been made within the last few years. To evaluate the design basis of the tornado missile hazard, NRC established criteria to provide an intentionally conservative design requirement to compensate for the statistical variabilities inherent in this hazard. The worst-case analysis, as emphasized and required in the NRC Standard Review Plans, may not be justifiable on the basis of risk of tornado missile hazard to plant safety. It became evident that a probabilistic assessment of tornado missile hazard was needed, particularly in the case of the more complex hazard presented by multiple missiles.

A sequence of incidental events must occur before a safety-related component at a nuclear plant is impacted and damaged by a tornado-borne missile. First, a tornado must pass through the plant site, and there must be potential missile objects near the plant. These objects must then be lifted and borne along by the tornado. Finally, they must be transported to and must hit a "target," or safety-related system, in order to actually pose a threat to the operation of the plant. The quantitative assessment of the tornado-borne missile hazard is complex. Many aspects of scientific disciplines are required in the development of mathematical models and the probabilistic evaluation of the hazard.

As part of a comprehensive program to assess and quantify tornado-resistant design requirements, Carolina Power & Light Co. undertook a project to develop a credible statistical methodology for assessing missile risk (RP616). The methodology included the formation of analytic models of the sequence of tornado missile events, the development of the required probabilistic methodology, and the evaluation and demonstration of the risk for hypothetical plant configurations. The methodology used in the project had five parts.

- National tornado data recorded over five years were analyzed to provide statistics on tornado occurrence rates and strike characteristics (such as the tornado passage width, length, and direction) as well as statistical distribution functions.

- A survey of seven nuclear plants in various stages of construction and operation was made to obtain quantitative and qualitative information on characteristics of potential missiles.

- A missile injection model and a random-orientation missile transport model were developed to characterize the paths of missile objects.

- An impact methodology, which incorporated impact test data obtained from EPRI's other tornado-related projects, was developed for a spectrum of missiles to provide the basis for prediction of structure damage.

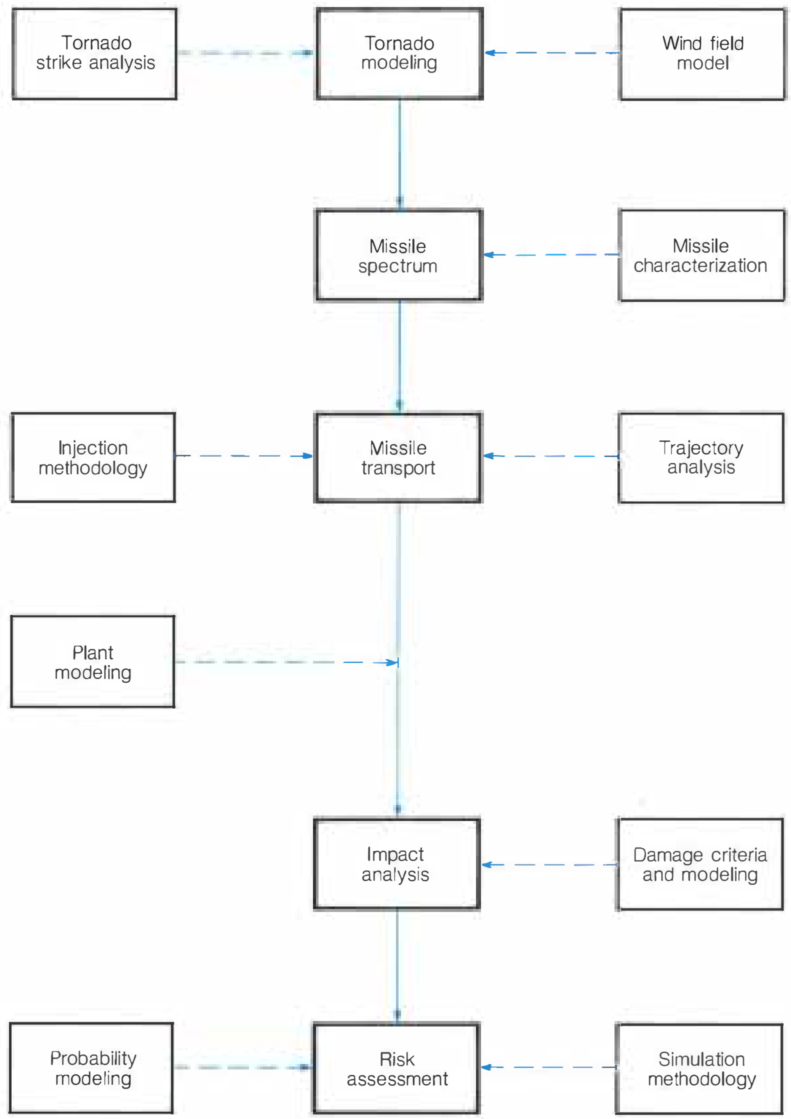
- The Monte Carlo simulation technique and variance reduction methods were applied to quantify the missile risk.

These components of the project were linked to form an integrated model (Figure 2), which also forms the basis for the computer code TORMIS.

Two hypothetical plant configurations, a single nuclear steam supply system unit and a two-unit plant, were analyzed by the TORMIS code to quantify the potential risks of tornado-borne missiles to plant operation. For different geographic locations of the plants, the estimated probability of missile hazard ranges from 10^{-7} to 10^{-9} for a single missile; the hazard of multiple missiles depends on the availability of missile objects in the plant vicinity as well as geographic location (NP-748 and NP-749).

A follow-on effort has been planned to refine and update the methodology and to improve and validate the risk assessment computer code, TORMIS. The objective is to implement the methodology as part of nuclear power plant design and of safety evaluation analysis for use by the electric utility industry. The second phase of this project will be contracted to Research Triangle Institute, Inc. *EPRI Project Manager: Boyer Chu*

Figure 2 The flowchart shows the five parts of a model built by the Carolina Power & Light Co. to analyze the risk of damage to nuclear power plants from tornado-borne missiles.



R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

UNDERGROUND TRANSMISSION

Particle-initiated breakdown of gas-insulated systems

One of the most severe problems in gas-insulated systems is the detrimental effect that metal particles have on the integrity of the gas insulant. This contamination radically reduces voltage breakdown values. If gas-insulated cable systems and substations are to be made more reliable and economic, a better understanding of contamination effects is needed. Since small quantities of metal particles are usually present in field installations, the objective is to understand and control particle effects rather than eliminate the particles.

The breakdown voltage of gas-insulated systems is highly dependent upon electrode configuration. Any foreign material can alter the electrode configuration and hence the electric field distribution. This has detrimental effects on system integrity.

Westinghouse Electric Corp. is investigating particle-initiated breakdown phenomena (RP7863) and will measure the breakdown characteristics of SF_6 that occur when impulse waveforms are superimposed on the 60-Hz voltage waveform with particular contaminants present. The objective is to determine whether this superimposition is a limiting case and if so, to statistically analyze the probabilities of failure.

Studies of particle-initiated breakdowns have shown that breakdown occurs when the particle is close to or in contact with the electrode of highest stress. A particle resting on an electrode surface is lifted off the surface when the electrostatic forces exceed the gravitational force on the particle. With increased electric fields, the particle can cross the gap between the electrodes. If the particle is lifted from a low-field region to a region of higher electric stress, breakdown may take place as a result of the local field enhancement that occurs when the particle moves into the higher-field region.

Computer studies of particle motion have shown that switching-surge voltages can deliver sufficient momentum to a particle at rest to cause it to cross to the central conductor of a coaxial system. However, the voltage reaches zero long before the particle reaches the central conductor. If the gap is already stressed with voltage, imposed or generated surges in the system can represent an increased threat of particle-initiated breakdown.

The tentative conclusions of the study have been interesting. The breakdown voltages resulting from superimposition of lightning and switching impulse voltages on a 60-Hz voltage with fixed particles were not found to be lower than those of the individual voltages applied separately. Breakdown voltages at positive polarity, under all conditions (including superimposition cases), occurred at well below the negative polarity voltages for both fixed and free particles. Particles at rest on the enclosure in a coaxial system under normal 60-Hz voltage were lifted by the superimposition of a switching impulse and remained in a levitated state during the entire time that the normal ac voltage was applied. This suggests that complete and positive trapping of all particles in a gas-insulated system is necessary for reliable operation. The probability of failure occurring in the gaseous insulation from the combination of conducting particles and superimposed transients in a gas-insulated system appears to be small compared with the effects of the long-term operating and short-term elevated 60-Hz stresses. *Project Manager: John Shimshock*

High-temperature gas-insulated systems

At present, the maximum operating temperature of conductors in buried gas-insulated transmission systems is limited by the enclosure-soil interface temperature. This interface temperature has a direct effect on the rate of moisture migration in soil, which in turn affects soil thermal conductivity and the ampacity of a system. For forced-cooled buried systems and for aboveground installations, the enclosure-environment interface temperature is no longer a constraining factor. In such cases, it is potentially advantageous to operate gas-insulated transmission systems at conductor temperatures considerably above recommended hot spot temperatures. It would also be advantageous to allow higher temperatures for contingency or emergency conditions.

To investigate the problems and prospects of higher-temperature gas-insulated systems, a project was initiated with Gould Inc. (RP7859). This project focuses on the economics, insulating materials, enclosures, and conductor joints associated with high-temperature operation. The primary objectives of the project are:

- Analysis of the economic effects of increasing the conductor hot spot temperature to 150°C in various environments
- Development of a cost-effective insulator for operation at 150°C and stresses to 59 kV rms/cm (150 kV rms/in)

Progress on major objectives has indicated mixed results. The economic effects of high-temperature operation have been evaluated with computer optimization programs. These programs use both energy and demand charges to account for system losses via present-worth methods. The results indicate that high-temperature operation can be economically attractive but only at optimized conductor temperatures considerably less than 150°C. The cost of losses associated with high-temperature operation constitutes a substantial portion of the total cost, and this has a significant impact on the conductor temperatures proposed for modified designs. A more realistic, economic hot spot conductor operating temperature is in the 105–110°C range. Even though there will be losses when system contingencies raise the temperature to 150°C, this range will still offer a significant operating advantage.

An extensive screening program for insulator materials has been concluded that covers more than 30 different materials. An epoxy compound has the best balance of properties to meet project goals. A radically modified disk insulator without molded-in metal inserts for stress control appears to be the most cost-effective design. Mechanical and electrical testing has been completed successfully on a few samples of the new insulator.

A full-scale prototype system that will incorporate all components suitable for high-temperature operation is now under construction and will undergo six months of thermal and dielectric testing. Concurrent long-term dielectric testing of a large group of insulators should provide additional encouragement. *Project Manager: John Shimshock*

Cable oil study

As the number and size of underground cable systems have increased, many utilities have purchased and installed the components of the cable systems themselves and have obtained filling oils directly from oil suppliers. With the growing availability of new and different cable-impregnating and -filling oils and the increasing practice of purchasing cables and components separately, the suitability and compatibility of filling oils have become more important. Existing specifications for the individual oils were found to be insufficient to guide utilities in the selection and qualification of filling oils, especially with so many cables and cable impregnants available.

In response to these problems, a contract has been awarded to General Electric Co. for a 30-month study of insulating and filling oils for high-voltage underground transmission cables (RP7872). The purpose of this project is to develop functional test methods and test equipment that can be readily used by the industry to qualify cable-filling oils. The test procedures would complement existing specifications and procedures and would permit verification of various cable-filling oils for use in existing and new cable systems.

The test cell that will be developed for the functional tests will be suitable for use by the industry. Performance of cable-filling oils will be correlated to insulation aging.

The functional test methods and test apparatus will be based on the simulated life-testing of insulation components and oils, and the relative functional performance of the filling oils will be determined from the measured effects on the aging processes and life of the oil-paper insulation system.

The test methods involve accelerated aging induced by temperature, by voltage stress at a selected temperature, and by a combination of temperature and voltage stress. Three acceleration temperatures and three voltage stresses will be combined for selected aging intervals ranging from 4 to 90 days. The effects of aging on the insulation components will be determined through power factor measurements, physical and chemical measurements on the paper, and analyses of the oils and gases during the aging period by liquid and gas chromatography.

Six combinations of representative synthetic and mineral oils will be evaluated and subjected to the complete series of aging tests for varying periods of time. The relative performance of the filling oils in the functional test will be determined from the aging tests and from analysis of the paper-oil aging kinetics under accelerated temperature and voltage stress. *Project Manager: Stephen Kozak*

DISTRIBUTION

System reliability

Distribution system outages contribute to more than 90% of all power interruptions to customers. Two ways of analyzing this situation have been tried. One is a practical approach, in which system performance is determined by collecting system outage data. The other is a theoretical approach, which uses modeling techniques to predict the performance of present and/or future system configurations.

EPRI is funding a project in which Westinghouse Electric Corp. will combine both of these approaches into a tool that distribution planners and designers can use for existing and proposed systems (RP1356). The 18-month project has five objectives.

- Evaluate the state of the art of reliability assessment procedures used by the utility industry
- Recommend a uniform outage-reporting scheme that can be used by most utilities
- Develop computer programs to calculate system reliability indices and to perform risk analysis
- Prepare an easily understood reliability handbook
- Incorporate the reliability and risk analysis model into the feeder model of RP570

Project Manager: William Shula

Wood pole research

Continued demand for solid wood poles, increasing production costs, limited supplies of suitable tree species, and competition from other industries for the wood that is available have indicated a need for suitable replacement materials. The primary objective of a research effort with the Institute of Wood Research at Michigan Technological University is to demonstrate the feasibility of manufacturing distribution and transmission poles and structures from composite wood material (CWM), which is made from woods of little commercial value, such as red alder or balsam fir (RP796). This material should be in adequate supply and have stable costs.

Several types of flakes from three species of wood were used to manufacture CWM, with phenolic resin as the adhesive. For all the strength properties measured—bending, tension, internal bond, and screw withdrawal—the superior CWM was that made from flakes produced by roundwood flakers.

A variety of section shapes were studied. After consideration of the efficiency and esthetics of these sections, an octagonal shape was selected for future work. The cross section of the pole is built up with laminations of CWM. The number of laminations depends on the stress on the pole at the section under consideration. Thus interface adhesives are required both to glue the panel surfaces together and to glue the edges to form the octagonal shape. Work has been done to determine properties of adhesives, and several appear to be good candidates.

Several sizes of octagonal poles were designed, and material volumes for these sizes were calculated. Costs of CWM and edge and panel adhesives were determined and used to calculate composite pole costs. These were compared with some solid-wood pole costs. The cost of a CWM duplicate of a 12-m (40-ft) Class 1 pole compares favorably with the present cost of a roundwood pole. For a 24-m (80-ft) Class 1 duplicate, the savings appear to be substantial—approximately 50%. *Project Manager: Robert Tackaberry*

AC SUBSTATIONS

Vacuum interrupter development

Although the vacuum interrupter has been available for more than 15 years, its application to circuit breakers has been limited to the lighter-duty distribution breaker and metal-clad switchgear. This limitation has resulted from shortcomings in the fault-current-interrupting ability and the low voltage ratings of individual interrupters. General Electric is developing a high-capacity vacuum interrupter for use in transmission-class power circuit breakers (RP754).

A distinct change takes place in the arc current as its magnitude increases. In the conventional vacuum interrupter, an arc is drawn and interrupted between the separated butt contacts. For currents of a few thousand amperes or less, the arc current is in a diffuse mode between the contacts. This permits an easy interruption at current zero. Contact erosion is minimal, and the interrupter's dielectric recovery is good. But when the current reaches a magnitude higher than a few thousand amperes, the current becomes constricted and concentrated at the arc terminals.

The current in this mode may erode contacts severely, affecting the interrupting performance and the life of the device. This has been the limiting factor in the current-interrupting and voltage-handling ability of vacuum interrupters. The problem has traditionally been handled by shaping the contacts to keep the arc moving, increasing the contact size, and selecting more suitable contact material.

By contrast, one of the goals of this project is to develop a rod-array electrode design that will keep the arc in a diffuse mode for current values through 80 kA. If this can be accomplished, the dielectric performance of the device should be greatly improved, and it should have a longer life. Another goal is to increase the continuous current rating of the interrupters to meet the basic power circuit breaker requirement of 3000 A.

Investigation is also under way to determine the mechanical requirements needed for reliable operation and to prevent contacts from popping because of the forces produced by high momentary current values.

So far the work on keeping the arc in a diffuse mode has been very encouraging. Work is now under way to improve the dielectric performance of the interrupter by improving the contact and electrode geometry.

This project should result in a vacuum interrupter with at least twice the overall capability of vacuum interrupters available today. *Project Managers: Narain Hingorani and Glenn Bates*

Transformer life characteristics

Transformers play a key role in all aspects of the electric power industry and are vital components in determining customer-service reliability and quality. Knowledge of their performance and characteristics under operating conditions is thus essential for optimum planning and operations.

The service life that can be expected for any given transformer is key information for specification and purchase. The anticipated service life also governs decisions concerning the installation of additional units and the timing of replacements. Furthermore, an accurate evaluation of the likelihood that a given transformer can satisfactorily endure emergency conditions at any point in its service life depends on knowledge of its predicted useful life.

There is general agreement within the industry that current guides for safe loading of transformers are not satisfactory. A tripartite committee made up of representatives from EPRI, the Institute of Electrical and Electronics Engineers, and the National Electrical Manufacturers Association was established some years ago to evaluate this situation and consider the alternatives. As an outgrowth of these developments, two projects have now been initiated, one with General Electric (RP1289-1) and the other with Westinghouse (RP1289-2), to develop a greater understanding of transformer life characteristics. Both programs will involve the study of varied stresses on model transformers to:

- Establish the significant parameters affecting transformer life in the 10- to 100-MVA range
- Establish criteria for test methods that may be employed in future research
- Gain a better understanding of the mechanism of transformer failure

Both projects were initiated in mid-1978 and will continue for approximately 30 months. *Project Manager: Bruce Bernstein*

Electrostatic field effects

The potential biological effects of electric fields are of concern to the electric utility industry (*EPRI Journal*, June-July 1977, p. 6) and are therefore given significant attention in EPRI's Substations Program. This program addresses both ac and dc field effects through a number of different projects. It is well known that the characteristics of ac and dc fields are quite different. Results from an ac field study are therefore not necessarily applicable to dc. The project described here, being conducted by Ohio State University, is a study of electrostatic (dc) fields in converter stations (RP1097). The objective of the project is to produce a design tool for predicting the electric fields around and within a converter station prior to construction of the facilities. This cannot be done with the technology available to designers today, since full-scale studies are too costly to be practical.

A similar project was successfully concluded for ac substations (*EPRI Journal*, June-July 1977, p. 44, and EL-632). For this study, Ohio State constructed a small-scale (1:67) model of a substation and used miniature instruments for measurement of the ac fields in the model. The model measurements were then converted to a field prediction for the full-scale substation. This method seems to be feasible for dc field predictions as well, and an adaptation of this technique is therefore being pursued for prediction of the dc fields in converter stations.

It is hoped that the method will be successful, but the prediction of dc fields is much more difficult than the prediction of ac fields. The dc fields have many nonlinear characteristics. Electron and ion flow from the energized parts of the converter station significantly alters the simple electrostatic field distribution, and while the electrostatic field distribution is easily computed (assuming a perfect dielectric), the space charge effects make it difficult to attain a reasonably accurate model for design. It is felt, however, that the scale model approach may have a greater chance for success than other methods. This assumes, of course, that the key model parameters can be determined.

The contractor is first conducting a feasibility study that includes field measurements in existing converter stations. These measurements will be used to establish a frame of reference for the modeling work. The field measurements have shown it is necessary to incorporate the space charge effects within the converter station model. The researchers are, therefore, concentrating on the modeling of very simple structures in an attempt to define the nonlinear parameters through proper selection of voltage scale, physical scale of the model, and selection of conductor scale. To be successful, this model must produce a scale version of the space charge distribution within a converter station. Some progress has been made, but complete feasibility for the modeling approach has not yet been established. *Project Manager: Stig Nilsson.*

Vacuum fault current limiters

Fault current limiters have received considerable attention from the electric utility industry, which has a need for fast-acting current-limiting devices at critical points in transmission networks. If reliable fault current limiters can be demonstrated on a system, their application can substantially extend the life of all series equipment—transformers, disconnect switches, circuit breakers, and so on. The economic advantage to utilities could be appreciable.

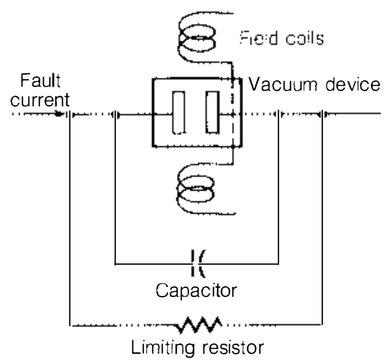
EPRI is sponsoring several projects that deal with the development of fault-current-limiting devices. Westinghouse is developing a current limiter that uses vacuum arc current commutation (RP564), and State University of New York at Buffalo (SUNYAB) and Gould are developing a vacuum arc fault current limiter (RP993).

In the Westinghouse study, the electrodes of a vacuum device are separated during a fault current rise so that a stable arc burns in the metal vapor evaporated from the electrodes. When the electrodes have been separated to a spacing of about 2 cm, a magnetic field is applied across the arc path (Figure 1). This field causes arc instability, with a resulting rapid rise in the arc voltage, thereby diverting the current to a parallel capacitor. When the vacuum arc is extinguished, the circuit current continues to flow into both the capacitor and the parallel current-limiting resistor. The resistive drop results in high voltage across the vacuum contacts, but the arc does not reignite because vacuum devices have a rapid dielectric recovery. This approach to a current limiter is attractive because the continuous current is carried by an in-line device, the device is not polarity-sensitive, the apparatus for causing a forced arc extinction can be isolated from line potential, and high voltages can be withstood at relatively short electrode spacings, thereby simplifying the actuator mechanism.

Work is continuing on RP564 to raise the current rating of a single, 72-kV device using a small parallel capacitance. This is done by optimizing significant features, such as electrode area, electrode material, and diameter of the external ceramic envelope.

SUNYAB and Gould are seeking to develop an effective commutation device for insertion of a current-limiting impedance. The essential requirement of the commutation device is that it rapidly generate high arc voltages. The objective includes replacing commutation fuses and associated selector and insertion switches with a reusable commutating switch that uses magnetically modulated vacuum arcs. The scope includes correlation of theory and test results, determination of design parameters, and evaluation of the feasibility of using a vacuum arc commutating switch for resistive fault current limiters. *Project Manager: Ivars Vancers*

Figure 1 When the contacts in a vacuum fault current limiter have separated approximately 2 cm, a magnetic field applied across the arc path causes arc instability, with a resulting rapid rise in arc voltage. This diverts the current to a parallel capacitor as well as to the current-limiting resistor.



POWER SYSTEM PLANNING AND OPERATIONS

Dynamic load modeling

The loss of a generating plant or the opening of a major transmission tie line causes changes in the voltage and frequency within the power distribution system. Such variations may be amplified or suppressed by the dynamic response of the connected loads. When voltage and/or frequency changes exceed certain preset limits, automatic protective devices (e.g., protective relays, motor controllers) may cause customer loads to be dropped. Engineering a robust power system—one that can withstand a major disturbance—requires an understanding of how power system loads can influence power system performance.

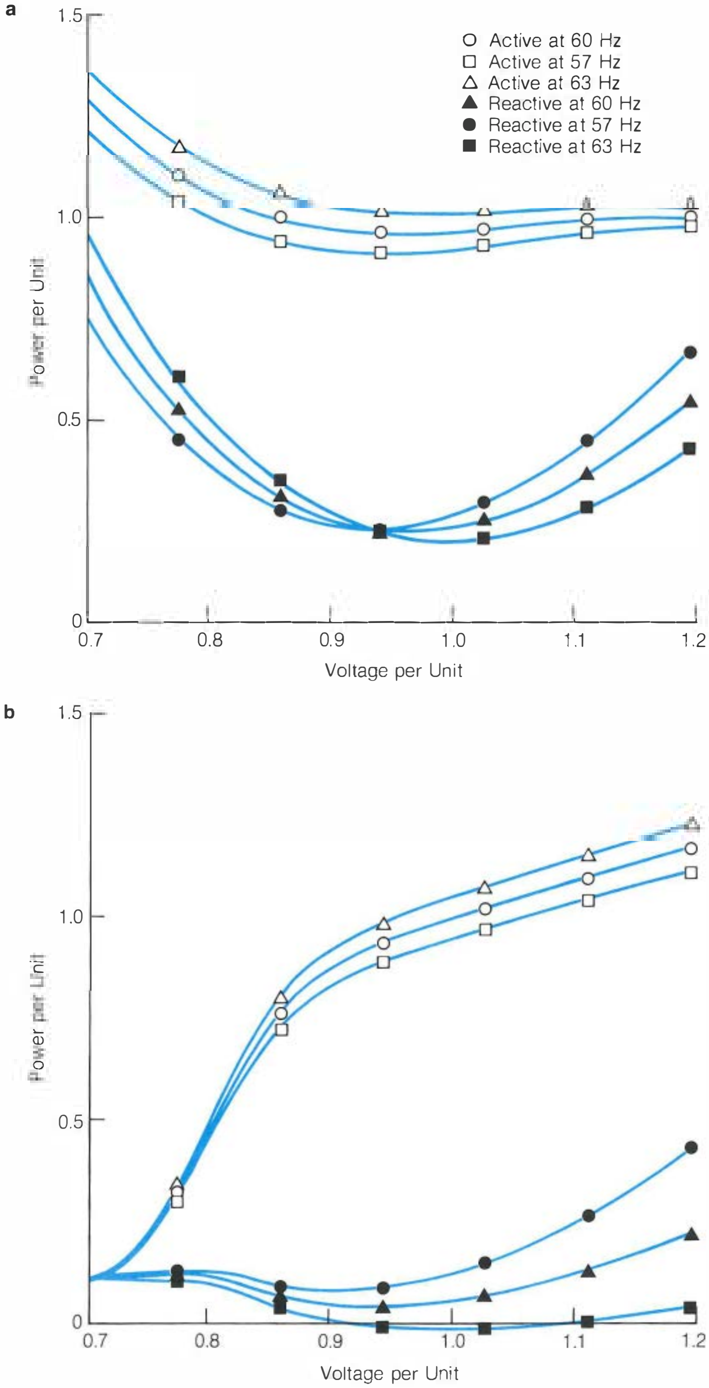
As described in the October 1977 issue of the *EPRI Journal* (p. 39), a research project is under way to develop a better understanding of the dynamic characteristics of loads, particularly when they are subjected to abnormal voltage or frequency changes (RP849). This 45-month project (now at its midpoint) has provided instrumentation to measure how system loads (MW and MVAR) react under various adverse conditions. Measurements have been made to obtain the response of component loads (ranges, refrigerators, air conditioners, etc.) to voltage or frequency changes. EPRI researchers seek a procedure that will enable electric utilities to model their loads more accurately as well as to predict the load response under dynamic conditions. Such models, when used in load flow and system stability computer programs, will help the power system planner improve power system performance.

The responses of component loads to changes in voltage and frequency (Figure 2) have been measured by researchers at the University of Texas at Arlington (UTA) with the cooperation and assistance of Texas Power & Light Co. Mathematical models for each of the components tested have been developed and are used as a data base for a prototype load-modeling procedure developed at UTA. Final reports on the UTA work and accomplishments are being published (EL-849, Vols. 1, 2, and 3). Instrumentation to measure the response of loads at the substation bus has been designed, fabricated, and tested by the Institut de Recherche de l'Hydro-Quebec. The Real-Time Digital Data Acquisition System (RTDDAS) has been installed in an instrumentation trailer and will be used to capture three-phase load bus currents and voltages at sample rates that will obtain the dynamic load response expected. Up to 150 samples per cycle per channel can be obtained.

Figure 3 illustrates both the expected activity flow for the remainder of the project and the way in which project results will be applied. The UTA-developed load-model-building procedure has been used by General Electric with test site customer data to produce models for selected load buses. These models have been used in test planning to predict load behavior when voltage and frequency changes are introduced at the substation bus. Field data are being captured by the RTDDAS and will subsequently be analyzed by General Electric. The objective of the field data analysis is to either validate the model-building procedure or revise the procedure and test it again. The project includes tests run during summer peak and winter peak periods in 1978 and during the summer peak of 1979. Tests will be made at selected sites on Long Island and at a site in Rochester, New York.

Southern Company Services, Inc. (SCS) has, with some help from UTA, used the model-building procedure on a part of its system. SCS has also modified its modular

Figure 2 Changes in the load source voltage and frequency (caused by disturbances on the transmission system) result in changes in the active and reactive power required by loads, such as air conditioners **(a)** and fluorescent lights **(b)**. Component load requirements may offset or amplify the total response at a particular voltage or frequency input.

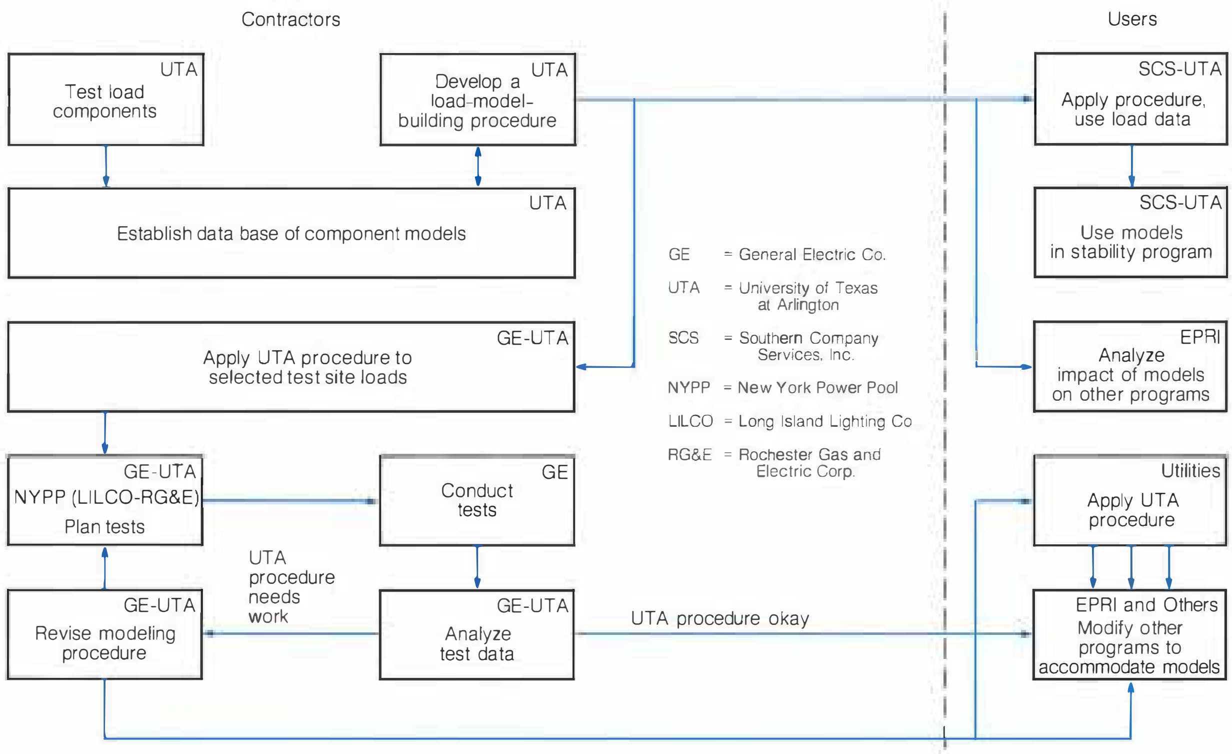


stability program, which is under development, to accommodate the UTA model. Although the UTA modeling procedure itself has not yet been validated, SCS has demonstrated the ease with which a modular program can incorporate such new models. EPRI researchers from other projects are developing analytic computer programs that incorporate load models. The load models resulting from RP849 will give results different from those of the load models being used today.

EPRI plans to assess the improvement in overall results that the UTA models would provide when incorporated into these EPRI-funded analytic tools. Utility companies, by reading the UTA final reports (EL-849) and the other RP849 final reports that will be published in early 1980, can estimate the benefits to be gained from modifying their own load flow and stability analysis computer programs. The effort required to incorporate RP849 results into utility company analytic programs will vary with the design of the program and the availability of information on customer loads.

Follow-on EPRI research is being planned to evaluate the cost-effectiveness of using RP849 results in analytic programs. *Project Manager: Donald Koenig*

Figure 3 Research on the dynamic characteristic of loads is being performed by General Electric Co. and the University of Texas at Arlington. Results will be applied by EPRI, as well as by individual utility companies. The dashed line separates the contractors' scope of work from the users' application of results.



R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

INDOOR AND OUTDOOR AIR POLLUTION

Striking differences between pollution levels of air inside and directly outside homes have been recorded by environmental scientists at the Harvard University School of Public Health (RP1001). Since most people spend all but a few hours each day indoors, this raises serious questions about the relevance of ambient air quality standards to human well-being.

Current air quality standards are based on outdoor air monitoring, which may or may not correspond to the levels to which most of the population is exposed. In the case of invalids or those with severe heart or lung ailments, the indoor environment is probably the only one to which they are usually exposed. Although the Clean Air Act mandates that the needs of these "sensitive" portions of the population be considered in setting air quality standards, the measurements on which the standards are based are made solely outside homes.

Sulfur dioxide (SO_2), for example, is almost exclusively an outdoor pollutant. Levels directly outside a home are usually at least ten times as high as those measured indoors. Since SO_2 is a very soluble gas, it reacts immediately with rugs, draperies, and furniture on entering a home, and very little is left suspended in indoor air.

Indoor levels of nitrogen dioxide (NO_2), on the other hand, appear to be related primarily to sources of NO_2 in the home. Outdoor levels appear to reflect principally the amount of automotive traffic near the home. Indoor levels, which are usually lower, appear to be related mainly to indoor combustion, such as the use of gas for cooking or for water and space heating.

Particulates, including sulfates, show a varying pattern. Outdoor measurements across a city are relatively uniform. Indoor measurements vary widely but are consistently higher than outdoor levels. Two factors appear to be related to high indoor particulate levels. The first appears to be the presence of young children in the home—their high level of activity, particularly on floors and furniture, causes constant resuspension of particulates that had settled out. The second consistent factor associated with high indoor particulate levels is the presence of one or more cigarette smokers in the home. Although the presence of a cigarette smoker in the home had no correlation with indoor SO_2 or NO_2 levels in the Harvard study, it was highly associated with levels of fine respirable particulates.

The presence of sulfates, which make up a portion of the respirable particulates, also showed a high correlation with cigarette smoking even though the source did not appear to be the cigarette smoke itself. Analyses performed by the Harvard group showed that sulfates are not a major constituent of cigarette smoke; however, the paper matches used by almost all smokers in these studies contributed an average of 107 μg of sulfate per match. Thus they suggest that activities associated with paper matches, such as candlelight dinners and the lighting of hearth fires, may be hazardous to health.

To investigate further the differences between indoor and outdoor air pollution, a second contract has been negotiated with GEOMET, Inc. (RP1309). Investigators will monitor indoor and outdoor pollution for nine homes and three office buildings having various types of construction and different facilities for heating and cooking. Results from these studies should provide more realistic bases for estimating actual human exposure to pollutants and hence define the necessity, if any, of attempting to control ambient air pollutant levels. *Project Managers: James McCarroll and Ralph Perhac*

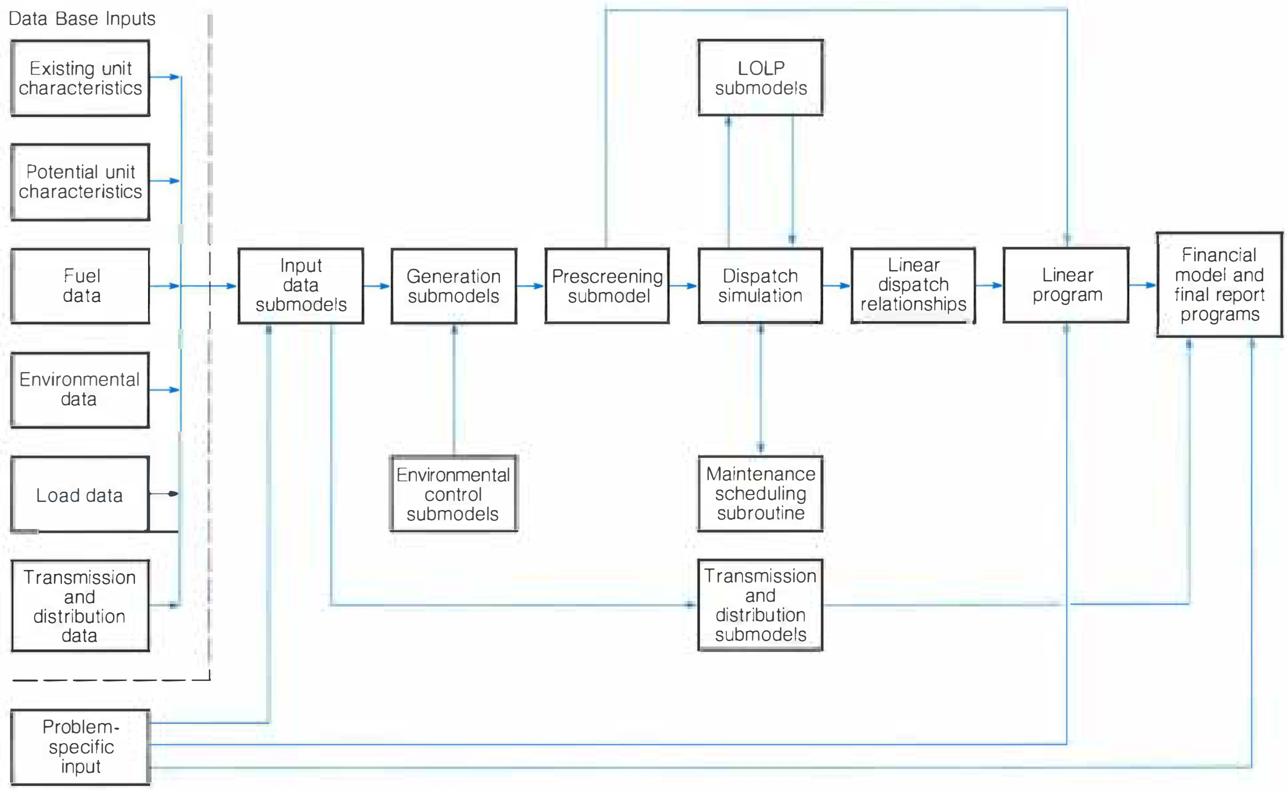
ELECTRICITY SUPPLY MODELS

Forecasting the future of electricity supply in a rigorous manner is one of the most important and challenging functions of the Supply Program. Although point forecasts of the future of the industry are frequently made without elaborate analytic tools, analysis of a wide range of technical options and government policies with incorporation of uncertainty is greatly facilitated by the use of comprehensive models of the industry. Such models, however, must be based on actual industry behavior and experience as well as on modeling expertise, and judgment must be applied carefully in interpreting the results.

To aid in its analytic and forecasting work, the Supply Program's electricity supply subprogram has had Gordian Associates Inc. and National Economic Research Associates, Inc. (NERA) adapt and improve existing models of industry supply functions (e.g., generation) as well as construct new submodels (e.g., for certain pollution control options) where needed (RP950). These models can be used to represent the long- and short-term decisions that the industry makes, and when combined, they form the electricity supply model, a characterization of the economics of electricity supply (Figure 1).

The electricity supply forecasting models have been developed mainly for use as forecasting tools, and they will aid in forecasting future electric utility use of coal, oil, gas, uranium, and other fuels. They will also be used in preparing forecasts of future mixes of plant types. In addition, the models contain sufficient financial detail for calculation of such accounting items as annual capital requirements and average and marginal revenues. The supply models can also help in the analysis of other factors, such as the supply of water for hydropower and the con-

Figure 1 The electricity supply model (RP950) comprises a series of submodels that describe processes of generation, transmission, distribution, and environmental control. The submodels are combined in a dispatch model and a generation expansion model.



sumptive use of water for cooling plants.

Two main models, as well as numerous submodels, are involved in the supply model. The principal model is a combined simulation and linear-programming model, normally referred to as the large model because of its size and complexity. The other main model is a smaller model used for making approximations to the large-model results and for other purposes.

The basic elements of the large model are engineering-economic process submodels of the various technologies used by the industry. This use of process submodels has many advantages because the relationship of the model's elements to the real world is much more direct and obvious than would be the case if abstract functional relationships dominated the model. This should increase the reasonableness of the model predictions and therefore the accuracy of the projections. Thus the utility decision maker has a better understanding of the model and more confidence in using it to evaluate new technologies. Disadvantages of such a detailed approach are, of course, the size of the model and the cost of running it. These disadvantages can be partially overcome by the use of the smaller companion model, which (once calibrated with the large model) can be used in many situations to approximate the large-model results.

Process submodels represent the engineering and economic relationships between the inputs and outputs of technical processes, as well as their current and historic operating behavior. Specifications are detailed enough to allow the examination of important economic trade-offs in the use of different technologies. For example, in addition to dealing with electricity output, the submodels examine the output of nitrogen oxides, sulfur oxides, particulates, and cooling water.

The process submodels describe technologies for generation, transmission, distribution, and environmental control. The generation submodels consist of a series of equations that relate physical and functional factors (such as unit vintage, size, type, heat rate, position on the load curve, and operating and maintenance characteristics) to economic parameters (such as capital investment, fuel cost, and operating and maintenance costs).

The environmental control submodels calculate the effect of a set of environmental control options on plant operation. These options include flue gas desulfurization, particulate removal, coal beneficiation, solids disposal, and thermal pollution control. The effects of these controls on power production costs are calculated as functions of fuel quality, water resource constraints, environmental regulations, various cost parameters, and the type of unit to which the controls are attached.

Transmission and distribution (T&D) submodels are included in the supply model to allow calculation of average revenue requirements for subsequent interaction with EPRI electricity demand models. In addition, the inclusion of T&D submodels permits the analysis of generation alternatives. T&D submodels are statistical estimations (i.e., econometric cost functions) of T&D costs for new equipment and maintenance requirements as functions of such parameters as load density and customer density.

The generation and environmental control submodels can be combined in a dispatch model and a generation expansion model to simulate the behavior of the electric utility industry.

The dispatch model can simulate the running of available units to meet hour-by-hour projected loads while simultaneously determining the reserve margin needed to satisfy the specified reliability criterion (e.g., loss-of-load probability [LOLP]). The simulation can also schedule maintenance so as to minimize contributions to LOLP while recognizing realistic limitations on the duration of a scheduled outage. The simulation model must be run before the capacity requirements for each year are known. Therefore, runs are repeated a number of times for a wide variety of types and sizes of generating units to obtain alternative expansion patterns. Linear equations that express unit availabilities and reserve margins as functions of capacity mixes and sizes are then estimated from these runs. These equations constitute part of the input to the linear-programming generation expansion model.

The linear program (LP) portion of the large model uses information from the above submodels to determine the optimal generation expansion path within the planning horizon. The LP determines the mix of new capacity additions that minimizes the present value of all future costs. Constraints in the model include forced and partial unit outages, plant operating limits, and a representation of energy storage and availability limits on particular plants as the plant mix changes over time. Finally, whereas an hourly dispatch is performed prior to the use of the LP in order to calculate LOLP, unit availabilities, and reserve margin requirements, the actual plant dispatch is repeated within the LP using an annual load duration curve. One set of constraints requires that capacity be available to meet peak demand plus reserve margin. Another set divides the load duration curve into as many as 20 segments to properly represent unit scheduling.

The inclusion of process submodels of generation technologies makes the larger model useful for the economic evaluation of new technologies. Relatively minor design changes can be modeled; hence the impact of such changes on the economic feasibility of an alternative generation process can be analyzed.

The larger model calculates the emissions (simulated hourly) of SO_2, NO_2, particulates, and radwastes. It also evaluates the effects of pollution control technology. Current and projected emission limitations are used as inputs to the model, which determines the method of achieving the emission limit at the least cost. This method may involve addition of a control technology (e.g., SO_2 scrubbers), conversion to some other generation type that emits lower levels of pollutants, or a combination of these methods. Thus, it is possible to estimate what effects the alteration of emission limitations will have on plant mixes, fuel use, electricity costs, and other variables. The results are, of course, subject to the uncertainties in the input data, particularly with regard to the performance of the pollution control technologies.

The smaller aggregate model was constructed to allow parametric analysis with many variations. Such analysis would be extremely costly to perform with the larger model. The smaller model has four basic components.

- A dispatch module determines the extent to which each plant is run for the year. A set of dispatch rules is used for the allocation, where input includes fuel costs and the exogenous load curve to be met.
- The portions of new generation capacity, categorized by plant type, are derived from an econometric estimate based on data from individual utilities. New additions are estimated as functions of relative costs of each plant type.
- T&D equations are used that are similar to those described in the larger electricity supply model.
- An accounting module is used to transform the average generation costs into average revenue requirements for use in EPRI demand models.

Both models are capable of examining a broad range of environmental, regulatory, financial, and special-interest issues. The relative effects of remote and central siting of plants can be analyzed. The financial health of the hypothetical "regional firm" can be simulated (large regions are modeled as if they consist of one private and one public utility). Interaction between the supply-forecasting system and EPRI electricity demand models allows analysis of questions dealing with the impacts of alternative pricing policies. *Project Manager: John Chamberlin*

FORECASTING INDUSTRIAL IN-PLANT GENERATION

Several EPRI projects are being directed toward the development of a comprehensive set of conditional forecasts of industrial in-plant electricity generation. These forecasts will be developed for key industries under a variety of assumptions about the supply costs of fossil fuels and utility-produced electricity, macroeconomic conditions, and federal and state policies. Some of the industrial areas that will be covered are paper and allied products, chemicals and allied products, petroleum and coal products, and primary metals.

In manufacturing, the portion of electricity that is provided by in-plant generation has declined from 25% in 1954 to 9% in 1976 (83 billion kWh) even though technology exists for the joint production of process steam and electricity (cogeneration) at industrial sites. This trend results in part from major uncertainties about boiler technology, availability of fuel sources, effects of air quality regulations, the temporal pattern of electric and steam plant loads, the unwillingness of industry to risk investment, and the nature of federal and state policies and regulatory actions. Despite this trend, a number of recent federally sponsored research projects have been optimistic about future in-plant electricity production, particularly cogeneration. These studies forecast a reversal of past trends. However, other investigators predict a continuation or stabilization of past trends. Overall, the future of cogeneration development remains uncertain, and utilities wish to make certain that their plans for in-plant generation in general and cogeneration in particular minimize costs to ratepayers.

Industrial customers' decisions to purchase or generate electricity will have large impacts on future utility system loads and costs and on EPRI's R&D planning. Several EPRI projects may lessen the uncertainty about the future of in-plant generation development. Although these projects deal with different aspects of the in-plant generation question, all will contribute to the development of a comprehensive set of conditional forecasts of in-plant generation for various key industries in all regions of the country during the next 25 years.

The primary research tool for these forecasts is being developed by Mathtech, Inc. (RP942-1). Its approach is based on a blend of econometric techniques and engineering process analysis. An energy system design module (ESDM) forms the core of the engineering-information input to the model. The technologies currently modeled by the ESDM include gas turbines, diesels, five types of steam turbines, a variety of process steam pressures, and five types of fuel. For a particular type of manufacturing plant with a given pattern of time-of-day and seasonal demands for steam and electricity, there are many technology options and an even larger number of operating schedules that would satisfy the plant's steam and electricity demands. The ESDM chooses the lowest-cost technology and operating schedule for those needs. With in-plant costs thus determined, the econometric model then predicts whether or not investment for in-plant generating equipment would be likely to occur. This aspect of the model takes account of the elements of business risk and human behavioral responses that will influence in-plant generation development.

In another project, information about time-of-day and seasonal demands for process steam and electricity will be developed by The Rand Corp., Gordian Associates, and NERA (RP1212). This information, plus additional engineering data on industrial processes and schedules of utility rates, will provide important additional input to the conditional in-plant generation forecasts.

A third project, Stanford University's simplification of engineering process models for forecasting electricity consumption (RP1214), will also provide inputs to the in-plant generation forecast. In this project, procedures are being developed that will allow small, accurate, easily manageable models to summarize large engineering process models. These procedures will be used to summarize the complex ESDM.

The data and analysis developed in the three projects will be integrated into an EPRI in-house forecasting tool. The integration and forecasting effort will take place at Stanford. The integrated forecasting tool will be used to develop the above-mentioned comprehensive set of conditional forecasts.

A number of overlapping scenarios will be used as starting points for some of the forecasts: (1) a variety of conditional assumptions about growth of national income, employment, wage rates, user cost of capital, investment, interest rates, electricity prices, other energy prices, and the regional distribution of these variables; (2) government subsidies, such as incremental investment tax credits, accelerated depreciation rules, and loan guarantees; (3) various federal regulatory actions; and (4) different types of environmental regulations. *Project Manager; Larry Williams*

Improving Nuclear Fuel Reliability

by Adrian Roberts and Howard Ocken

Sophisticated methods for tracking fuel reliability on a corewide basis and fuel rod design modifications are being developed, which could save millions by boosting plant capacity.

The basic heat-generating entity in a light water reactor (LWR) is a 12-ft-long (3.7-m) fuel rod that consists of about 300 slightly enriched cylindrical UO_2 fuel pellets surrounded by a thin-walled zirconium-base alloy (Zircaloy) tube. A square array of fuel rods are bound together to form a fuel assembly, and a large 1000-MW (e) reactor consists of an array of a few hundred of these assemblies. The heat generated by the fissioning process is conducted through the Zircaloy cladding to the flowing water, which serves as both coolant and moderator.

Fuel rods are designed to retain their integrity (i.e., the coolant should not gain access to the fuel pellets) and should generate heat at the rate demanded. Only very few failures can be tolerated because of rigid limitations on radioactive releases. Experience over the last decade, based on commercial reactor operation, suggests typical rates of fuel rod failures on the order of 10^{-4} to 10^{-3} (3–30 rods) per reactor per year.

Such low failure rates, however, are achieved only at the expense of reduced plant capacity factors, as utilities adhere to vendor recommendations specifying permissible rates of overall and local changes in power levels. These limitations on ramping rates are imposed in response to deficiencies in fuel rod materials that are a consequence of pellet-clad interaction (PCI). This PCI phenomenon is generic to reactors that employ Zircaloy-clad UO_2 fuel. PCI-induced fuel rod failures have been observed in the heavy-water-moderated Canadian Candu reactors, in the British prototype steam generating heavy water reactor (SGHWR), and in European-designed LWRs. The magnitude of the problem is such that in the United States alone, loss of plant output because of restrictions designed to reduce PCI events leads to replacement power costs of over $100 million a year. This figure may rise to more than $400 million by 1985 if a solution to the problem is not found.

Adrian Roberts is program manager, Core Materials, and Howard Ocken is project engineer, Nuclear Fuels, in the Nuclear Power Division.

With this clear economic incentive to provide a remedy to the PCI problem, a significant portion of the budget for the Fuel Performance Program in the EPRI Systems and Materials Department is directed toward gaining an understanding of the underlying mechanisms responsible for the PCI-induced failure of Zircaloy cladding. The EPRI program to address this problem uses a combination of laboratory, test reactor, and power reactor experiments, and support is also being provided for analytic studies. This article summarizes the key information that has emerged from these projects and on the basis of these results, indicates the directions of remedy-oriented projects that are being planned or that are under way.

Conditions for PCI

Consider the conditions required for interaction between the fuel pellets and the inner cladding wall: The fuel rod must first accumulate some in-reactor exposure (burnup). When power is raised initially, the Zircaloy cladding is ductile, and the as-fabricated gap (space) between the fuel pellets and the cladding is sufficient to accommodate the larger thermal expansion of the fuel pellets. Later in life, however, the mechanical properties of Zircaloy cladding become somewhat degraded because of its exposure in the intense neutron environment of the reactor core. Also, the pellet-clad gap decreases because of dimensional increases in the fuel pellets and in the case of pressurized water reactors (PWRs), to inward motion of the cladding (creepdown) as a response to the applied coolant pressure. Under such conditions, if the power is increased over the entire core, local power changes in a given fuel rod may be of sufficient magnitude to lead to failure of the Zircaloy cladding, as evidenced by a rise in coolant activity.

Early observations of such failures were termed *PCI failures* because they were attributed to a combination of localized pellet-induced strain of the cladding and its reduced strain-to-failure capability following irradiation.

Recent information suggests that volatile fission products generated in the fuel pellets as a consequence of the fissioning process and subsequently released to the gap during steady-state operations or during an increase in power are essential to the degradation of the cladding and its eventual failure. Most investigators now accept the view that both the presence of aggressive chemical species and high, localized stresses are prerequisites for power-ramp-induced PCI failures, although the relative contributions of these two factors remain to be resolved. Failure of susceptible metals under combinations of both load and aggressive environments (when either factor acting alone would not cause failure) is designated stress corrosion cracking (SCC). EPRI-sponsored research proceeds from the assumption that PCI-induced fuel rod cladding failures are a consequence of SCC in Zircaloy.

Characteristics of fuel rod failure

The first EPRI project to address PCI-induced failures in power reactors started in 1974 with Combustion Engineering, Inc., and examined fuel rods from the Maine Yankee reactor (RP586). Increased coolant activity during cycle-1 operation had indicated the presence of failed fuel rods in the core. The appearance of the cladding cracks that were examined was typical of stress corrosion cracks produced in laboratory and test reactor experiments. Of equal significance, this study established that degradation of the Zircaloy cladding was not necessarily a consequence of high cladding stresses induced by large power increases because the Maine Yankee reactor had been subjected to only modest power changes. The data suggested large releases of aggressive fission products occurred as a result of a fuel rod design that led to poor heat transfer across the gap region. Subsequent improvements in fuel rod designs (specifically, prepressurization of PWR fuel rods and the use of UO_2 fuel pellets that are resistant to in-reactor densification) eliminate the possibility of a high incidence of failures in PWR fuel rods of current design.

To establish that SCC in Zircaloy is, in fact, also responsible for failures observed in fuel rod designs of more recent vintage, a second project was initiated with Battelle, Columbus Laboratories; Argonne National Laboratory; General Electric Co.; Westinghouse Electric Corp.; and ASEA-Atom (RP829). The object was to locate PWR and BWR fuel rods that based on in-reactor operating history might be suspected of having PCI damage and then to conduct a detailed examination of these cracks. To avoid complications caused by water contamination of cracked surfaces, emphasis was placed on detecting and characterizing incipient (i.e., partial through-wall) cracks. Because by then the vendor recommendations on maximum rates of power change were in effect, a compromise had to be reached between selecting older fuel, operated prior to the limitations but characterized by a higher failure probability, and selecting new fuel, operated after the limitations were imposed so that the failure probability would be lower. The choice was finally made to examine rods from (1) a 14 × 14 PWR fuel assembly from Point Beach-1, which had apparently failed during a reactor startup at a rate over 10 times faster than that now recommended, (2) an early 7 × 7 BWR fuel assembly from Dresden-3, which had failed as a result of a control rod withdrawal error, and (3) a new 8 × 8 BWR fuel assembly from Oskarshamn-1, a Swedish reactor, in which the fuel assembly had failed. This failure was a result of a planned control rod withdrawal experiment.

This work and other examinations of suspected PCI damage in power reactor fuel provide an impressive body of evidence supporting SCC as the principal mode of Zircaloy fracture following PCI events. This conclusion appears to be valid for a wide range of reactor operating conditions ranging from the high fission product release found in the Maine Yankee fuel rods to the high stress caused by severe power ramps in the Dresden-3 and Oskarshamn-1 fuel rods.

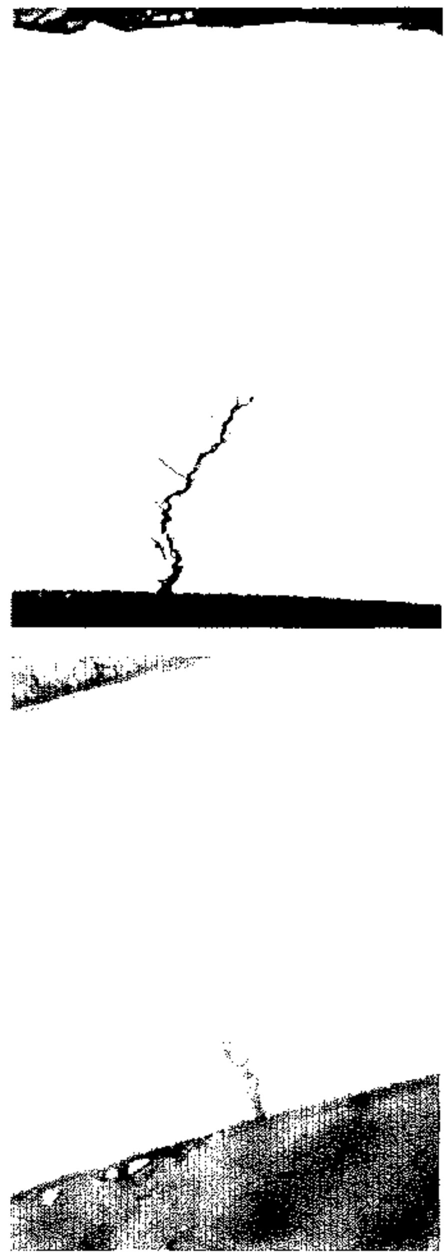
The macroscopic appearance of the cracks that form in-reactor—perpendicular to the cladding surface, with large length-to-width ratio, branched appearance, and essentially macroscopically flat fracture surfaces (Figure 1)—strongly reflect their SCC origin. More convincing evidence is that where detailed scanning electron microscope examinations of the fracture surfaces are possible, features of the cracks that form in the reactor mirror those that form in laboratory SCC experiments (Figure 2).

Laboratory investigations

Given the difficulty and expense of performing examinations of irradiated fuel rods in hot cell facilities, a significant effort is under way to learn about the key steps of the SCC of Zircaloy from laboratory experiments. SRI International has provided information about the chemistry inside a fuel rod under in-reactor conditions (RP455). SRI concluded that aggressive fission products are released as a vapor from those portions of the fuel pellets that operate at high temperatures. These vapors then migrate and form compounds that condense on the cooler inner surface of the cladding. This approach has proved fruitful in serving to rationalize the fission-product-bearing deposits that were observed on the inner surface of irradiated specimens of cladding examined under RP586. It appears the species most aggressive to Zircaloy are iodine, cadmium, and cesium.

SRI has also provided important information on the details of the crack formation and crack propagation processes in Zircaloy. Crack formation was studied by mechanically loading a sample in an iodine atmosphere under conditions expected to lead to stress corrosion crack formation. The topography and chemistry of the resultant cracks were then investigated and found to agree with the observations from irradiated cladding (see, for example, Figure 2). Failure criteria for Zircaloy were obtained by internally pressurizing short lengths of tubing

Figure 1 Partial through-wall cracks in **(a)** Dresden-3 (BWR) and **(b)** Maine Yankee (PWR) cladding caused by SCC in Zircaloy.



a

b

Figure 2 Scanning electron microscope view of **(a)** a laboratory specimen, **(b)** PWR cladding, and **(c)** BWR cladding, illustrating similar cleavage and fluting features of stress corrosion cracks.

a

b

c

specimens that were loaded with iodine. This test procedure provides an accurately known state of general stress and local stress intensity that reasonably simulates that which exists in the fuel rod cladding and also permits the surface concentration of the aggressive iodine to be calculated. Similar procedures to study the response of irradiated cladding obtained from various joint EPRI-vendor bundle surveillance programs are being used by Argonne National Laboratory (RP1027).

The available information suggests that crack formation is the critical step in the iodine-induced failure of internally pressurized Zircaloy tubing. Stress, rather than strain or stress intensity, is the key parameter in crack formation. The data show the existence of a threshold stress (defined as that hoop [circumferential] stress below which no failures were observed in long-term [≥100 h] tube pressurization tests). This threshold stress depends most strongly on irradiation—irradiated Zircaloy being inferior to unirradiated Zircaloy. Available data indicate that irradiation effects predominate over differences in initial microstructure. Temperature (in the range 593–633 K), alloy composition (Zircaloy-2 versus Zircaloy-4), and iodine concentration (in the range 0.06–6.0 mg/cm² of Zircaloy surface) have little influence on the threshold stress (Figure 3).

Crack formation studies indicate that two types of crack nuclei are formed in unirradiated Zircaloy. Small, nonpropagating cracks form at stresses well below the threshold stress. These innocuous cracks generally seem to form at intergranular sites and occur where the local stresses generated during plastic deformation are exceptionally large.

Crack nuclei of the second type are larger than those of the first type, are generally transgranular, and always occur at sites in the metal surface that contain higher-than-normal concentrations of alloying elements or at impurities that appear to be introduced during the tube-processing operation. These crack nuclei are observed only in specimens stressed to levels above the threshold value. We therefore conclude that the threshold stress is the stress required to form transgranular cracks at material inhomogeneities and that progagation of such cracks causes failure.

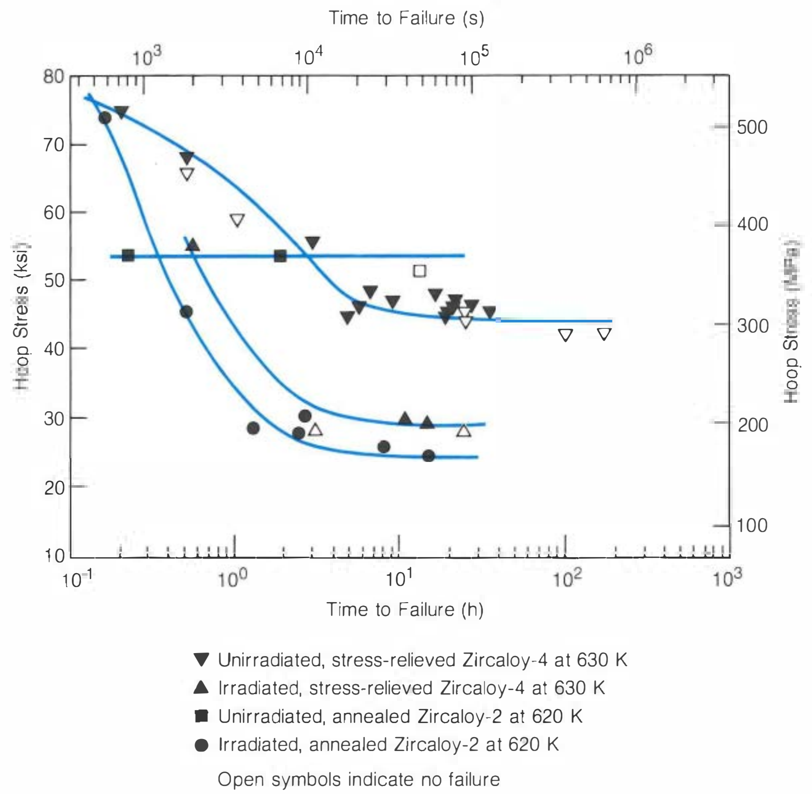
In addition to experimental studies of Zircaloy SCC, EPRI is also supporting analytic work on the general deformation behavior of Zircaloy and on the SCC phenomenon in particular. In the former area, Stanford University is investigating the response of Zircaloy when it is loaded beyond the elastic limit, a condition that can occur during reactor power ramps (RP456). The goal is to develop a model that can predict the effect of fabrication and the in-reactor duty cycle on the stresses and distortions that arise in Zircaloy tubing. Of particular benefit to the SCC issue is the success of this model in accounting for various irradiation-induced effects on the mechanical response of Zircaloy cladding.

Modeling the failure process

Using data from laboratory studies as a basis, Failure Analysis Associates and Stanford University are developing a micromechanical model of the SCC failure process (RP700). Failure is considered to occur by two distinct mechanisms as the crack grows: environmentally assisted cleavage occurs in grains appropriately oriented with respect to the applied load, and the remaining grains fail by a ductile plastic process. The combination of these two processes gives rise to the typical cleavage and fluting features seen on surfaces as illustrated in Figure 2. The model suggests that grains fail more easily by the second process in irradiated Zircaloy compared with unirradiated Zircaloy, which is in accord with the observed lower threshold stresses measured on irradiated Zircaloy (Figure 3).

The key feature of the model of PCI-induced fracture of Zircaloy cladding that emerges from our combined experimental and analytic program is a threshold stress below which cracks are unable to form. The hoop stress imposed on the cladding must exceed this threshold value for a finite time for cracks to form. Irradiated Zircaloy cladding can, however, sustain stresses larger than the rather low threshold value without failing, provided that the time during which the imposed stress is greater than the threshold value is not excessive. This conclusion is demonstrated by the very low number of PCI-induced failures observed in power reactors. Models of Zircaloy failure must therefore ultimately contain a probabilistic aspect—the probability of failure must increase as either the time spent or the stress, or both, above the threshold value increases. Time and stress are coupled through the stress relaxation properties of the Zircaloy—the more quickly the cladding is capable of relaxing, the shorter will be the times above the threshold value. The time component, however, may also require a contribution to allow for conditions at the inner surface to become ripe for cleavage to begin. One would therefore anticipate and, in fact, one observes a wide variation in

Figure 3 The degradation of resistance to SCC from irradiation effects, measured by tube burst tests.



failure times under in-reactor conditions, even when test conditions appear identical. This perspective also provides a basis for a damage-accumulation law for Zircaloy: a number of short-time excursions above the threshold value should have an impact comparable to a single, long hold time above the threshold value.

Therefore, although we are developing a phenomenologically based deterministic model of PCI-induced Zircaloy SCC, this model will serve as but one component of a probabilistic fuel reliability model. The other components of this model are field data on the incidence of PCI-induced fuel rod distortions and failures as a function of duty cycle, both types of data being obtained from test reactor and power reactor studies. This effort is being undertaken by Entropy Limited and Science Applications, Inc., and the first-generation model is scheduled to be completed late in 1978 (RP971).

This fuel reliability model, together with power change information, will be incorporated into the Power Shape Monitoring System (PSMS) project (RP895). Scandpower Inc., Nuclear Associates International, Inc., Exxon Nuclear Co., Inc., and Nuclear Services Corp. are the contractors. The objective is to develop and test a fully automated system for tracking and simulating core power changes with the view of evaluating the impact of planned power changes on the response of the fuel. The computer system provides for continuous tracking of core power conditions on a near-real-time basis and for the first time will permit detailed predictions of the effects of anticipated power maneuvers on fuel reliability. Such a computational framework will enable the utility operator to select power change paths that will result in the least amount of degradation to the Zircaloy cladding, and it therefore represents the most effective near-term means to increase plant capacity. The PSMS will be tested initially (using an earlier fuel model) at the Oyster Creek reactor late in 1978.

Prospective remedies

Sufficient information has emerged from the EPRI-sponsored projects and related programs at other laboratories to suggest directions for testing of prospective PCI-resistant fuel rod designs and material remedies for introduction in the early 1980s. The general agreement between observations and theoretical analyses—indicating that crack formation is the key step in the SCC process and that the threshold stress for crack formation is low when the supply of aggressive fission products is ample—has immediate implications in the search for remedies to the PCI–SCC problem. Of the three factors—stress, susceptible material, and aggressive environment—that must coexist for SCC to occur, remedies must address the last two factors because it appears that stresses in operational fuel rods cannot be maintained below the measured SCC threshold values of the standard commercial Zircaloys. Remedies, then, must either limit the amount of fission product release from the fuel pellets or make it more difficult to form a crack at the cladding inner surface (which would raise the SCC threshold stress).

Perhaps the greatest gain in resistance to SCC in the near term can be obtained by minimizing the amount of aggressive species that reaches the cladding inner surface. This requires fuel pellet or fuel rod designs that minimize fission product release from the fuel pellet. The reduction in peak rod powers in new, larger array fuel assembly designs (8 × 8 BWR, 16 × 16 and 17 × 17 PWR) that resulted from LOCA–ECCS considerations represents a move in this direction.

A second prospect is to prepressurize BWR fuel rods, as is currently the practice in PWR designs. This should stabilize the internal thermal environment (i.e., fuel-to-clad-gap heat transfer), thereby eliminating the possibility of the sharp temperature rise and high fission product release that were observed in the unpressurized Maine Yankee fuel rods.

Modifications to the fuel pellet itself that would reduce or eliminate fission product release also appear practical. EPRI is pursuing testing of two such concepts in the Halden test reactor program (RP355). The first experiment will evaluate large-grain-size fuel fabricated with Nb_2O_5 as an additive. The large grains serve to delay the release of fission products. The second idea is more complex in that it requires a dual enrichment pellet. The outer region is enriched uranium, while the inner core is natural uranium. At the same rod power, the average fuel temperature is lower and the temperature gradient is flatter in the new design than in a conventionally enriched pellet. Thus, the driving force for fission product migration and release is reduced. Both of these fuel pellet types were fabricated by British Nuclear Fuels, Ltd.

An alternative approach is to improve the resistance of the Zircaloy itself to SCC. One possibility is to use a texture (the relative orientation of grains in the tubing) more resistant to crack formation and propagation. This argument is currently based on limited data, but this conclusion is supported by our theoretical analyses. SRI International is investigating unirradiated Zircaloy of different textures, which are being fabricated by Sandvik Special Metals Corp., to provide a more extensive test of this hypothesis (RP455). If these laboratory tests support the view that texture plays a role in establishing the SCC threshold stress, confirmatory test reactor experiments would begin in 1979.

A longer-term approach to modify the inner surface of the Zircaloy cladding is based on observations from the crack initiation studies on unirradiated cladding. Cracks always formed at metallurgical impurities. Initiation sites were characterized either by locally high concentrations of the standard alloying elements (Fe, Cr, Ni), with Fe being particularly deleterious, or by impurities (Al, Si) that were presumably introduced during the tube processing operations.

A potential method for eliminating these vulnerable surface sites would be to remelt and rapidly self-quench a thin layer of the surface so as to achieve a uniform distribution of alloying elements. United Technologies Corp. used a CO_2 laser to carry out this in situ melting and resolidification (TPS77-733). Laboratory tests on such treated Zircaloy sheet indicate that second-phase particle formation can readily be suppressed to a depth of a few mils. Subsequent testing in an iodine environment will determine whether crack formation is inhibited in the surface layer.

Regardless of the effectiveness of these modifications to the Zircaloy cladding and the UO_2 fuel pellets, one cannot deny that Zircaloy is susceptible to SCC attack by aggressive species released from UO_2 fuel. Consequently, although threshold stresses might be raised and other conditions for PCI--SCC made less likely through the remedies discussed above, a completely PCI-resistant fuel design, capable of unrestricted load following in a BWR, for example, might require complete isolation of the cladding from the fuel pellets—that is, a physical barrier may have to be placed between the UO_2 pellets and the Zircaloy inner surface. Since such barrier concepts represent significant changes from current design, a long and expensive demonstration program is required before commercial utilization would be justified. This approach, then, represents a potential nil-capacity-loss fuel design that would be available in the long term (late 1980s). The Canadians have developed a graphite barrier for the Candu fuel, which is also being considered for use in LWR fuel rods. General Electric Co. has developed metal barrier concepts that are at the power reactor demonstration stage, and a demonstration program in conjunction with Commonwealth Edison Co. is being funded by DOE.

New Technical Reports

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

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

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

Standing orders for free copies of reports in EPRI program areas may be placed by EPRI member utilities, libraries of U.S. national, state, and local government agencies, and the official representative of any foreign organization with which EPRI has an information exchange agreement. For details, write to EPRI Communications, P.O. Box 10412, Palo Alto, California 94303.

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

ELECTRICAL SYSTEMS

Parallel Processor and Pipeline Computers: An Annotated Bibliography

EL-764-SR Special Report

This bibliography was collected and annotated to acquaint power system engineers with the architecture and capability of parallel processor and pipeline computers. It also indicates the extent of research on the application of these computers to problems similar to those in the power industry. *EPRI Project Manager: Paul Anderson*

ENERGY ANALYSIS AND ENVIRONMENT

Health Effects of Mercury and Its Compounds

EC-224 Quarterly Report (RP859-1)

This study by Science Applications, Inc., found that over 90% of the mercury in coal is released to the atmosphere as Hg vapor. Coal combustion for electric power generation accounts for about 12% of U.S. mercury emissions. A lack of data on preexisting ambient levels of mercury in the atmosphere makes assessment difficult; however, loadings from power plant operation probably do not pose a significant threat to human health. *EPRI Project Manager: James McCarroll*

Comparative State-of-the-Art Assessment of Oil Supply Modeling

EA-609 Final Report (RP665)

Mathtech, Inc., made a state-of-the-art comparison of 10 major oil supply modeling efforts, which are categorized in this report according to three general types: hybrid structural models of resource economics, pure econometric models, and resource base–geologic models. *EPRI Project Manager: Rex Riley*

The Impact of Electric Passenger Automobiles on Utility System Loads, 1985–2000

EA-623 Final Report (RP758-1)

In this study of the future of electric passenger vehicles, Mathtech, Inc., developed models of supply and demand for the vehicles, projected their sales and stock for the period 1985–2000, and assessed their impact on utility loads. *EPRI Project Manager: Anthony Lawrence*

Initiation of Integration

EA-837 Final Report (RP954)

Four contractors—Data Resources, Inc., Decision Focus, Inc., the National Bureau of Economic Research, and the University of Texas—explored alternative methods of integrating research findings from EPRI's Energy Analysis and Environmental Division to meet the needs of the research user. The emphasis was on assembling information to meet a specific client need, using whatever analytic tools were required for the problem, rather than on building comprehensive long-term models for more general use. *EPRI Project Manager: Jerome Karaganis*

FOSSIL FUEL AND ADVANCED SYSTEMS

Gasification of COED Chars in a Koppers-Totzek Gasifier

AF-615 Final Report (RP264-1)

FMC Corp. gasification tests were conducted to demonstrate the char oil energy development (COED) process in Koppers-Totzek gasifiers. The results were encouraging for the design of larger (30 t/h), more modern Koppers-Totzek gasifiers based on the gasification of COED char. *EPRI Project Manager: Neville Holt*

Requirements Assessment of Photovoltaic Power Plants in Electric Utility Systems

ER-685 Final Report, Vols. 1, 2, and 3 (RP651-1)

General Electric Co. developed a rational approach for considering the application of solar photovoltaic (PV) power plants to electric utility systems. This method was used perform a requirements assessment and preliminary impact and penetration analyses by studying PV generation in three actual utility systems. Conventional utility loss-of load probability and production simulation methods were used, along with a PV plant performance model developed for study. Evaluations were based on the comparison of total utility generation system costs with and without PV plants.

Vol. 1 (ER-685-SY) contains the summary report, Vol. 2 the technical report, and Vol. 3 the appendixes. *EPRI Project Manager: Edgar DeMeo*

Development of Lithium–Metal Sulfide Batteries

EM-716 Progress Report (RP116)

The Atomics International Division of Rockwell International Corp. undertook the development of high-temperature lithium-silicon–iron sulfide batteries. The program consists of a number of specific tasks in battery development funded separately by EPRI, Argonne National Laboratory, and Rockwell International. Efforts in this period were aimed at developing lithium-silicon negative electrodes, ferrous sulfide positive electrodes, and ceramic separators stable in the cell environment. *EPRI Project Manager: James Birk*

Interim Cost Estimates for Advanced Battery Systems

EM-742 Interim Report (RP787-2)

Arthur D. Little, Inc., applied the standard costing methodology it had developed earlier in this project to cost data from EPRI's contractors in advanced battery development. Interim cost estimates were calculated for the sodium-sulfur, sodium–antimony trichloride, lithium–iron sulfide, and zinc-chlorine battery systems, and important cost elements were identified for each.

All the calculated battery costs fall within the narrow range of \$34–\$40/kWh. However, the numerical significance of these estimates must not be overemphasized, because there are uncertainties in many of the assumptions used in their derivation. The main value of the estimates rests in the attention that they focus on the major factors affecting the cost of various advanced battery systems. *EPRI Project Manager: James Birk*

Solar Heating and Cooling Computer Program EMPSS

ER-770-SY Summary Report (RP926)

Unlike several other programs for analyzing the performance of solar heating and cooling equipment in buildings, this computer program, developed by Arthur D. Little, Inc., is capable of estimating the cost of backup electric energy both from a utility's actual cost of supply and from its rate structures. These features allow a consideration of costs on both sides of the electric meter and thereby help identify systems compatible with the needs of both the consumer and the utility. *EPRI Project Manager: John Cummings*

Status of Electroslag Processing for Production of Large Rotor Forgings

FP-799 Final Report (TPS77-721)

The characteristics of electroslag-processed steels hold out the promise of higher quality rotors and larger high-quality rotor forgings than are currently available from conventional techniques. Because of the potential of electroslag steels, Battelle, Columbus Laboratories conducted a survey to determine and summarize the worldwide status of the new technology and electroslag products. Electroslag remelting, the basic process, and the modifications of electroslag hot topping, central zone remelting, and electroslag welding were of primary interest. *EPRI Project Manager: Robert Jaffee*

Solar Heating and Cooling of Buildings (SHACOB): Requirements Definition and Impact Analysis

ER-808 Final Report, Vols. 1, 2, 3, and 4 (RP553)

Systems for the solar heating and cooling of buildings usually require a backup system, often electric, to take some portion of the load on days of low insolation and to carry the entire load during extended periods of low insolation. Thus their use may have a significant influence on the economic operation of electric utilities. In this study, The Aerospace Corp. assessed the economic impact of various SHACOB design concepts on utilities and their customers and defined system requirements for optimizing this impact. A summary report on the project is also available (ER-808-SY). *EPRI Project Manager: James Beck*

Thyristor Voltage Safety Factor

EM-825 Final Report (RP840)

In this project, Power Semiconductors, Inc., investigated the theoretical and experimental bases for reducing the derating factor applied to thyristors in solid-state converter designs. This factor, known as the voltage safety factor (VSF), represents a margin of safety to protect thyristors from voltage transients. For force-commutated (or self-commutated) converter designs, a VSF in the range of 1.4 to 1.8 must be applied to result in a unit that is economic for utility application with batteries and fuel cells. The report shows that these low margins can be used in successful designs, and it defines and examines the VSF components and their dependence on circuitry and thyristor characteristics. *EPRI Project Manager: James Beck*

Fuel Cell Catalyst Sintering Studies

EM-833 Final Report (RP583-1, -2)

This report describes the results of the second year of studies by Exxon Research and Engineering Co. on the problem of catalyst surface area loss in phosphoric acid fuel cells. Phosphoric acid fuel cells use platinum catalysts dispersed as small crystallites on carbon supports. These crystallites are metastable and tend to grow (sinter) to larger size with lower surface area under the influence of surface energy forces.

In previous studies it was discovered that platinum supported on North American P-100 carbon, a high-surface-area active carbon, showed minimal surface area loss compared with platinum on other supports. The objectives of the current program were to extend these promising initial results and to learn more about the mechanisms responsible for catalyst sintering. Initial findings indicated that the residual phosphorus in P-100 carbon, introduced in an H_3PO_4 pretreatment during carbon manufacture, played an important role in stabilizing the platinum crystallites. The special emphasis in recent research has been on defining the impact of phosphorus chemistry in controlling the sintering phenomenon. *EPRI Project Manager: Edward Gillis*

NUCLEAR POWER

Long-Term Performance of Charcoal Absorbers Removing Radioiodine in Ventilation Exhaust Air

NP-534 Final Report (RP274-1)

Science Applications, Inc., studied the efficiency of charcoal filters in absorbing iodine-131 in ventilation exhaust air by making continous measurements for 416 days (May 1975 to July 1976) of two filters at the Ginna nuclear power plant. New charcoal was installed in one filter at the time the measurements began; the charcoal in the other filter had been exposed for two years. During the last 280 days, efficiencies for four chemical forms of iodine-131 were measured. *EPRI Project Manager: Henry Till*

Peach Bottom Atomic Power Station Unit 2 at End of Cycle 2

NP-564 Topical Report (RP1020-1)

General Electric Co. performed turbine trip transient and low-flow stability tests at the Peach Bottom-2 BWR/4 nuclear power plant before it was shut down for refueling at the end of cycle 2 in April 1977. The turbine trip transient tests were conducted to investigate how the pressure transients generated in the reactor vessel after a turbine trip affect the neutron flux in the reactor core. The purpose of the low-flow stability tests was to determine the power-to-void feedback stability margin of the BWR core at an operating condition above the rated power-flow control line, and to investigate the sensitivity of core stability to changes in reactor operating conditions. These tests were also intended to demonstrate the practicality of using small pressure perturbation tests to determine the stability margin of a large BWR core. *EPRI Project Manager: Robert Whitesel*

ATWS: A Reappraisal, Part III—Frequency of Anticipated Transients

NP-801 Interim Report (RP767)

Science Applications, Inc., documented from nuclear power plant records the frequency of various events that have led to a reactor scram. In the absence of scram, some of these events could lead to undesirable system response; these are the transients of significance in the ATWS question. *EPRI Project Manager: Gerald Lellouche*

Determination and Microscopic Study of Incipient Defects in Irradiated Power Reactor Fuel Rods

NP-812 Final Report (RP829)

This final report presents the results of nondestructive and destructive examinations carried out by Battelle, Columbus Laboratories on the Point Beach-1 (PWR) and Dresden-3 (BWR) fuel rods selected for the study of incipient defects induced by pellet-clad interaction. The report also includes results of the examination of sections from Oskarshamn-1 (BWR) fuel rods.

The nondestructive examination included profilometry, gamma scanning for gross gamma activity and cesium-137 activity, and eddy current scans using encircling coil and probe coil systems. The destructive examination consisted of fission gas collection and analysis and metallography. *EPRI Project Manager: Adrian Roberts*

Hydrodynamic Impact Analysis

NP-824 Interim Report
(RP812-1, -2, and -3; RP965-3)

This project is concerned with identifying appropriate methods for analyzing hydrodynamically impacted structures. It is part of an EPRI program for the development and verification of computational techniques for coupled fluid-structure analysis.

The development of a verified rigid-cylinder impact analysis is a necessary first step. Because of the complexity of the problem, four methods were selected for investigation: explicit Lagrangian fluid method (STEALTH), Science Applications, Inc.; boundary integral method, Lockheed Missiles & Space Co., Inc., Palo Alto Research Laboratory; finite element method, Marc Analysis Research Corp.; and incompressible Eulerian fluid method (SOLA–SURF), Los Alamos Scientific Laboratory. Computational techniques for hydrodynamically impacted flexible structures are also under development. It is hoped that these results will be useful in assessing the importance of fluid-structure interaction when pool swell impact loads are applied to BWR pressure suppression system components (an event that could occur during a LOCA). *EPRI Project Manager: John Carey*

Stress Analysis of PWR Steam Generator Tube Denting Phenomena

NP-828 Interim Report (RP700)

Failure Analysis Associates used analytic models to study mechanical aspects of tube denting phenomena. The models ranged from closed-form analytic solutions to state-of-the-art numerical elastic-plastic computer programs for moderate strains. It was found that tube dents like those observed in operating PWR steam generators are associated with yielding of both the tubes and the support plates. Also studied were the U-bend stresses caused by the deformation of support plate flow slots. *EPRI Project Manager: Floyd Gelhaus*

SWELL3/SURGE: Computer Models for Hydrodynamic Response of Mark I Suppression Pools

NP-835 Final Report (RP693-2)

This report by Jaycor describes in detail the analytic models (including the computational techniques for their solution) that are being used in a continuing study of the pool swell phenomenon in Mark I pressure suppression systems during a postulated LOCA. A calculation using ¼-scale test conditions as input is given as an example. *EPRI Project Manager: Charles Sullivan*

BIGIF Fracture Mechanics Code for Structures

NP-838 Key Phase Report (RP700-1)

The BIGIF computer code has been developed to perform accurate, inexpensive fracture mechanics life predictions for a wide range of two- and three-dimensional stress fields and cracks and structural geometries when the elastic stress solution for the uncracked structure is available from an independent source.

This general description manual, compiled by Failure Analysis Associates, is the first of three manuals documenting BIGIF. It is designed to provide a general understanding of the program's capabilities and enough information to enable the reader to decide whether or not to use BIGIF. The second and third manuals, a user's guide and a programmer's guide, provide more detailed information. *EPRI Project Manager: Floyd Gelhaus*

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

NONPROFIT ORGANIZATION
U.S. POSTAGE
PAID
PERMIT NUMBER 7577
SAN FRANCISCO, CALIFORNIA

EPRI

ADDRESS CORRECTION REQUESTED