T&D: The Measured Move Underground

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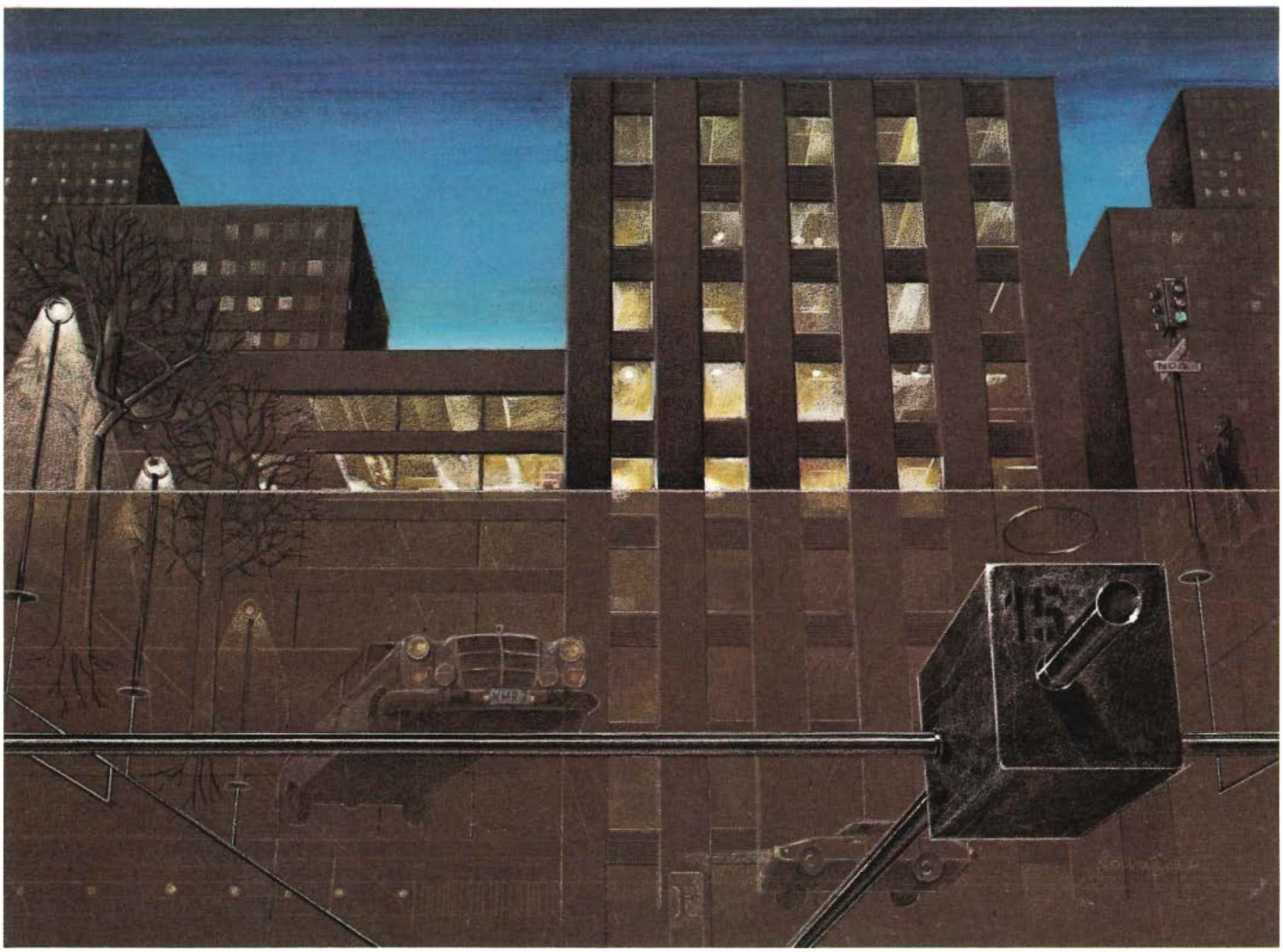

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COVER: A horizon of city streets conceals the growing T&D network from which urban light and power dawn around the clock.

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Universal Undergrounding Is Not the Solution

Once every 30 months the Power Engineering Society of IEEE convenes a special meeting to review and update the state of the art of burying utility T&D systems. Originally limited to consideration of underground rural distribution systems, this meeting was known as the "URD Show." But, in time, higher-voltage cables and cable accessories began to appear, both in the exhibits and in the technical papers presented. Transmission became an official topic for the first time at the Dallas meeting in April 1974 and has a very large part in what is now known as the IEEE Underground T&D Conference, being held in Atlantic City this month.

Perhaps, therefore, it is now time to assess the importance of undergrounding transmission circuits compared to undergrounding distribution circuits. Both are important to the utility industry, but for somewhat different reasons. Beyond this, the problems they pose and the solutions they require are entirely different.

The history of undergrounding distribution circuits is a long one. In congested urban areas, where load densities are very high, circuits began going underground right after World War I. Without that change, pole lines would be pervasive on city streets today, with hundreds of wires suspended from rows and rows of cross arms.

Much more recently (in the late 1940s) rural undergrounding began to catch on, and suburban residential developments advertised "all underground" as a selling feature. Initially, the cost was high, but systems have now been developed that minimize the premium. Most new distribution today—at least in residential areas—is being installed underground. And, here and there, existing overhead circuits are being replaced with buried circuits. It is essential that the cost of these circuits be kept to a minimum without sacrificing reliability.

Transmission presents a radically different picture. Here again, the use of underground circuits began in congested urban load centers. However, the cost of buried systems exceeded the cost of overhead transmission lines by a factor of 20 or more, and it remains difficult to close this cost gap.

Even so, growing loads demand transmission circuits with higher voltage and power ratings than ever. And the sheer unavailability of land, as well as specific environmental decisions, assures that many of these circuits will be buried.

The feature article in this issue describes cooperative EPRI–ERDA research that is attacking the problems associated with power cable and cable accessories. Much of that work—but not all—focuses on transmission cable problems. While the research emphasis is on technical solutions to technical problems, an eye is also kept on the economic aspects. Thus, even the underground cable system that is perfect from a technical viewpoint will not be installed if its cost is prohibitive, and the majority of transmission circuits will continue to be overhead lines.

John J. Dougherty, Director
Transmission and Distribution Division

In the JOURNAL earlier this year, EPRI's Frank Young wrote about "packing the power corridor," summarizing the factors that can result in more effective use of overhead transmission lines and their rights-of-way. Even though overhead is undeniably far more than half the story throughout the world of utility networks, E. Robert Perry now receives equal time on behalf of underground.

Buried cable systems are almost without exception dictated by considerations other than cost. They get the nod when overhead right-of-way is either absent or prohibitively expensive, or when agreed-upon but subjective value judgments come into play. At these times it doesn't help for utility engineers to doubt whether cable can perform or to feel that cable costs are greater than they need to be. Dispelling such concerns is a research necessity in order to continue what Perry sees as "The Measured Move Underground" (page 6).

□ E. Robert Perry came to EPRI as director of the Transmission Department, in the Transmission and Distribution Division, in July 1974, after serving as director of research for I-T-E Imperial Corp. Before 1968 he had been with Allis-Chalmers Corp. for 15 years, the last 5 as manager of advanced R&D.

Perry holds more than 30 patents in circuit breakers, switchgear, transformers, and underground transmission equipment. In 1972 his research department at I-T-E Imperial won recognition from the National Society of Professional Engineers for outstanding achievement in the development of compact gas-insulated substations.

Besides writing extensively on technical and management subjects, Perry was a Lloyd Hunt lecturer (1975). He is now serving on a technology evaluation panel of the National Academy of Engineers.

Perry

□ Overhead is also a topic this month, but in a very different way. This time it is a meteorologic phenomenon—the tornado—and its implications for nuclear power plant design.

What conditions must be considered? To begin with, there must be a high enough wind velocity at ground level. Next, there must be a massive object—perhaps a utility pole or pipe section—that conceivably can "fly." In turn, this projectile must hit a structure with some defined impact. To measure the risk, there must be some probability attached to each of these conditions—and to all of them. Finding answers to these implied questions is the purpose of an EPRI program discussed in "Nuclear Plant Tornado Safety" on page 12.

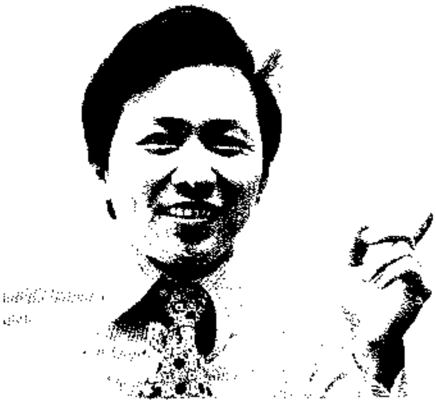
□ Conway Chan has worked with the dynamics of structures and their materials since 1962, when he left the University of California with a BS in civil engineering and an MS in structural mechanics. Two years later he returned to university work, first as an instructor in civil engineering at the University of Hawaii and later as an instructor in applied mechanics at the University of Illinois, where he also earned a PhD in nonlinear elasticity in 1970.

Late in 1969 Chan began a three-year association with Argonne National Laboratory, working as a mechanical engineer on projects in nuclear safety. On his return to his hometown of San Francisco in 1972, he became a senior engineer in structural design with Bechtel Power Corp.

In December 1973 Chan joined EPRI's Nuclear Power Division, where he now manages the tornado missile program in the Safety and Analysis Department.

Chan

Sliter



Chu

▫ George Sliter, project engineer, is a specialist in dynamic loads, with a BS in civil engineering from Manhattan College (1960) and an MS in applied mechanics from the University of Illinois (1962). He earned a PhD at Illinois in 1964.

Sliter's early work for the Martin Company involved analysis of stresses in space program reentry vehicles. From 1966 to 1974 he was with the Stanford Research Institute, where he became a senior mechanical engineer on dynamic load studies of missiles, automobiles, and bridges. For a year of this period he was a visiting scientist at the Ernst Mach Institute in Freiburg, West Germany.

Sliter came to EPRI in November 1974. In the tornado missile program, he has been particularly concerned with the response of structures under impact loads.

▫ Boyer Chu, project scientist, is a mechanical engineer with both academic and professional specialization in mathematics and statistics. He earned his BS at the University of Houston (1967) and his PhD at the University of Wisconsin (1972).

As a senior mathematician at Westinghouse Research Laboratories, Chu performed reactor core probabilistic analyses, empirical and mechanistic modeling, and statistical data analyses. Later, with Gulf Nuclear Fuels Co., he worked in fuel rod design and analysis and in the development of computer codes.

A member of EPRI's staff since March 1974, Chu is involved in the development of probabilistic methods for nuclear safety analysis. As a part of that work he has been responsible for assessing the risks associated with tornado-borne missiles.

▫ Distinctly different from the energy processes applied to electric power production are the administrative processes of R&D management. One of these is program planning. The planning process is often forgotten (or misunderstood) when we look only at budget categories and dollar allocations. "How EPRI Plans" (page 18) goes behind the numbers for a look at the premises, priorities, and procedures—and the people—that shape EPRI's overall work statement. This article was prepared by Stan Terra, JOURNAL staff writer, and is based on information from Ric Rudman, director of planning, and staff members Walt Esselman and Dick Schulte.

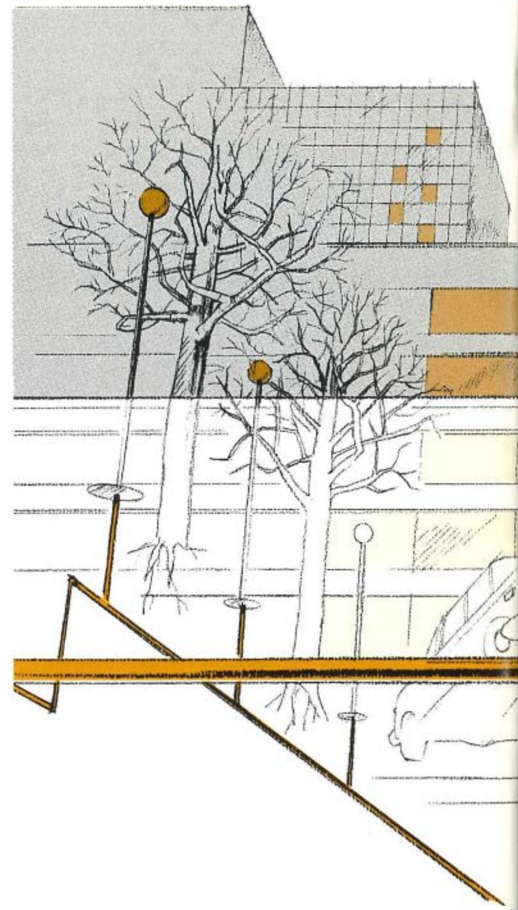
T&D: The Measured Move Underground

by E. Robert Perry

A judicious compromise must be struck between the public's concern over visible power facilities and the industry's ability to furnish low-cost electric energy. Several research efforts now underway hold promise of a workable solution to this problem. ▫ An EPRI state-of-the-art feature

Engineering is a world of compromise, perhaps nowhere better exemplified than in the utility industry's transmission and distribution networks. Power lines and substations have, until recently, been installed as a classic compromise between function and cost. Appearance has seldom been a primary concern.

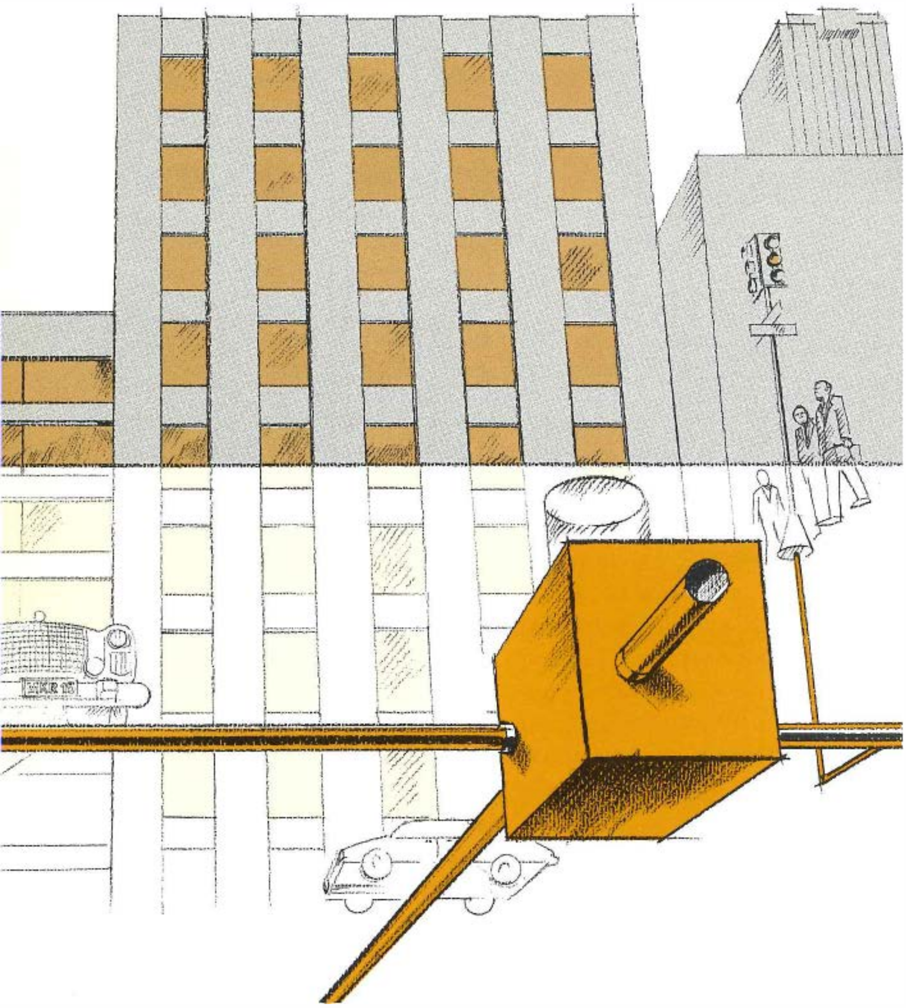
The public's current sensitivity to social and environmental issues, however, has brought about a demand for more attractive T&D lines and substations, as well as more productive use of rights-of-way. Value judgments having come into play, compromise is no longer easy. There are as many opinions about what is or is not environmentally acceptable as there are designs and public action groups. Hence, a new trade-off must be made between cost, function, and appearance. And utilities are therefore faced with a complex dilemma: How much improvement in appearance can they make while maintaining outdoor T&D networks at a reasonable cost?



We believe a strong case can be made for a positive commitment to undergrounding *certain* power facilities. Others could remain above ground and visible—for example, lines and substations serving industrial demands, which account for 40% of the utilities' load. There is neither economic incentive nor public pressure to conceal this type of line. Besides, the public now seems willing to accept the need for certain power corridors, especially if the rights-of-way can be made to serve as parks and recreation areas as well.

But there are some in the utility industry who still find themselves at odds with even the gradual conversion of overhead facilities to underground. They recognize the advantages of underground power delivery in only a few circumstances, such as near very large structures or in heavily congested areas. After all, Chicago's problems today may be found in Atlanta or Houston—or even in Boise—tomorrow. Therefore, it is worthwhile to review current advances in technology and especially to consider some sobering

E. Robert Perry is director of the Transmission Department in EPRI's Transmission and Distribution Division.



facts about the magnitude of tomorrow's power transfer needs and the capacity for meeting them. Hopefully, this may lead to consideration of new economic options in underground T&D.

Some sobering realities

Today we are building overhead transmission lines at the rate of 10,000 miles per year. These lines require approximately 20 acres per mile, which will add up to a lot of acres in the next 25 years—and this is for transmission alone, meaning the high-voltage circuits between power plants and load centers, as well as the network ties between utility systems.

Distribution lines are another matter. Extending into cities and within neighborhoods, they account for even more mileage, but not with exclusive rights-of-way requiring dedicated acreage. They are subject to severe environmental constraints, because the public is more aware of their presence.

The power transfer capability is sure to be built one way or another. Power use by the year 2000, according to conservative estimates, will exceed 7500 billion kWh annually. Though almost four times the present level, this is equivalent to a growth rate of only 5.66% per year.

So what should we expect by the year 2000? A massive congestion of poles and wires? No—neither the utilities nor their ratepayers look forward to the continued proliferation of outdoor T&D plants. But the other extreme—cities devoid of any visible lines and substations—is equally unlikely.

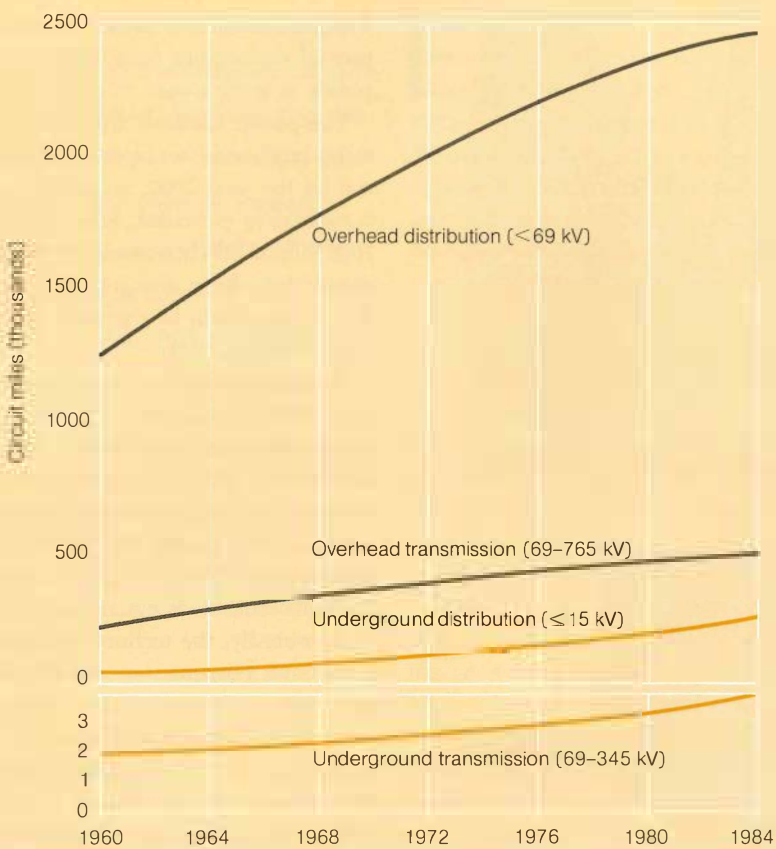
Admittedly, the technology exists to place both transmission and distribution lines underground. But placing only *new* T&D lines underground would cost the utility industry \$15–\$20 billion annually. This is in addition to the normal cost of operations. The utilities' total annual revenue is \$40 billion. The additional cost of undergrounding tomorrow's T&D lines would have to be borne by the consumer—and this burden would of course be rejected. In fact, the increase in power costs that would be required for undergrounding, together with the already higher costs of power plants and fuel, would place the convenience of electricity beyond the reach of most consumers. This cannot be justified.

Judicious choices and priorities

Clearly, there are some "targets of opportunity" amenable to focused R&D that will substantially reduce present installation and operating costs. We

Comparative extent of overhead and underground power delivery systems is shown by estimated and projected totals of circuit mileage from 1960 to 1984. Underground distribution is projected to have the sharpest percentage growth (650%) during the period; the other three classes are expected approximately to double.

NEMA data for overhead and underground transmission are the basis for these curves, with supplemental figures from EEI. Nationally, overhead distribution is seen to be from 6 to 5 times more extensive than overhead transmission. The growth in underground distribution reflects ratios of 20 to 60 times the mileage of underground transmission.



must therefore make judicious choices among these research opportunities and set priorities for their accomplishment. The areas of research that satisfy immediate needs and promise the greatest benefits obviously should have priority over other candidates.

Some targets of opportunity lie within the technical progress of other industries and can be adapted for application by electric utilities. Indeed, we can benefit from advances in the chemical, primary metals, electronics, plastics, and ceramics industries, to name but a few. Application of foamed glass, for example, may soon result in power utility poles that cost half as much as their wood counterparts and perform better in every respect. In addition, the new poles will use fly ash as a filler material—fly ash endlessly produced as a waste from electricity generation by coal-burning power plants.

Power in a flexible pipe

An exciting new development, adapted from the communications industry, may soon lead to more efficient transfer of bulk power either underground or underwater. It is called flexible gas transmission, and has been used in both Europe and the U.S. since the 1950s to transmit radio signals in a corrugated tube. The same type of tubing, with modifications, can be used to carry power, as the present corrugation technology is being expanded to accommodate power cables.

An EPRI project with I-T-E Imperial and Kabelmetal of Germany is expected to result in transfer of this technology to the U.S., complete with a machine to corrugate aluminum into 15-inch continuous tubes. Corrugated tubing can be fabricated in long sections (300–800 feet) and dispensed from reels. Shipping, field welding, and splicing will be reduced and simplified. Within the next 10 years, we believe, flexible compressed-gas cable systems will be available at 345 kV and possibly above.

More economical rigid gas cable systems will be attained by three-in-one technology (three conductors in one grounded enclosure) at 345 kV and above. This should permit a 10–15% reduction in cost from the rigid isolated-phase design. Such a system has been developed for 345-kV operation and is being offered for commercial use. This technology also holds promise of operation at 500 kV and above.

A novel form of forced convective cooling of underground transmission cables, called electrohydrodynamic (EHD) pumping, is now being investigated. The EHD concept is based on the pull exerted by a high-frequency electric field on electric charges. These charges, in turn, pull molecules of oil along the underground cable system, which works to cool the cable's insulation. The anticipated result is a smooth flow of oil through a long cable system without a pressure drop.

Cooling to increase current flow

The use of cooling to increase the capacity of cables has important implications as power production and use become more concentrated—in generation "parks," on the one hand, and in growing urban load centers, on the other. Drastic cooling into the cryogenic range (at or below −190°C) dramatically reduces the electrical resistance to current flow in conductors and suggests a way to transport energy at much higher density. Cryogenic cable systems may become a major option for contending with the cost and difficulty (if not practical impossibility) of establishing new transmission rights-of-way through developed areas.

Cryogenic research by EPRI today encompasses 23 projects concerned with hardware development as well as with basic phenomena and materials. Some of the work addresses what is called the cryoresistive temperature range (about −190°C), where conventional conductor resistance is about one-tenth its ambient value. Other work deals with superconductivity, the complete absence of electrical resistance exhibited by some materials when cooled nearly to absolute zero (−263°C to −273°C).

An ac superconducting cable, cooled by pressurized liquid helium and using niobium conductors, has already been designed under a contract with the Linde Division of Union Carbide. Two additional projects are now in progress: one, under EPRI sponsorship, to develop the thermal insulating containment for this cable; the other, under ERDA sponsorship, to develop conductors and their spacers.

EPRI and ERDA together have six concurrent projects for development of improved, higher-temperature conductors. (If reduced resistance can be achieved at temperatures above −190°C, the requirement for expensive cooling apparatus can be cut.) Five of the projects, with as many contractors, involve an attempt to optimize certain niobium-tin and niobium-germanium alloys for better current density, decreased ac losses, or higher operating temperatures. Each contractor has a different method for producing the conductor. One deposits thin films (1 μm) of superconducting materials, using electron beams. Another employs a variety of methods, including chemical vapor deposition. Still another fabricates its conductor by shaping concentric cylinders of niobium, bronze, and copper into tapes. In the sixth project, the crystalline form and structure of samples received from one contractor are being studied.

Underground transmission

Bulk power transfer into urban centers is not a problem for the future alone. Environmental encroachment is already a public issue, and utilities are concerned even now about transmission into congested areas. For the present, undergrounding must rely on proven cable systems, usually in rigid pipe-type enclosures.

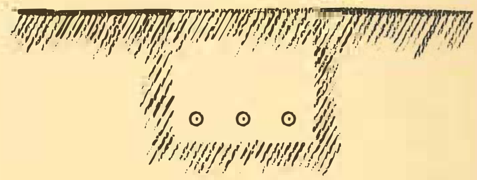
At the same time, efforts are being directed to improving each of the three principal cable types. Longest in use is cable wrapped with oil-impregnated paper tape that functions as both thermal and electrical insulation. In a newer form, the cable is enclosed in a high-pressure oil-filled (HPOF) pipe; natural oil movement smooths temperature differences that may occur, or pumped oil (forced cooling) continuously removes heat to make higher performance possible. A second conventional cable employs an extruded plastic coating as its dielectric (nonconductive) insulation. Gas insulation—also contained in a pipe enclosure—capitalizes on the better dielectric properties of certain gases.

R&D on taped cables is oriented toward higher voltages, higher ampacity, and more economical systems, as well as toward the solution of major problems in existing systems.

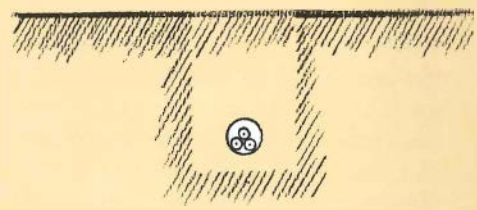
Eleven EPRI projects are concerned with various aspects of HPOF cable development. Four manufacturers have successfully developed 550-kV HPOF cables. Investigation of the operation of these cables at higher temperatures and higher voltages has since established capacity limits for all of them. For example, one finally failed while being tested at the 800-kV level,

Four principal cable types serve the ranges of transmission (T) and distribution (D) voltages shown. In the figure, common scale reveals their relative dimensions and trench requirements. Extruded dielectric cable is directly buried in long, variable lengths. High-pressure oil-filled cables are welded assemblies of 40- to 60-ft pipe sections, with continuous conductors pulled into place. Three-conductor gas-insulated pipe sections are also 40 to 60 ft long; the preassembled hollow aluminum conductors mate, and the pipe girth seams are welded. Rigid isolated-phase gas-insulated cable is similar, but a corrugated version of it may be fabricated in lengths of from 300 to 800 ft.

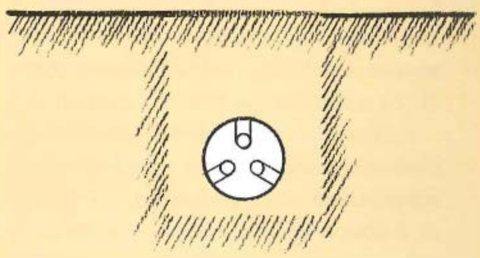
Extruded dielectric cable
T, D: 5–138 kV



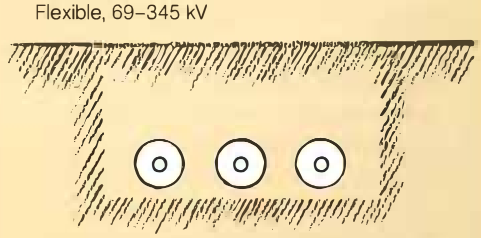
High-pressure oil-filled cable
T: 69–500 kV



Three-conductor gas-insulated cable
T: 69–500 kV



Isolated-phase gas-insulated cable
T: Rigid, 115–1200 kV
Flexible, 69–345 kV



and should thereby furnish performance data on low-viscosity oil as a cooling medium under high-temperature gradients. Four projects involving forced cooling should result in reliable tools for estimating the cooling obtainable for pipe-type electric cables by free and forced convective cooling schemes. This should lead also to improved means for determining the current-carrying limits of electric cable.

ERDA is sponsoring a study of the properties of various dielectric fluids for self-cooled and forced-cooled underground transmission systems. And EPRI is undertaking the installation and operation of a full-scale test facility for more accurate determination of design parameters of forced-cooled, pipe-type cable systems at the Waltz Mill test site.

Improved solid insulation

Extruded cables offer the best near-term solution for underground power transfer at the lower power levels (138 through 345 kV); this should contribute to the conservation of natural resources as well. The energy and materials required to produce a typical future extruded cable circuit appear to be less than for a conventional HPOF circuit. Of the 10 projects included in the program, 7 are concerned with improved quality, and therefore improved reliability, and with lower cost of the extruded dielectric insulation.

Perhaps the most widely used solid dielectric material is polyethylene subjected to a "cross-linking" process as a means of improving its performance at elevated temperatures and then extruded on a conductor to form cable. A research project studying the mechanism of electrical breakdown in cross-linked polyethylene (XLPE) should give us a base on which to develop cables with thinner walls, greater reliability, longer life, and reduced cost.

Even the most carefully formulated XLPE, however, may contain microscopic voids that tend to limit its withstand voltage. Therefore, methods to introduce a liquid impregnant are also being investigated, together with techniques to "gel," or immobilize, the impregnant so it cannot diffuse out of the voids. These refinements may extend the use of XLPE insulation to higher voltages.

Meanwhile, independent work on another project is continuing to optimize the design and manufacture of solid dielectric cables so as to achieve a significant increase in quality and thus permit operation at higher electrical stresses. This should lead also to the development of cables rated 138 through 345 kV, with reduced insulation thickness and attendant cost savings. The 138-kV development will include design of the transitions needed for cable splices and for termination connections to other apparatus.

One other solid dielectric cable project funded by ERDA concerns the use of sodium as a conductor with conventional insulation. ERDA also has under development a glass-insulated cable with a stranded copper or aluminum conductor. The sodium conductor cable is intended for operation at 138 or 230 kV. The glass dielectric cable not only is capable of higher operating temperatures, compared with conventional dielectrics, but offers the advantages of simplicity and economy for 1000- to 4000-MVA capacity at voltages of 138 to 345 kV.

Several system-oriented studies that are underway have to do with cable installation, detection of underground obstacles, and design of termination equipment. One project involves design of a research program to reduce installation costs of underground systems, while another reviews the existing technology of guided tunnelers. Two projects that have been completed define methods of mapping underground obstacles and of assessing the environmental impact of installing underground systems.

Underground distribution

Improvement of underground distribution cables and of attendant hardware components also offers a range of projects worthy of directed R&D.

EPRI's short-term objectives in underground distribution are threefold: (1) reduction of corrosion, (2) definition of thermal limitations of present cable insulation systems and development of improved systems, and (3) development of equipment and work methods that are compatible with the total underground distribution concept.

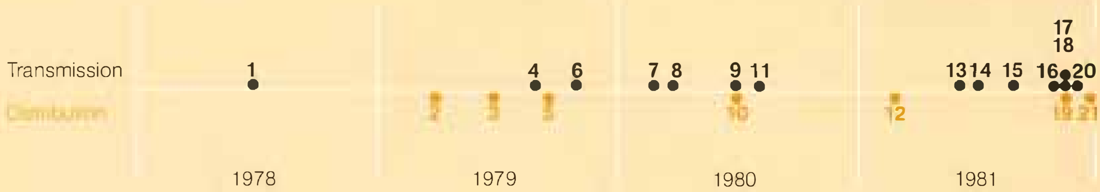
One problem of growing concern is the corrosion of neutral conductors—usually concentrically wound copper—on underground cables. Deterioration of these neutrals has serious implications both for the economics and for the protection of underground distribution cables. Two EPRI projects are underway to develop methods for mitigating corrosion. The first involves a state-of-the-art study of neutral corrosion. The second is evaluating use of a semiconducting jacket to prevent corrosion. Another project includes field tests and computation to ensure the safety of these jacketed designs (up to 35 kV) under fault conditions when laid in the same trench with telephone and TV cables. (Joint use of a trench by electric and communications utilities can eliminate costly separate ducts, wasteful allocation of land, and half the cost of excavation and backfill operations.)

Because of high material and equipment costs, utilities have been forced to increase current loading on all existing underground cables. And since overloading of cables can lead to serious outages, a new project by EPRI will seek to define emergency ratings for solid dielectric cables.

Three additional projects sponsored by EPRI will evaluate the susceptibility of solid cable insulation to subtle electrochemical deterioration, the use of lasers to detect voids as they are created during the formulation and extrusion of XLPE insulation, and new equipment and techniques for locating buried cable faults.

Voltage surges are another subject of inquiry. These transient "spikes" may

UNDERGROUND T&D RESEARCH MILESTONES



1. Cryogenic tape conductor (Nb_3Ge in 10-m lengths) operating above 12 K
2. Copper concentric neutral corrosion research complete
3. Equipment complete for monitoring and evaluating the integrity and degradation of cable insulation
4. Isolated-phase 345-kV flexible gas cable prototype ready
5. Fault-locating methods and equipment research complete
6. 550-kV semisynthetic taped cable field-tested
7. Improved methods available for detecting cable faults and leaks
8. Cellulose paper-taped cable field-tested at 800-kV
9. Improved refrigeration concepts proven for cryogenic cable
10. Emergency rating tests done for XLPE and EPR cables and accessories
11. Emergency heat exchanger and advanced cooling equipment components evaluated
12. Methods developed to mitigate equipment corrosion
13. ±100-kV DC extruded cable prototype field-tested
14. Equipment and techniques available for testing long lengths of gas-insulated cable
15. Cable load monitoring and forced cooling validated on utility system
16. Full-scale prototype of new cable installation equipment available
17. 800-kV semisynthetic taped cable field-tested
18. 138–345-kV extruded cable system field-tested
19. Distribution cable accessories developed
20. Advanced refrigerator prototype available for superconducting cable
21. New generation of 35-kV sectionalizing equipment developed

be caused by lightning, by switch operation under certain conditions, or by short circuits. On overhead lines they tend to decay quickly, and the resulting circuit behavior is well understood. But little is known about the surge response of underground distribution systems, where confinement may mean momentary propagation—or even amplification—of transients. The increased use of direct-buried concentric neutral cable and of a new generation of surface-mounted equipment has placed new demands on protective equipment. To meet these needs, EPRI has funded a project to assess underground surge propagation and to perform tests on installed cables according to the models derived. This project will result in a guide to application of surge protection devices.

A final word about compromise

This review of selected research and development efforts should clearly demonstrate that a wide range of opportunities exist for improvement of the underground delivery of power.

EPRI, in cooperation with ERDA, is seeking out those research opportunities that can be of greatest benefit to utilities. Choices must be consistent with available industry and federal funding, but already this coordinated program is the largest ever undertaken on behalf of power transmission and distribution. It is well underway, with close to 200 projects, at a joint cost of more than $40 million this year. R&D is balanced between overhead and underground programs, with emphasis on short-term objectives. Approximately 60% of the research should become useful to utilities within the next 5 years, 30% within the next 10 years, and 10% after that.

Advances by other disciplines, including the space program, are constantly assessed for possible application to utility equipment needs. This is in addition to cooperative efforts with power equipment manufacturers.

The ultimate compromise between overhead and underground power delivery is up to individual utilities, according to their perception of the benefits to society versus the economic burden that the public is willing to bear.

As the research arm of the electric utility industry, EPRI has the task of providing the technological options that are clearly needed to meet future power delivery requirements in an environmentally acceptable way.

Nuclear Plant Tornado Safety

by Conway Chan,
George Sliter,
and Boyer Chu

Wind tunnel research and tests with rocket-launched missiles are confirming the conservatism of current nuclear power plant design practice and providing a more realistic basis for engineering analysis. □ An EPRI technical article

Conway Chan, a program manager in the Safety and Analysis Department of EPRI's Nuclear Power Division, heads the tornado missile research program. George Sliter is project engineer for the testing effort, and Boyer Chu is project scientist for the risk studies.

The tornado is a relatively short-lived phenomenon, occurring from early spring through summer in an area that covers much of the central United States. Only a small fraction of the thunderstorms that result from the interaction between polar and maritime air masses develop into tornadoes.

Characterized by swirling winds and occasionally by flying debris, tornadoes sometimes cause damage—nearly always to residences, stores, and similar structures but seldom, if ever, to industrial buildings. Nevertheless, nuclear power plants are now required to be designed in such a way as to withstand tornado damage, whatever the likelihood of its occurrence.

Because the probabilities and mechanics of tornado damage have never been determined quantitatively, research on this subject is of considerable importance. EPRI's research program covers five areas:

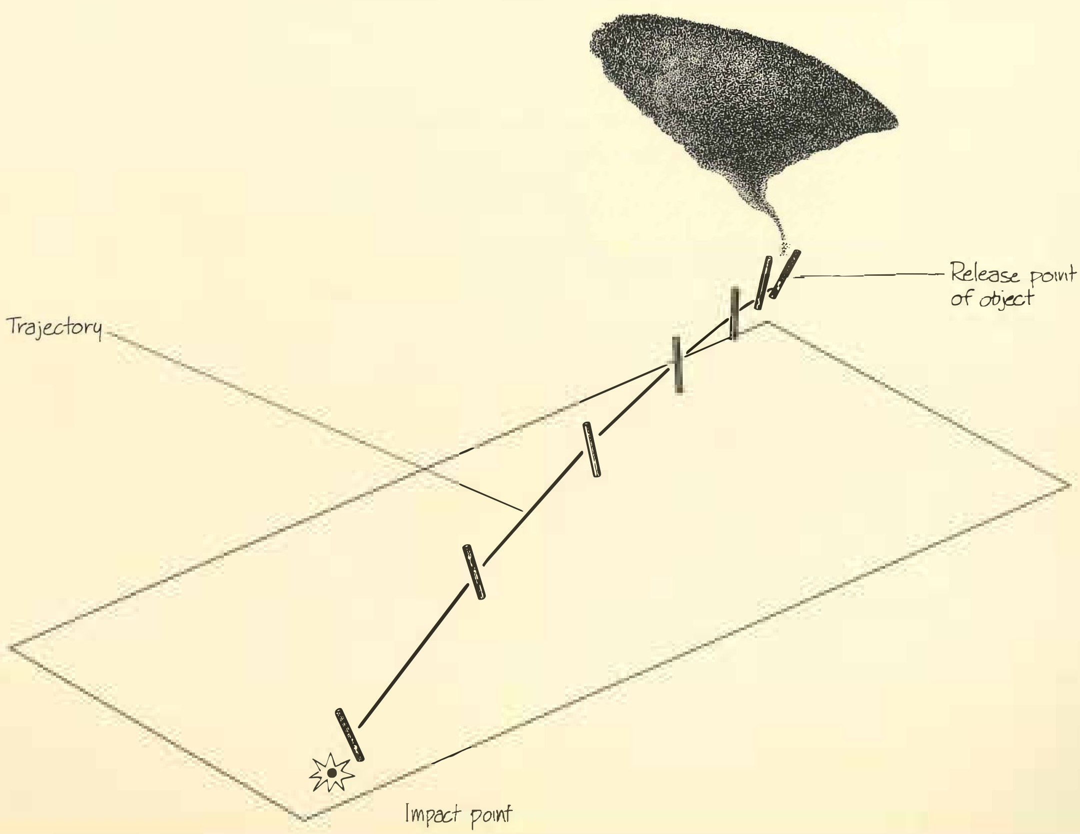
- Tornado wind fields
- Trajectories of tornado-driven projectiles
- Full-scale impact tests
- Local response of concrete to impact
- Missile risk analysis

An interdisciplinary approach is taken in this integrated program for providing the industry with useful tools based on realistic calculations and simulations.

Work in each of the five areas addresses concerns arising from current design practice. First, for example, the maximum tornado wind speed postulated in an NRC regulatory guide (*1*) has been consistently higher than estimates by various measurements and predictions. Thus there is a need for establishing a theoretically consistent wind model to simulate and bound the tornado wind speed. Second, a correct missile trajectory model would provide bounds for the possible positions and velocities of tornado-driven projectiles at impact. Third, full-scale impact tests, in turn, would provide a data base that could be applied immediately to current design. Fourth, these data must be interpreted on the assumption that the missile test speeds represent very conservative design conditions of wind speed and missile trajectory. Fifth, the missile risk analysis will take into account the question of the possibility of multiple missiles.

Individual projects under this EPRI program are wind field and missile trajectory determinations at the Jet Propul-

Figure 1 Mathematical simulation of the trajectory of a long slender object (such as a pole or pipe) as it is picked up, accelerated, and driven into a wall by a tornado permits development of aerodynamic tumbling coefficients to predict behavior of such objects.



sion Laboratory (JPL); full-scale impact tests at Sandia Laboratories; tests of the response of reinforced concrete to impact at Stanford Research Institute (SRI); and risk analysis at Carolina Power & Light Co. (CP&L).

Wind field and trajectory models

Predicting maximum tornado wind speed has been the subject of lively debate (2). One technique has been to relate the damage caused by a tornado to its wind speed. This technique results in a large degree of uncertainty involving assumptions on both the actual condition of the buildings damaged just before impact and the failure mechanisms. Other models have for the most part been derived empirically from the Dallas tornado of 1957.

An obvious solution would be the direct measurement of tornadoes. However, instrumentation placed at selected sites faces the uncertainty associated with predicting the tornado path. Also, experience has prompted some questions about the instruments' response characteristics and reliability.

The National Severe Storms Laboratory (NSSL) has recently embarked on a program using mobile equipment to track and measure tornadoes. As this data base grows, one would assume that most of the questions about maximum wind speed can be resolved. It is noteworthy that a recent NSSL report (3) cites documentation of wind speeds in the range of 175 to 225 mph. This contrasts sharply with the present maximum wind speed for which nuclear power plant builders must design: 360 mph (1).

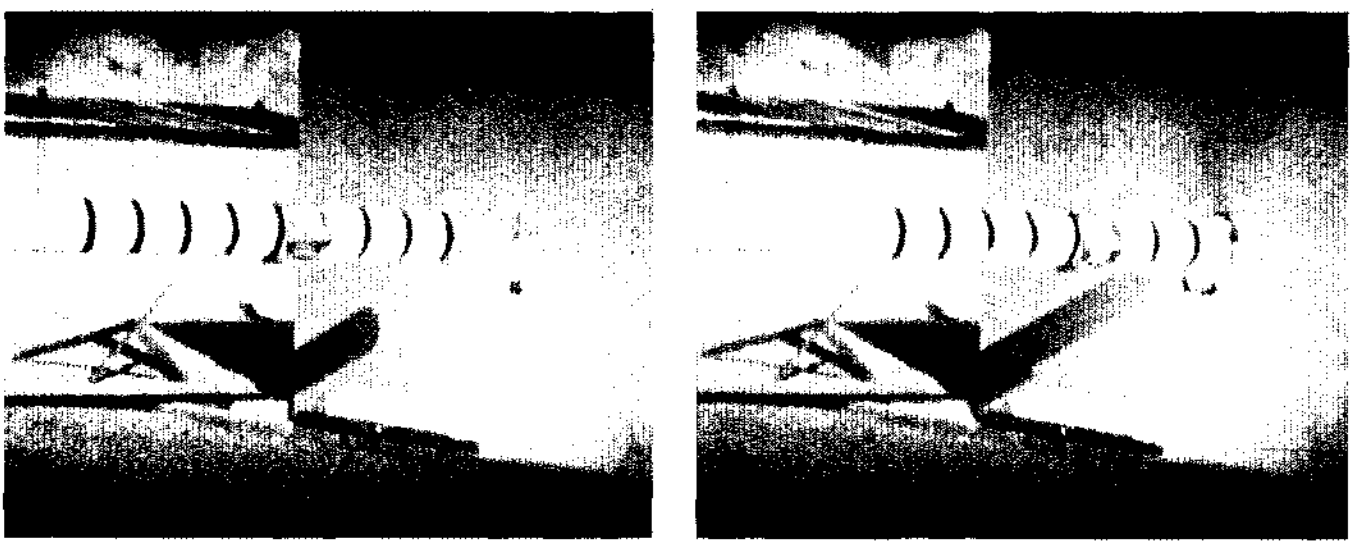
The effort at JPL is to establish tornado wind speed by means of a simple model that complies with the laws of fluid mechanics and thermodynamic fundamentals in a general sense. This approach cannot, of course, replicate in detail local uncertainties associated with a tornado, but the general analytic form of the model will result in a more consistent basis applicable to different tornadoes. The model being developed appears to provide a useful technique for estimating maximum tornado wind speeds. Subsequent efforts will focus on the wind field near the ground, where missiles might be picked up, and on their trajectory.

There is a lack of usable data on aerodynamic coefficients for the simple postulated missile shapes such as pipes, utility poles, and automobiles. This has led to worst-case analysis based on the assumption that a hypothetical missile's entire trajectory is at constant attitude with flow normal to the missile's surface. Such an analysis, in turn, has resulted in a rather large variation of predictions by different authors. In an attempt to include more realistic behavior, such as tumbling, some authors have used variations of the drag-averaging approach to obtain random tumbling coefficients.

To help meet the need for usable data, EPRI is sponsoring an experimental program of free-flight tests at JPL. These tests at the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT) wind tunnel are designed to determine aerodynamic coefficients. It is quite difficult to determine such coefficients experimentally, since there are special requirements for modeling supports and balances for the wind tunnel tests, or, in the case of free-flight tests, complications in data reduction.

To establish the testing technique, a short test was conducted on a cylinder with a length-to-diameter ratio equivalent to that of a utility pole. Additional experiments will be performed to establish aerodynamic coefficients over a complete range of missile attitudes relative to the wind. Near-ground effects influencing the possible pickup of debris as potential missiles will also be investigated.

Figure 2 Front 70 inches of a standard utility pole are pulverized into sawdust as a rocket-launched pole is driven at 140 mph into a 12-inch-thick concrete panel.



All these efforts will be integrated with a six-degrees-of-freedom trajectory model being developed for EPRI by JPL (Figure 1).

Plant protection against impacts

Besides its regulatory guide, NRC has issued a list of hypothetical tornado-driven objects and associated impact velocities that nuclear power plants must be designed to withstand (*4*). These range from an 8-lb steel bar at 216 mph to a 4000-lb auto at 72 mph. Most of the objects, such as utility poles and pipes, are long and slender. A major source of potential missiles is the construction stockpile of a plant being built adjacent to an already operating unit.

Even NRC's formidable list of hypothetical missiles is no match for the massive 3–5-ft concrete containment walls that protect the reactor itself. However, the thickness of the thinner turbine and auxiliary building walls, many of which protect safety-related equipment, is usually controlled by impact design loading in regions of higher tornado intensity. These walls are designed not only to prevent missile perforation but also to prevent pieces of concrete from "scabbing" off the back of the wall. Such pieces could conceivably behave as secondary missiles and damage equipment inside the building.

Several conventional "penetration formulas" are used to design against scabbing (*5*). They were derived by empirical or semiempirical means from military tests of nondeformable, solid steel projectiles traveling at speeds greater than 500 fps. Their applicability is questionable for predicting impact damage from deformable missiles such as wooden poles and from hollow missiles such as pipes at speeds well below 500 fps.

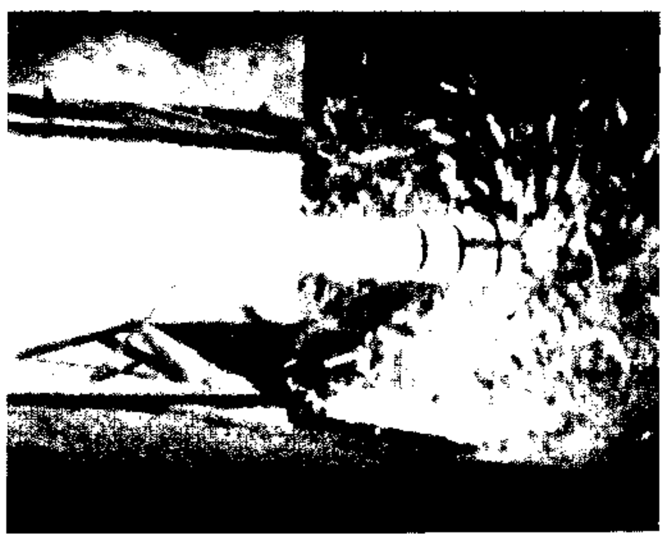
EPRI recognized a need for full-scale tests of tornado missile impact to assess the adequacy of conventional design formulas and to provide direct data for design. The test program could also confirm the ability of existing walls to withstand postulated impacts without endangering plant safety.

Rocket-launched "tornado" missiles

To perform full-scale tests, an experimental technique was needed to propel missiles to the prescribed velocities and accuracies. This capability was found at the testing facilities of Sandia Laboratories near Tonopah, Nevada. Sandia developed a rocket launcher in which the missile is propelled along a 130-ft guide rail by a rocket-driven sled. A bumper at the end of the rail stops the sled abruptly, permitting free flight of the missile to the target wall. Impact speeds, as measured with a high-speed movie camera, have proved to be within 5% of planned values and the impacts less than ½ in. from the targeted point. The rocket launcher technique was so successful that it will be used to do impact testing for EPRI with turbine missiles weighing several tons.

The 17-ft square reinforced concrete panels used in the tornado missile tests are supported along their edges by a massive backup structure. The target panels, designed to have the minimum strength allowed by current standards, are typical of balance-of-plant walls and roofs. Thicknesses of 12, 18, and 24 in were used to establish a lower limit of vulnerability.

The results (*6*) showed that of four missile types tested three were comparatively ineffectual in producing impact damage. A 1500-lb utility pole at 204 fps produced virtually no damage in a 12-in panel, the impact energy being absorbed by disintegration of the front 70 in of the pole (Figure 2). An 8-lb steel bar at 303 fps and a 78-lb 3-in pipe at 208 fps penetrated several inches into panels, but no backface scabbing resulted.



The fourth missile, a 743-lb 12-in-diam pipe, produced the most damage. At the 210 fps velocity specified by NRC, it penetrated about 7 in into both 18- and 24-in panels. Its impact produced backface scabbing in the 18-in panel, but the 24-in panel survived with its backface cracked but intact. The deformed pipe is shown in Figure 3.

In addition to visual damage data, electronic data were recorded during impact. Measurements of reactive forces, panel motion, and strain are useful for understanding the effects of impact loading on the overall response of the panel and the loads transmitted to its support structure in a nuclear plant.

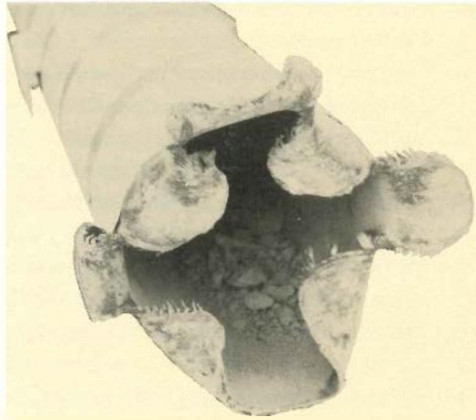


Figure 3
Twelve-inch pipe is grossly deformed after having been rocket-driven at 212 fps into a 24-inch-thick concrete panel.

Predicting impact damage

Although the full-scale impact tests may lead to improved design formulas, such simple formulas cannot be expected to yield accurate predictions of impact damage. The impact process is a complex one, involving intense dynamic stresses that propagate from the impact region. These stresses produce crushing, shear failures, and tensile fractures that would be difficult to predict even if the loading were static and the material homogeneous. Actually, however, the dynamic load introduces strain-rate dependence in a material that is nonhomogeneous (cement grout interspersed with stone aggregate and reinforcing steel).

If the material behavior could be characterized mathematically, advanced numerical codes such as EPRI's STEALTH (RP307) could be used to predict impact damage. SRI is therefore conducting an experimental and analytical program (RP393) to determine the dynamic material properties for reinforced concrete.

Laboratory gas guns are being used at SRI to strike concrete specimens with flat plates, rods, and pipes. Two types of plate-impact experiments display one-dimensional behavior under high strain-rate loading. In one, a layered concrete target is struck with a Lucite projectile. Gages between layers provide stress-strain data for loading and unloading. In other plate-impact tests, the duration of the impact shock wave is varied to measure its effect on tensile fracture. Tensile strength was found to be an order of magnitude higher than that observed in conventional static tests.

For three-dimensional behavior under high strain-rate loading, 1-in-diam solid rods and pipes are used in impact experiments. The 10-in-diam reinforced concrete targets show the same types of failure modes as the full-scale tests at Sandia.

Mathematical models of failure are used to simulate impact response in a finite difference code similar to STEALTH. If successful in describing the 3-D gas gun impacts, the code can be used to calculate damage in the full-scale tests. The results will indicate whether scale modeling can be useful for studying impact on reinforced concrete. If it is, research in turbine missile, pipe whip, and aircraft impact would benefit from the lower cost of scale model testing.

Probabilistic hazard assessment

Attempts have been made in the last several years to quantify the effects of tornado-propelled objects on the safe operation of nuclear power plants. With regard to tornado missile hazard, NRC has established guidelines (*1*) and criteria (*7*) to provide design requirements that are intentionally conservative so as to compensate for the statistical variables inherent in this potential natural hazard.

Work thus far suggests that the worst-case analysis required by the *Standard Review Plan* (4) may not be justifiable on the basis of tornado missile risk to plant safety. There is thus a great need for a rational probabilistic assessment of the tornado missile hazard—particularly for the more involved design criteria having to do with multiple missiles and the case for redundant component protection.

For a safety-related component of a nuclear power plant to be damaged by a tornado-generated missile, a sequence of accidental events would have to occur. Such a sequence typically includes (1) a tornado in the plant vicinity, (2) availability of missiles along the tornado path, (3) the tornado's lifting of objects that become missiles, (4) flight of these missiles, (5) missiles' striking the safety-related structure, and (6) damage to the structure. Description of a simulation of the events in this sequence provides a simple method for visualizing the components of probability analysis of tornado missile hazard.

In some instances, the event of interest is the multiple missile phenomenon. The event sequence for this case may be constructed from that for the simple missile by attacking its components serially to form a multistage model. However, because of the relationship between tornado intensity and missile aerodynamics, the simulation experiment must

PROBABILISTIC EVALUATION OF TORNADO MISSILE RISK

The general formula for evaluating the probability of any tornado-missile-related event E can be expressed as

$$P(E) = \int \int_{S_E} \ldots f(x_1, x_2, \ldots, x_n)\, dx_1\, dx_2 \ldots dx_n$$

where S_E is the integration region that can result in the outcome event E, and the function $f(.)$ is the joint probability density function that describes the statistical characteristics of the aforementioned event sequence. The quantity $P(E)$ could be, for instance, the probability that a particular structure or component will experience some defined criterion of damage due to the strike of a tornado missile. However, because of the unavailability of a relevant tornado-missile-related data base and the complexity of tornado missile phenomenology, this general integration approach is analytically intractable and not amenable to solution. Discrete event space is assumed as an approximation in evaluating the potential tornado missile hazard.

For the assessment of tornado missile hazard, the tornado intensity, missile type, missile source, impact location, and structural damage mode are of interest. These quantities can be subdivided into a finite number of regions in a discrete event space. With an appropriately defined event space, it is possible to represent a mutually exclusive and collectively exhaustive set of the tornado missile hazard outcomes that are induced from all possible collections of the input event space. For a given tornado occurrence in the plant vicinity, the probability of a missile impact that results in a prescribed damage D_q can be expressed (*8*) by:

$$P(Eq) = \sum_{i=1}^{i_{max}} P_1(F_i) \sum_{i=1}^{j_{max}} P_2(M_j \mid F_i) \sum_{K=1}^{k_{max}} P_3(S_K \mid F_i, M_j)\, P_4(D_q \mid F_i, M_j, S_K)$$

where $P_1(F_i)$ is the probability of occurrence of the given tornado of intensity F_1; $P_2(M_j \mid F_i)$ is the conditional probability that a missile of type M_j is available along the path of the given tornado of intensity F_i; $P_3(S_k \mid F_i, M_j)$ is the conditional probability that the structure S_k is impacted by the missile type M_j of a given tornado with intensity F_i; and $P_4(D_q \mid F_i, M_j, S_K)$ is the conditional probability that the structural damage D_q results from the conditions F_i, M_j, and S_K. In a probabilistic event tree, which represents a discrete formula of the tornado missile hazard for a given tornado occurrence, the upper limits of the indices i, j, k, and q are the number of subdivisions of the tornado intensity, missile type, impact location, and degree of structural damage, respectively. The Monte Carlo simulation technique can be employed to estimate the conditional probabilities P_l, $l = 1, 2, 3, 4$.

start with the occurrence of the tornado rather than at the pickup of a missile. The method for quantification of multiple missile hazard is still in the preliminary development stage.

The EPRI-sponsored project at CP&L is developing a probabilistic formalism to quantify realistically the tornado missile hazard. This involves integrating regional meteorologic data, data for missile object availability in the vicinity of nuclear power plants, the JPL tornado wind field model, and the experimental results from the full-scale missile tests at Sandia. A topical report (*8*) summarizing the state of the art and discussing the research efforts still required to accomplish the stated objective was issued in January 1976.

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How EPRI Plans

From first draft to final approval, EPRI's R&D program plan is a cooperative effort, reflecting the best judgment of EPRI's technical management, its planning staff, and its industry advisory groups.

How can each R&D dollar best be spent to meet the current and future technological needs of the electric utility industry and thereby benefit the public served by that industry? Answering this question is what EPRI's program planning is all about.

EPRI's R&D plans, which are formulated on both a projected five-year and a current-year basis, have evolved from the legacy inherited from the Electric Research Council and set forth in detail in the 1971 report of ERC's R&D Goals Task Force. From that base the EPRI staff, working closely with utility industry task forces and various advisory committees, has sought to achieve a balanced program that takes into account the broad range of requirements of the member utilities and of consumers, in light of increasing government regulations. The restraints imposed on the industry by these regulations, together with the technological complexity of most of the new power generation options, have made R&D more important than ever.

Dynamics of EPRI planning

EPRI's program plan reflects the collective judgment of the Research Advisory Committee, divisional advisory committees and industry task forces, and the Advisory Council, as well as the staff. Final approval of the plan rests with the Board of Directors.

In all stages of the planning process there is considerable give-and-take among the various groups, which thus provides a check. Attention is given to achieving a balance in programs among EPRI's four technical divisions, in view of the near-term, mid-term, and long-term research objectives.

Evaluation is a continuing process in EPRI's planning. At the beginning of each year the five-year plan is updated by the technical staff and then reviewed by more than 300 experienced utility people in EPRI's advisory committee system. These advisers help define specific research goals, thus ensuring that the programs continue to deal with recognized industry needs.

Basic premises

Three main premises underlie EPRI's R&D planning:

- Our society and economy could be adversely affected by substantial restrictions on electric power, such as might result from high costs or limited availability. Thus, the electricity production target for the nation should be large enough to prevent such restrictions.
- Dependence on foreign fuel sources is undesirable for reasons of national security, balance of payments, and unforeseeable costs. Thus, electricity generation options must concentrate on native fuel resources–mainly coal and uranium–at least until the year 2000.
- Long lead times, as much as decades for some systems, are required to change the national energy mix, whether it be forms of energy supply (coal, uranium, etc.) or energy use (automobiles, home heating, etc). Thus, development of feasible technical options must be undertaken decades ahead of projected need.

Given the many requirements and broad interests of the electric utility industry, the potential for valuable research and development is unlimited. It is therefore essential for the staff and the industry committees to screen many important research and development activities. To make such an assessment possible, the six major research areas are considered:

- Primary energy resource processing
- Conversion systems
- Transmission and distribution systems
- Storage systems
- Environment and conservation
- Energy R&D planning

Selection criteria

With wide-ranging and highly complex problems vying for R&D consideration, criteria governing program emphasis and level of support must be applied to the various proposed activities. Perhaps the most important criterion in the evaluation of program proposals is based on the needs of the utility industry and on the urgency of requirements for new information. Some of the proposals address specific questions related to the environment, public health, safety, and other regulatory requirements. These are placed in the highest-priority category of "survival" issues. (The term *survival* refers to the ability to continue to supply the electricity needed by the consumer.) Without effective R&D in this area, there might be crippling restrictions on the use of electric energy. The BWR containment problem is an example of such a high-priority issue.

Another important issue confronting the utility industry is to ensure that future options are available for processing and converting primary sources (coal and uranium) into electricity. Only by developing adequate alternatives can the future supply of electricity be assured. Programs in this category include the liquid metal fast breeder reactor, coal gasification, and liquefaction.

Working on ways to achieve efficiency or cost improvements in operation, maintenance, and capital investment is another priority consideration. The economic competitiveness of electricity as a desirable form of energy must be ensured if consumer needs are to be supplied. Research on transformer steel, on wood pole preservatives, and on lowering the cost of underground transmission cables would fall within this category.

A further criterion is concerned with determining whether a program, because of its nature, should be a responsibility of EPRI, the utilities themselves, the federal government, or the equipment manufacturers. And, of course, program and project proposals are evaluated in terms of the probability of their success and the likelihood and degree of their payoff for the utility industry.

A key consideration in discriminating among programs is the timing of the R&D proposed, that is, the period in which the anticipated technology is likely to become commercially available. The time frames are near-term (to 1985), mid-term (1985–2000), and long-term (beyond 2000). The objective is to obtain a balanced effort, with appropriate emphasis in each period so that the needed technology will be available at the proper time.

It is of interest to note that EPRI's early R&D focus was on development of advanced technology that would be commercially available around 1990. But in the three years of EPRI's existence, that initial emphasis has been expanded to encompass critical current problems that utility operators face in keeping their existing power plants on line.

This expanding scope of EPRI's R&D is reflected in the proportion of funds allocated: 45% each for near-term and mid-term; 10% for long-term. This means that the research objectives have expanded from such areas as advanced systems development and technology demonstration to generic design problems, plant reliability, and regulatory uncertainties. Research in advanced options still includes coal conversion, batteries, fuel cells, LMFBR, goethermal, solar, and nuclear fusion. On current problems, additional work is being done in control of oxides of sulfur and nitrogen emissions from fossil fuel systems, improved power plant reliability, support of nuclear licensing and regulatory questions, nuclear fuel performance and external cycle, seismic criteria for nuclear plants, and cooling system intake.

Advisory system

The Research Advisory Committee, a 21-member group of operating, research, and engineering utility executives, works with EPRI's president and Board of Directors in identifying and ranking the R&D needs of the industry and in considering technical policy issues; RAC also coordinates the activities of the entire advisory system.

The goal of the EPRI program is to develop technology in the best interests of all segments of society. Through the

Advisory Council, composed of leaders from public interest groups, government, labor, education, science, the environmental movement, and business, liaison is maintained between the public and EPRI's Board of Directors, officers, and staff. The Council reviews proposed programs, providing insight into social, economic, environmental, and political factors that may affect growth of demand, fuel resources, and regulatory policy. Its objectives are accomplished through quarterly meetings with EPRI officers and staff and through the work of its four subcommittees on national issues affecting EPRI, environment and ecology, power sources and uses, and communications.

The entire five-year plan, including newly expanded detail for the coming year, is thoroughly reviewed by the Research Advisory Committee before Board approval is sought.

Another important link in the planning chain is the divisional committees, which correspond to EPRI's four technical divisions and provide support to the division directors in assigning priorities and recommending program emphasis. These committees have major responsibilities in drafting and reviewing program plans.

Several task forces, appointed by the divisional committees, work more closely with the technical staff to formulate the program elements, with alternative approaches, and to sort out priorities at the project level. They also are now responsible for reviewing individual research projects to ensure that they conform to the objectives set forth in the program plan.

Cooperation with other agencies

Many EPRI programs are related to those being carried out by federal agencies; and in a number of areas of resource development and basic research, federal funding is substantially higher than industry's. Where appropriate, EPRI programs are designed to complement those of the government. Joint funding with the federal government on pro-

A CASE IN POINT

How EPRI can act quickly under special circumstances, as well as how its program emphasis is shifting toward greater concern for near-term industry needs, is illustrated by a project undertaken just over a year ago.

In June 1975, 15 utilities faced a regulatory review with the prospect of having to shut down 18 Mark I boiling water nuclear reactors then in operation. A total shutdown would have meant the loss of a combined generating capacity of 14,500 MW and replacement power costs that could have exceeded $2.5 million per day.

While designing an advanced version of the Mark I containment, the manufacturer encountered questions about the integrity of the reactor's containment vessel in the event of a loss-of-coolant accident (LOCA). As a result, the Nuclear Regulatory Commission (NRC) scheduled a hearing in July to determine whether the questions raised were serious enough to warrant a temporary shutdown of the reactors.

The 15 affected utilities had formed what became known as the BWR Owners Club and approached EPRI for research support in resolving the questions bearing on the integrity of the Mark I containment. Since the request was both urgent and outside EPRI's normal planning cycle, action by the Board's Executive Committee was needed before the Institute could participate.

Under the authority of EPRI's president, Dr. Chauncey Starr, initial work was begun. Subsequently, a project proposal was presented to the Executive Committee, which concurred in Dr. Starr's action to get EPRI moving on the immediate problem. But the Committee deferred to the full Board, which sanctioned the project and clarified relevant policy at its September meeting.

The Safety and Analysis Department of the Nuclear Power Division drafted specifications for scale model tests intended to yield an understanding of wetwell pool response during the early phase of a simulated LOCA. The model was designed, assembled, instrumented, and tested in three weeks; the results, including high-speed films of seven tests, were turned over to the BWR Owners group and its supporting organizations in July. These, in turn, presented the results to NRC as part of a larger interim response on the generic functional integrity of Mark I pressure suppression systems under hypothetical LOCA conditions. The test data and analysis were taken into account in a regulatory decision that allowed the Mark I plants to remain in operation while NRC continued its evaluation.

After responding to the immediate need of the BWR Owners group, EPRI's Nuclear Power Division submitted requests for additional funding to continue and expand the scope of the scale model tests and computer modeling of the hydrodynamics in the Mark I pressure suppression system. Significantly, the results have a bearing on newer BWR containment systems—the Mark II and, to a lesser extent, the Mark III. The importance of this R&D effort to the industry is readily apparent.

The subsequent research proposals have flowed through EPRI's normal advisory channels—task forces, divisional committees, and the Research Advisory Committee—and been approved by the Board.

It should be noted that from the beginning this project confronted EPRI with a policy question: Is it within the EPRI charter to provide technical support for urgent problems? After considerable discussion by the Executive Committee, EPRI's Board of Directors in September 1975 issued a policy defining the proper functions of the Institute.

EPRI has three principal functions, the Board decreed: (1) to develop advanced hardware options; (2) to conduct studies on health, safety, and environmental issues; and (3) to engage in studies on long-term generic problems. On a selective basis, the Board continued, EPRI may perform a fourth function: to undertake product improvement and cost reduction studies. The Institute should be resistant to requests, the Board said in further clarification of policy, for providing technical support for urgent problems or for providing technical support and services.

The task presented to EPRI by the BWR Owners group fell within the category of providing technical support for urgent problems, an area normally outside the main scope of EPRI's interests. But owing to the unfavorable effect the problem could have had on the industry as a whole, EPRI deemed it proper to undertake work on the generic aspects of the issue.

This crucial R&D project is now a part of the EPRI research plan. Not only does this demonstrate EPRI's flexibility in responding to immediate problems that may affect a large segment of the industry, but it also exemplifies EPRI's increasing emphasis on near-term research.

grams of mutual interest is another option employed.

To facilitate cooperation with the government, formal agreements have been entered into between EPRI and the Energy Research and Development Administration (ERDA), the National Aeronautics and Space Administration (NASA), the National Bureau of Standards (NBS), and the Environmental Protection Agency (EPA). During 1976, the EPRI program plan anticipates close cooperation with these agencies in the areas of near-commercial LMFBR; Battery Energy Storage Tests (BEST) facility; solar energy; coal gasification and liquefaction; transmission and distribution; nuclear fusion; safety and reliability of nuclear power plants. Moreover, EPRI's Washington, D.C., office facilitates close coordination between the EPRI research programs and parallel efforts of federal agencies.

EPRI has also concluded agreements with the Central Electricity Generating Board in Great Britain, Electricité de France, and the Ministry for Research and Technology of the West German Federal Republic. These agreements permit EPRI to maintain close collaboration with European research teams and to exchange technical information on subjects of mutual interest.

Two years of R&D planning by the utility industry and EPRI staff are reflected in the current five-year plan, which covers 29 programs and over 130 subprograms in terms of objectives, key events, and estimated funding requirements. Within these programs, EPRI has more than 700 projects. The total value of this R&D exceeds $400 million, including $120 million in cosponsoring funds from federal agencies, the contractors themselves, and other sources.

This five-year plan will be updated annually, with appropriate revisions in program emphasis to reflect new problems and state-of-the-art changes in energy technology. It is a dynamic set of guidelines for keeping the EPRI program on target and continually responsive to the most important needs of the utility industry.

R&D Status Report
TRANSMISSION AND DISTRIBUTION DIVISION

John J Dougherty, Director

UNDERGROUND TRANSMISSION AND DISTRIBUTION

EPRI's Underground Transmission and Distribution programs are an extension of research objectives initiated nearly a decade ago by the industry. These include the expansion of existing systems and the introduction of advanced systems that may provide underground T&D cables of greater reliability and lower cost. The total effort consists of 25 projects funded by EPRI and another 25 jointly funded by EPRI and ERDA.

Part of the Underground Transmission Program is divided into subprograms by cable technology, that is, taped cables, extruded cables, gas cables, and cryogenic cables. Additional subprograms are concerned with cable application, dc cables (which could use any of the previously mentioned technologies), forced cooling, installation methods, cable systems maintenance, and new concepts. The major cable systems test facility at Waltz Mill, Pennsylvania, is also considered a transmission subprogram. Projects are underway in all the major subprogram areas, most of which were described in the June issue of the JOURNAL. Some of the newer projects are taken up below. *Department Director: E. Robert Perry*

Underground Transmission

A project with Ohio State University will attempt to develop an underground obstacle detector. Work is scheduled to begin in January 1977 and to continue through 1978. Ohio State has already developed a third-generation ground-penetrating radar system designed for deep earth penetration (greater than 3 feet) to detect buried obstacles, specifically pipes. The sensor would be portable and battery operated. Also included in the project is the design of processing and mapping algorithms to produce maps of target location, depth, and identification.

A project with the Los Alamos Scientific Laboratory has recently developed a higher transition temperature, lower power loss superconductor by means of the chemical vapor deposition (CVD) process, using Nb_3Ge. The significant breakthrough in this project was the production of a material having losses at 12 K that are comparable to those of the best Nb_3Sn at 4 K. This factor-of-3 increase in the operating temperature is equivalent to a factor-of-27 increase in heat capacity and to a factor-of-3 reduction in refrigeration needs. A major follow-on project will develop the material suitable for cable production. Ten-meter lengths are presently envisioned.

Extension of forced-cooling tests on high-pressure oil-filled (HPOF) cables at elevated voltages is the objective of a project with Westinghouse. Testing to date at the Waltz Mill site has proven a 550-kV HPOF cable for utility application. Included in the comprehensive test program completed in 1975 were periods of voltage application at 930 kV (equivalent line-to-line voltage).

The next phase in this test series was to have been an evaluation of the effect of long-term forced cooling on paper-oil insulation. During the initial steps in this phase a failure was experienced in the cellulose-paper laminated joint. A second joint, made of cellulose-polypropylene laminate, appears to be in satisfactory condition. A final analysis and evaluation will be made to determine the repair or replacement required for continuation of this project. This evaluation is being conducted with the assistance of the Waltz Mill UHV Operating Committee, which includes both utility and manufacturing experts.

Improved solid dielectric transmission cables rated 130–230 kV are the object of a project with Phelps Dodge. This three-year project is based in part on the results of an earlier one, with the same contractor, on the breakdown mechanism of XLP insulation. In the earlier project it was found that microporosity in extruded dielectrics plays an important role in their electrical breakdown. Further, the impregnation of the microvoids with liquids substantially improved the dielectric strength of the cable.

The main thrust of the new project is to develop dielectric liquid impregnants that can be immobilized in microvoids through polymerization after impregnation. Such a structure would not require a pressurized pipe system to contain the liquid impregnant. The dielectric improvements potentially attainable with such a system would permit the design of cables with thinner insulation walls or greater reliability and hence lower cost.

The General Cable Co. will attempt development of three separate XLP cables rated 138, 230, and 345 kV. A reduction of the level of common dielectric imperfections (impurities, microscopic voids, and shield protrusions) would permit reliable operation at higher voltage stresses than presently used.

The goals of this project, therefore, are to develop (1) a special extrusion system that provides on-line compound purification, and high-pressure extrusion and cross-linking in a steam-free system; and (2) cables rated 138 to 345 kV with reduced insulation thickness. So far, the model cables have shown excellent dielectric properties.

An extension of gas-insulated transmission technology is to develop and fabricate a 362-kV flexible gas-insulated cable. This is being pursued under a contract with I-T-E Imperial. A milestone in this project was the recent fabrication of 140 meters of a 300-mm-dia cable in Hanover, West Germany. Sections of this cable have successfully passed preliminary dielectric and mechanical testing.

The next major step should be the purchase and installation of a machine in the United States that is capable of manufacturing flexible gas cable rated 362 kV (and possibly higher). Estimates of total installed cost savings of the flexible cable over rigid gas cable range from 25 to 50%.

A secondary objective of another project with Westinghouse is an analysis of forced cooling as applied to compressed-gas-insulated transmission lines. This portion of the project has been completed; the findings are reported in *Analysis of Forced Cooling of Compressed Gas Insulated Transmission Lines* (EPRI TD-228).

The analysis shows that forced cooling of the sheath of a compressed-gas cable is an economically attractive and technically feasible method of doubling its current rating. The technique can be applied on a continuous basis.

Due to the low cost of adding forced cooling (typically 5% of the total cost), this alternative is also attractive as a peaking or emergency rating option. One line could be cooled for short-time overloads or could handle the loads of two self-cooled lines when a parallel circuit is out of service for maintenance or repair. The analysis shows that forced cooling is applicable to long lengths of compressed-gas cables.

Novel methods of cooling underground cables have been a subject of continuing interest. A project with Battelle-Northwest was undertaken to investigate evaporative cooling for underground transmission cables, which appeared to be a viable method for economically increasing the capacity of such cables. Originally this project was to look at the use of a single fluid, both as a coolant and as a dielectric within the evaporating fluid. The fluid in the vapor phase would flow through the high electric field region and act as a dielectric. It was questionable, however, whether this would offer any great economic advantage over other nonevaporative forced-cooling methods. In addition, such a system would severely restrict the type of fluids used, in view of the difficulty of finding a fluid that would have the properties of both a coolant and a dielectric.

We felt that the important thing was to remove the vapor from the liquid phase of any fluid to avoid increased viscosity and ensuing effects, such as increased pressure drop and friction; the vapor would have to be totally removed from the confines of the cable and recirculated. Essentially, only the liquid near its boiling point would flow inside the inner conductor of the cable.

Additionally, we requested that the contractor consider other methods of forced-cooling the inside of a cable conductor. We did so because even though evaporative cooling showed great advantages over present methods, we wanted to ascertain how much the advantage would be over non-evaporative forced-cooling methods.

Economic analysis showed that all these internal forced-cooling methods offer significant reductions in capital costs and operating costs over present methods. In fact, they would permit up to three times the self-cooled capacity in a compressed-gas-insulated cable, for example. Capital costs were estimated to be reduced up to 60% at three times the self-cooled capacity. Operating costs were found to be reduced correspondingly.

Unfortunately, as suspected, the evaporative cooling was found to offer only marginally lower capital and operating costs compared with those of the other still untried but viable methods of internal forced cooling using single-phase fluids.

Underground Distribution

The underground distribution research underway comprises several cable projects, a project to investigate surge behavior in underground systems, and a completed project on location of underground faults.

The completed project assessed the effectiveness of underground fault-locating techniques. The contractor, BDM Corporation, estimated that the total number of faults occurring on primary and secondary distribution cable and on transmission cable approaches 165,000 annually. A survey of utilitymen showed that half of these faults are readily located with available equipment and another 40% can be located without any equipment at all. The remaining 10% accounts for the major share of the costs in fault-locating efforts—$12 million in 1974.

The total cost of fault location is made up of four elements:

Cost Element	*1974 Cost* ($M)
Equipment	1.0
Training	0.5
Operation	5.5
Design	5.0
	12.0

According to BDM, through better technology the training costs could be cut in half, the operating costs could be reduced by 20%, and enough could be cut from the design penalty to generate a cumulative saving of $670 million by the turn of the century. The cost is expected to grow rapidly, to $128 million per year by the year 2000, unless there is a significant advance in technology.

BDM points out, however, that there is not much incentive for manufacturer R&D, because average sales of each supplier are less than $200,000 per year. Hence, this represents a prime candidate for EPRI-sponsored research.

One cable project involves development of both 15- and 35-kV concentric neutral cable that is covered with a semi-conducting jacket to prevent corrosion of the neutral and to permit joint random-lay installation in a trench with telephone cable. Since utilities are turning increasingly to the use of 35-kV systems, it is important to determine whether the jacketed 35-kV cable is satisfactory for joint random-lay construction.

Initial tests of the 15-kV cable show that it exhibits a voltage distribution in the immediate fault vicinity and at remote points equivalent to that of the bare concentric neutral cable already approved by the National Safety Code. The utility industry would gain an immediate alternative method to mitigate concentric neutral corrosion and thereby reap the benefits of joint random-lay construction.

Completion of this project will include testing on soils of varying resistivity. This will allow completion of a computer modeling program. Utilities in various locations then will be able to predetermine the voltage distribution and safety associated with cables before these are placed in the ground.

Two additional underground distribution cable projects were initiated as a result of action by the Board of Directors in February. One concerns the possible use of laser-scattering phenomena to detect voids and contaminants in polymeric insulation for power cables. It may be possible to use this technique to continuously monitor extruded dielectric power cables during the production process and thereby identify voids of microporosity, one of the suspected causes of cable treeing. In addition, this process holds promise of detecting internally shielded voids, which constitute the majority of voids formed in high-voltage power cables. These voids slip by the presently used corona-detecting equipment. This two-year project is being carried out by United Aircraft Research Laboratories.

Fault duties have risen dramatically with distribution system growth, and so has the cost of the equipment that can withstand increased fault duty. The resulting overvoltages and overcurrents account for most distribution equipment failure and damage. Although much is known about surge behavior on overhead lines, little is known about surge response on underground distribution systems. The consequences of failures on underground systems are greater than those on overhead systems because of the longer repair times, the need for more costly equipment, the associated inconvenience to the customer, and the loss of revenue. Accordingly, EPRI is sponsoring a project to assess surge propagation in underground cable systems and to perform tests on installed cables according to the models derived. This project is expected to result in a guide to application of surge protection devices, which will be written by the contractor, McGraw-Edison Company.

R&D Status Report
ENERGY SYSTEMS, ENVIRONMENT, AND CONSERVATION DIVISION

René Malès, Director

ENVIRONMENTAL ASSESSMENT DEPARTMENT

Transport and Interactions

The objectives of this subprogram are to learn more about the physical transport and chemical reactions that pollutants undergo during their movement through the environment and to better understand their ultimate fate. Reaction and fate studies are not final goals in themselves but, rather, provide information vital for studies related to human health and ecological effects. Perhaps the most important role of EPRI's Environmental Assessment Department is to support research that gives a better understanding of the effects that contaminants derived from energy production have on humans. Such an understanding is predicated on reliable identification of contaminants and their physicochemical behavior in the environment. It is this latter aspect that concerns the transport and interactions subprogram.

The emphasis so far has been almost exclusively on air pollution studies related to the burning of coal in power plants. These studies have included (1) field research into the plume chemistry of ozone and sulfur dioxide, (2) evaluation of salt "drift" from cooling towers at plants where brackish water is used for cooling, and (3) evaluation of existing air quality models. Some of the research has satisfied immediate needs of the utility industry; other studies have dealt with longer-range problems.

The transport and interactions subprogram is in the process of broadening its perspective on research in two aspects. The first emphasizes generic problems facing the utility industry as a whole (as opposed to site-specific problems). Certainly, generic studies include data collection at specific sites, but the aim is to use those data to draw conclusions that have broad applicability.

The second aspect is concerned with problems stemming from the use of a variety of fuels (primarily coal, oil, and nuclear) and with the need to support research on water and land pollution, as well as air pollution. For the next few years, however, the major focus will remain on air pollution studies related to the burning of fossil fuels, primarily coal.

Over the next five years, programs will concentrate on four main research areas: (1) atmospheric conversion of sulfur and nitrogen oxides to more highly oxidized products, primarily sulfates and nitrates; (2) chemistry of organic pollutants (for example, POM) in the atmosphere and in disposal pond waters; (3) pollution problems related to the disposal of wastes (fly ash and sludge) from fossil-fired plants; and (4) environmental behavior of selected radioisotopes, which may include $^{229/240}Pu$, ^{14}C, ^{85}Kr, and ^{129}I.

The main emphasis will still be on atmospheric pollution problems, especially on those related to transport and chemical conversion. To a large extent, the atmospheric studies will center on the forthcoming SURE (sulfate regional experiment) program, a large EPRI-supported field-monitoring program designed to yield a means of predicting regional ambient concentrations of sulfates in terms of local sulfur dioxide emissions.

The four specific areas listed above, which are central to the five-year program, were chosen for investigation not only because they are important but also because they encompass a number of distinct components for which answers can be obtained with limited funds. *Project Manager: Ralph Perhac*

ENERGY DEMAND AND CONSERVATION PROGRAM

Residential Sector

Work in the residential sector has continued to proceed along two main paths: (1) technical performance and measurement and (2) energy demand analysis. Research in technical performance and measurement provides increased depth of information on how specific energy-using residential equipment performs and how and when it is used. These data are part of the input to research in energy demand analysis, in which the primary focus is an increase in understanding of residential energy-using behavior and an application of that understanding to the forecasting of long-run residential energy use.

Technical Performance and Measurement

Fuel Utilization in Residential Heating and Cooling (RP137) is the keystone of our work in this area. The objective is to develop the best information possible on the performance of major heating system alternatives. In this project, researchers from Ohio State University have developed detailed information on building and household characteristics and have placed extensive, comprehensive instrumentation in six houses and two apartments in the Columbus, Ohio, area. These dwellings were instrumented to capture information on energy used by furnaces, heat gain and heat loss through infiltration, load carried by other appliances, door and window openings and closings, and other variables of potential importance. Detailed data recorded at 15-min intervals have been compiled and correlated with weather station information, including direct and indirect solar radiation. This information will become a data file serving as the basis for a comprehensive simulation model of fuel utilization in heating and cooling. This model is to be generalized and simplified and then validated on information from a sample of houses throughout the rest of the United States.

The study has been divided into two phases. The first phase, which consists of reporting on the data collection and analysis of the Columbus site, is expected to result in a document to be completed in the fall of 1976. The second phase involves the validation of the simplified model on data collected from the remote sites over a one-year period. In order to accomplish the validation, eight residences are being metered for approximately one year in each of six utility service areas, representing a spread of degree-days across the United States. In each area there is a special weather station that collects data on temperature and on direct and indirect solar radiation. At present, data are being collected and sent to Ohio State from these remote sites. It is expected that the final report on the remote site validation of the simulation model will be completed in the first half of 1977. A steering committee of utility industry representatives has been formed to provide technical advice on this project. In addition, a panel of consultants has been convened to review the report on the first phase.

Another study (RP432) examines the load and use characteristics of residential heat pumps in actual household operation. Jointly sponsored by the Association of Edison Illuminating Companies, the study is performed by the Westinghouse Advanced Systems Technology Division. It has as its objective the development of data on homes with recent-model heat pumps. (This project was discussed at some length in the July/August issue of the JOURNAL). Instrumentation and measurement are consistent with the data developed for RP137, discussed above. The load data will be useful in further projects aimed at determining the impact of residential heat pumps on utility system loads.

In addition to developing the basic data in this project, Westinghouse is running simulations of heat pump performance, using its own proprietary computer programs. These data are expected to be of considerable interest to the utility industry. Similar runs with the heat pump data will be performed under a separate EPRI contract, using the simulation programs being developed at Ohio State University under RP137. Data are being collected from between 8 and 11 homes in each of 12 utility services areas—a total of 120 homes. The participating utilities were selected to give degree-day representation for climates ranging from Florida to Minnesota. Each area has its own weather station identical to that in RP137. Thus, between RP137 and RP432 there is under development a set of direct and indirect solar radiation data for 19 areas that is expected to be of value in other heating and cooling studies.

A third project in the technical performance and measurement area is a survey of monthly watt-hour consumption of major appliances, sponsored jointly with the Federal Energy Administration (RP576). Its objective is to provide representative data on household appliance usage and correlated socioeconomic characteristics. The data are expected to be the best source of information on this subject comparable across regions and also a valuable input in conducting household-level studies of energy-using behavior.

Energy Demand Analysis

Two types of work go on in this research area: (1) aggregate energy consumption studies that will be introduced directly into EPRI's energy consumption forecasting efforts and (2) microanalytic studies that focus on individual unit behavior. Thus far, most of our research has been concentrated on aggregate studies, which consist of estimating the parameters of econometric models of total household consumption as it relates to energy prices, personal income, and other variables. (For further information, see James W. Boyd's article "Forecasting Energy Use: The Residential Sector," EPRI JOURNAL, April 1976.) The models are used for forecasting consumption of electricity and other forms of energy. The resulting forecasts become an input to EPRI's R&D planning efforts, as well as increasing the general state of knowledge on the electric utility industry's future requirements.

A major contribution in this area is the work done under RP431 in estimating aggregate residential energy demand functions. In this study, a model has been constructed that takes explicit account of energy consumption implications of the declining block structure of residential utility rates. In addition, explicit account has been taken of the stock of appliances and heating and air conditioning equipment in houses in order to model utilization more precisely and also separately from appliance and heating saturation. The residential stock data have been developed by Data Resources, Inc., in another part of RP431. The study is expected to provide much more precise information on the relationship between residential energy usage and relevant explanatory variables than has been obtained in the past.

Another study in this area (RP488, conducted by Charles River Associates) assesses the implications of emerging and prospective energy-conserving technologies, such as the heat pump. It attempts to develop a general approach to assessing the market potential of such technologies by using data on performance characteristics of the heat pump and competitive technologies and also an advanced statistical technique called logit analysis.

Future research in the energy demand analysis area will concentrate on microanalytic studies using data from the Bureau of Labor Statistics' Consumer Expenditures Survey and data developed in RP576, mentioned above. Also, a great deal of refinement is expected in the realm of aggregate consumption forecasting, through more precise and detailed knowledge of the composition of housing and the appliance stock. Data developed for RP137 and RP432 will be coupled with the methodology of RP488 to conduct a comprehensive study of residential heating systems' market saturation and possible implications for typical electric utility system loads. *Program Manager: Robert Thomas Crow*

ENERGY SUPPLY

Supporting Resources

Since World War II, energy supply analysis has rarely had to concern itself with the availability of nonenergy resources. The economy and the physical environment apparently could, with few exceptions, meet any demand placed upon them by the energy industries. But in recent years the availability of such resources as water, construction sites, labor, and capital has led to possible limiting factors in the expansion of energy supply. Certainly, in planning for the long-term expansion of the energy industries or in simply analyzing the growth prospects, increased attention must be given to these items.

In a macroeconomic sense, economists have long been concerned with the role that land, labor, capital, and water play in the growth of the economy, designating them as "factors of production." The supporting resources subprogram is concerned with the availability and cost of these factors as they affect the nation's ability to expand energy production. The subprogram also is concerned with studying the supply of scarce equipment such as draglines or scarce materials such as catalysts. Two studies that exemplify the work of this subprogram are Water Supply Data Systems for EPRI R&D Planning (RP762) and Critical Assessment and Modification of the Bechtel "Energy Supply Planning Model" (RP664).

There is a great need for information on the availability of water for expansion of energy production. EPRI is involved with projects relating to cooling-water technology and water use for existing and new energy sources. To adequately answer technical questions relating to such projects an extensive set of data on water availability and quality is needed. A centralized source for this information is critical for efficient R&D planning within EPRI.

Without information on technical availability, economic characteristics, and legal constraints, data on the natural supply of water are of little value. For maximum usefulness a data base should account for all the restrictions on water use. Biological and ecological parameters must also be part of any comprehensive characterization of water availability.

Data on water have been collected by the Water Resources Council, the U.S. Geological Survey, the Environmental Protection Agency, state agencies, and others. The amount of data compiled is massive, but the efforts are relatively uncoordinated. From an outside user's viewpoint, it is sometimes difficult to use these data bases efficiently, particularly when two or more data bases are needed to obtain the desired information.

Under RP762, the University of Arizona is working closely with EPRI staff to ensure that the data base being designed will contain the information needed to describe water supply in a way that will be useful both to EPRI in its R&D planning and to the industry. The research strategy is to construct a host data base that will contain both data and pointers (guides) to the information in the data collections (support data bases) mentioned above. This will allow the user, by means of the host data base, to access efficiently the support data bases in order to obtain a required combination of information. The support data bases will probably include the large federal data bases, such as WATSTORE and STORET. The research contractor will design the host data base and implement it for water resources in the Colorado River basin, including parts of Arizona, California, Colorado, Nevada, Utah, New Mexico, and Wyoming. It is in this geographic area that the energy/water interface is particularly critical. As research results become available, the work may be extended to other areas. In a coordinated parallel effort, the Environmental Assessment Department of the division is examining the biological and ecological parameters of water resources.

Related to this work are the review and improvement of the internal consistency of an important modeling and data effort, which was conducted by Bechtel Corporation under contract with the National Science Foundation (RP664). The Bechtel effort, The Energy Supply Planning Model, is essentially an accounting model that includes the procedures and data base necessary to calculate the direct capital, manpower, and material resources required to bring on line and to operate the necessary energy supply facilities for any specified future supply-demand scenario. The purpose of this study is to correct a number of data inconsistencies that limit the quality of results from the model and to improve its capabilities for linking with other energy supply modeling efforts. The modifications of this model will allow the Energy Supply Studies Program to identify areas where material constraints may be critical for the production of increased amounts of energy. *Project Manager: Rex Riley*

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FUSION

Fusion power research represents a closely cooperative, worldwide R&D effort of $1.5 billion per year. The EPRI Fusion Program alone has been allocated $4.5 million for 1975–76. In addition, U.S. utilities are spending $1.4 million annually on fusion programs. These efforts assure that the industry will be accurately informed of developments in this major energy area.

The worldwide fusion effort is now in a transition phase—moving from basic research to goal-oriented development of a new energy source for the utility industry and for society as a whole. Research has progressed to the point where fusion machines capable of energy break-even conditions are now under construction—some costing more than a quarter of a billion dollars. Design of net-power-producing reactors is underway, as are the first conceptual designs of eventual fusion power plants.

The EPRI Fusion Program, as a primary source of input for U.S. and foreign fusion programs, has an extremely important role. Research and development decisions made during this transition period will have enormous impact on the utilities. The situation is analogous to that in the 1950s with regard to nuclear fission power. R&D decisions made then, largely without utility involvement, are the underlying causes of many problems affecting the industry today.

Many options are available for fusion power. However, because long lead times and costly developments are involved, these options are being narrowed quickly. Thus, decisions that are made now can determine the types of fusion systems the utilities will be able to choose from in the future. A technological demonstration of fusion power does not assure that the system developed will be one that can meet utility needs or justify a rapid introduction into the future utility grids of this country. The utility industry—the ultimate user—now has the opportunity to head off future problems by providing a guiding influence early in the development of fusion power.

The EPRI Fusion Program has concentrated on assessing options and defining the factors necessary for successful interfacing of fusion plants to utility grids. These factors include reactor size, plant reliability and availability, electrical performance, remote maintenance requirements, power conversion systems options, resource requirements, radioactive waste and safety consideration, system complexity, and reactor and plant control. As it progresses, the EPRI program will seek to demonstrate the viability of more utility-favored directions for the physics, engineering, materials, and total system elements.

The EPRI Fusion Program is divided into six subprograms. The first two—Interface of Utility Systems with Fusion Power and Fusion Subsystems for Utility Applications—serve to assess fusion power in terms of its impact and usefulness to the utility industry. Three other subprograms—Alternative Fusion Reactor Concepts, Advanced Fusion Power Systems, and Off-Line Utility Applications of Fusion Energy—consist of research and exploration of advantageous options (such as advanced fuels) that are receiving relatively little emphasis in the national effort. The sixth subprogram—Implementation of Utility Objectives—constitutes the foundation of the EPRI program where design, analytical, and experimental programs of sufficient scope are carried out to selectively impact the national effort. Representative projects in three of the subprograms are discussed below.

Experimental Power Reactor

The fusion experimental power reactor (EPR) is the step between the plasma physics experiments that achieve energy break-even conditions and the large-scale production of electricity for fusion in the first demonstration power plants. In 1974, three conceptual design efforts were initiated for EPRs based on the mainline ERDA fusion concept, the tokamak. The EPRs were designed to fully model the behavior of the burning of deuterium-tritium (D–T) fuel in a power reactor and to assess the magnitude and cost of the engineering tasks ahead. Operation of one or more fusion EPRs is scheduled for the mid-1980s to early 1990s.

ERDA funded two tokamak EPR designs, one at the Oak Ridge National Laboratory and the other at the Argonne National Laboratory. EPRI funded the third EPR design at the General Atomic Company (GA), the only EPR design effort by an industrial manufacturer. With the help of utility advisers, important industry design goals were established, such as demonstration of net electric power (ORNL design does not provide for this), safety, maintainability, and a firmly based cost estimate. (The EPRI design is the only one to use an architect-engineering firm.)

Tokamak fusion systems tend to be large and costly, and therefore might not be easily introduced into and accepted by the utility industry. A greatly improved potential for achieving a viable tokamak fusion reactor at a reasonable cost and size is offered by the doublet plasma shape. This uses a special noncircular plasma cross section that makes more effective use of the confining magnetic fields, though with somewhat increased plasma physics development risks. The doublet was selected for the EPRI design study. The major test of the doublet physics will occur in early 1978, when Doublet III is scheduled to operate at GA. Designed by EPRI and being constructed by ERDA, the Doublet III will attempt to achieve the break-even plasma condition.

The fusion experimental power reactor plant shown in Figure 1 was designed for GA by the Ralph M. Parsons Company. The facility includes the various reactor and plant auxiliary systems, as well as the power conversion system. The major radius of the fusion reactor is 4.5 meters. The plasma chamber is surrounded by a 25-cm-thick modular blanket of 316 stainless steel structure and graphite blocks. This, in turn, is surrounded by the toroidal magnetic field coils using niobium-titanium superconducting magnets that produce a maximum field of 78,600 G. The nominal burn time is 105 sec, with a dwell of 20 sec between burns to remove ash. Shielding on the reactor is sufficient to permit contact maintenance outside the shield envelope 24 hours after reactor shutdown. Hot cells are provided for maintenance operations on activated components. A superheated steam cycle, supplied by two recirculating helium-heated steam generators, is used for the power conversion system. The cost of the entire facility is estimated at $700 million, including engineering and contingencies (1976 dollars). Approximately two-thirds of the cost is for the fusion steam supply system; the rest is for the balance of plant (BOP). Construction time from start of Title I to completion is seven years.

For the remainder of 1976 and throughout 1977, EPRI will continue EPR studies directed at clarifying three critical problem areas: (1) an experimental check via a lithium plasma simulation of the reactor scaling law currently in use; (2) an investigation of in situ refurbishment of the silicon carbide liner that faces the plasma; and (3) the fueling of fusion plasma during the 105-sec burn cycle.

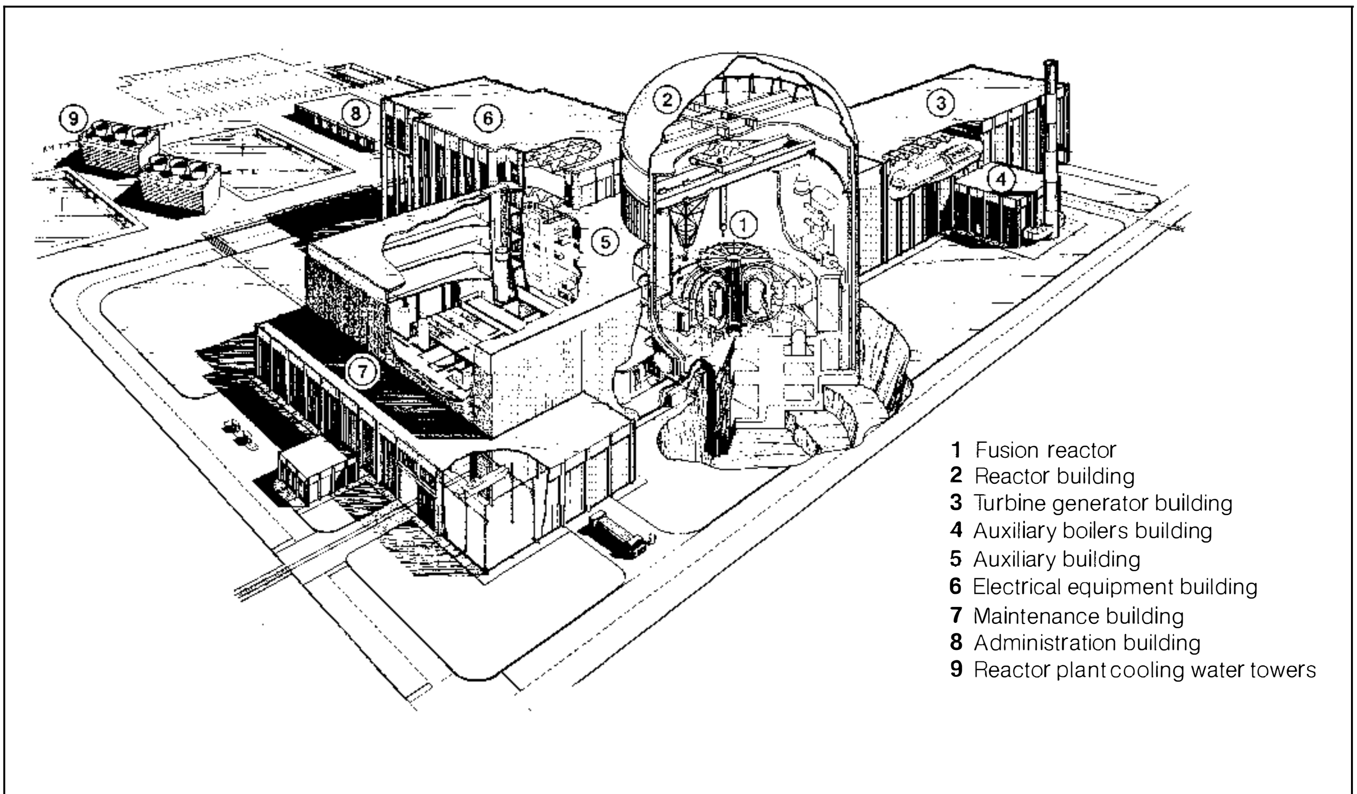


Figure 1 A cutaway line drawing of the fusion experimental power reactor (EPR) facility designed for the General Atomic Company with EPRI funding.

Laser-Fusion*

In the past few years a substantial international effort has been underway to achieve controlled fusion with lasers. This method relies on inertial, rather than magnetic, confinement. What is laser-driven fusion? Is it a viable alternative to magnetic confinement? Will it be achieved sooner? Does it also face serious obstacles? Is it suitable for commercial use, as well as for the military applications for which it was originally intended? To provide the utilities with answers to such questions, EPRI formed a Laser Fusion Assessment Council and commissioned K. A. Brueckner and Associates to make a study and evaluation of laser fusion from an independent point of view.

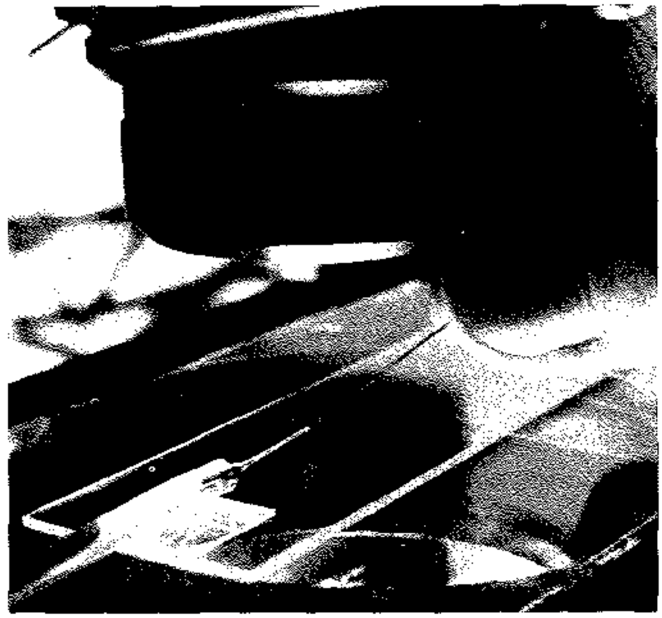
Laser-driven fusion, in contrast to the long-studied and more familiar magnetically confined fusion, depends on the laser-initiated release of explosively generated fusion energy from an inertially confined fusion pellet. This process can be produced at a useful efficiency only if the pellet is very highly compressed into an optimum condition for ignition and subsequent explosive burning.

Although the desired conditions are well known, major uncertainties exist in many features of the physical phenomena of laser-pellet interaction, energy transfer, and compression. Present experimental results fall far short of a demonstration of scientific feasibility, the compressions achieved being too low by a factor of 100 to 1000. Implosion velocities have been achieved that would be sufficient to produce ignition in large pellets. However, these velocities have been associated with strong irreversible shock heating and hence are of little relevance to the conditions of quasi-adiabatic heating essential for high-gain pellets.

Analysis of reactor efficiency shows that pellet energy multiplication close to the computed maximum is required for driving a pure fusion reactor. The number of unresolved scientific problems now identified, each of which can seriously affect scientific feasibility, raises serious questions concerning eventual demonstration of high pellet gain and hence of engineering feasibility of pure fusion systems. In recognition of this problem, increased attention is being given to classified designs that may have higher gain than those appearing in the literature today. Interest is also increasing in fusion-fission hybrids that give large energy multiplication by fast fission in a fissionable blanket and from the subsequent breeding of fissile fuels. These large multiplications tend to relax the laser and/or pellet gain requirements. Consequently, the EPRI Laser Fusion Assessment Council concluded that "*as of this time*, production of net power with unclassified target designs does not seem likely. Rapid progress is, however, a characteristic of this field; and one cannot conclude that the outlook for unclassified pellets will not improve with further development."

*Based on the draft final report of the EPRI Laser Fusion Assessment Council and the KAB Associates report of the working group. The report will soon be published by EPRI.

Figure 2 By means of a delicate probe, a technician mounts a tiny microsphere on a thin support fiber (approximately 3 μm in diameter), which in turn is attached to a glass capillary drawn from a piece of tubing. Mounted in this fashion, pellets can be readily transported to the target chamber to be irradiated by the laser.



In 1968 a milestone in the magnetic confinement fusion program was achieved when it was found that "Bohm diffusion," an anomalously fast plasma escape rate, could be overcome in tokamaks. The observed loss rate, though not classical, was slow enough to allow design of prototype reactors. The EPRI assessment concluded that laser fusion has not yet reached a comparable milestone. This conclusion is based on the observation that anomalies in laser energy absorption and transport in the pellet are only now beginning to be recognized and that the understanding and solution of the plasma problems are yet to come. To reach a comparable milestone in laser fusion two critical measurements need to be made: (1) the achievement of high density with quasi-adiabatic compression (100 g/cm^3 at 3–5 keV) and (2) demonstration of coupling of energy to D–T fuel of high enough efficiency to allow projected pellet gain of the order of 50–100. These experiments, which would produce considerably less yield than scientific break-even, are possible in the next year or two at several laboratories in the United States and the Soviet Union.

Aside from the question of scientific feasibility, laser-driven and magnetic-confinement reactors have some very difficult problems in the nuclear core. A fusion reactor using magnetic confinement requires large magnetic fields; high plasma purity; possibly divertors to remove wall-produced contaminants (in tokamaks); neutral-beam, radiofrequency, or other types of auxiliary heating for ignition; D–T fuel injection; lithium for tritium breeding; heat removal from within the magnetic field; a first-wall subjected to severe radiation damage; and possibly large single unit size for economical plants. The laser-driven reactor has the tritium-breeding requirement and a somewhat different (possibly more severe) first-wall problem. The other characteristic features of the magnetic fusion reactor are absent, but instead there are the major problems and uncertainties of the laser and laser-beam injection and pellet design, fabrication, and cost. The physics of the laser-driven system allows lower average power units and greater redundancy of critical elements than does the magnetic approach.

Laser-driven fusion is presently less well demonstrated as a scientific possibility than magnetically confined fusion systems. The appropriate size and characteristics of the laser to drive the implosion cannot yet be specified. However, once the two barriers of scientific feasibility and laser technology are overcome, it is felt that the reactor-associated problems are easier to solve than in a magnetic fusion device. That is, many of the first-wall problems can be solved by increasing the diameter of the vessel, thereby increasing the cost at a lower rate than in a magnetically confined system, but reducing the neutron, charged-particle, and photon flux to levels that can be accommodated with reasonable wall lifetime.

Because classified targets lead to a more optimistic prognosis for laser-fusion, the Council believed that a classified briefing was needed to supplement the report, which is based entirely on unclassified information. Such a briefing, arranged by ERDA, was attended by several members of the Council.

The following statement was written by those members and was approved by ERDA for release.

> The unpublished laser-fusion target designs suggested by recent LLL and LASL studies offer a very interesting and important possibility of pellet gain markedly exceeding that achievable with the presently published designs. The new design concepts, however, still require a very extensive experimental program. They depend on several aspects of the laser plasma interaction and pellet hydrodynamics which will be studied in the planned ERDA programs within this decade, with some important results probably achievable by the end of CY'77.
>
> To explore these important possibilities on an optimum schedule appears to require some restructuring of the ERDA program and in particular much increased emphasis on target fabrication.
>
> The proposed targets are more complex and difficult to fabricate, but in compensation they offer an important trade-off in laser characteristics. The economic and technological optimization of a reactor may be altered in a fundamental way by this flexibility in design.
>
> Some possibly important results of these developments are not available to the open engineering and scientific communities because of the classification placed on the work. In any case, characteristics influencing reactor design, such as pellet yields, should be made available as soon as possible for use in unclassified reactor studies.
>
> No unusual problems in a fusion reactor appear to arise from the new target designs, aside from possible difficulties with pellet fabrication and cost. Several of the problems may in fact be alleviated by the expected changes in pellet output. We note however that very high pellet yields require large containment vessels and possibly lead to difficulties in economics and in compatibility with power grid requirements.

Should classified pellet designs be needed for net power production from laser-fusion, the utilities would be faced with an unpleasant, but not insurmountable problem. There is, of course, a possibility that declassification would occur long before the industry is ready to build commercial plants. Failure to declassify could lead to the necessity for the federal government to design, construct, and control the entire laser-fusion core of the energy conversion plant and for the utilities to purchase thermal power from the government and to operate the plant. Precedent for this pessimistic scenario can be found in the N reactor at Hanford, which is government-operated even though only the fuel is classified. The arrangement, though workable, is awkward.

It is possible that, because of the need for full public disclosure, public utilities would suffer more from classification than private utilities. Furthermore, industrial support for classified power plants would be affected by the impossibility of foreign sales. The greatest near-term impact of classification, however, probably lies in the time lag caused by the lack of information on particle and energy output in classified pellets.

The EPRI assessment emphasizes the problems of progress in achieving scientific feasibility, as distinct from the problems of engineering and laser development. This emphasis is merely a reflection of the information currently available. EPRI has system studies underway that will lead to a better understanding of significant engineering differences between magnetic and laser-fusion reactors.

Laser-fusion is but one possible means of initiating the fusion burn in an inertial confinement system. Alternative inertial confinement schemes employ relativistic electrons or ion beams rather than laser light to implode a pellet. EPRI will be assessing these options in the future.

Fission Waste Reduction via Fusion Neutrons

The potential of transmuting (burning) nuclear fission reactor wastes by use of fusion reactor neutrons has been evaluated by EPRI through a number of companion contracts. This work extends earlier, less-comprehensive studies that concluded that the use of fusion neutrons for accomplishing actinide transmutation and transmutation of certain fission products was not only theoretically feasible but also possibly advantageous. Those studies, however, were based on ideal conditions. The approach taken by EPRI was to evaluate technical feasibility and to estimate time scales based on more realistic assumptions.

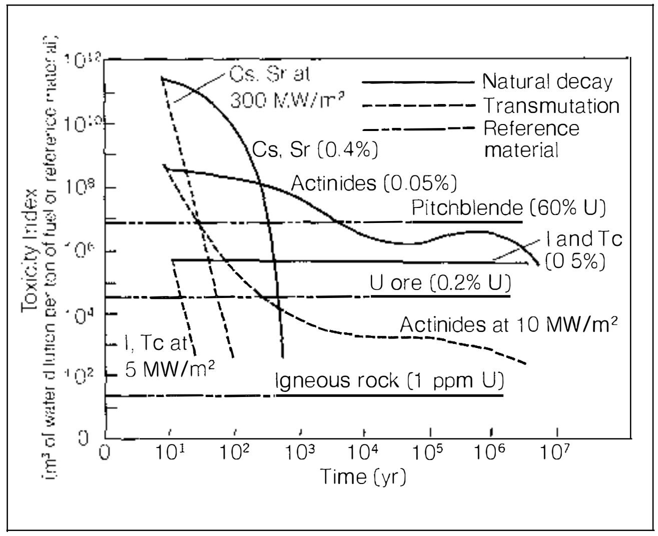
Four contractors participated in the program: Battelle, Pacific Northwest Laboratories (which had performed the earlier studies), Westinghouse Electric Corporation, McDonnell Douglas Astronautics Company–East, and the University of Texas at Austin. Taken together, the studies addressed a wide range of topics, including a detailed conceptual design of a fusion-driven actinide burner to assess the earliest possible date that fusion might contribute to the disposal of radioactive fission waste. This design, carried out by Westinghouse, was based on a minimum extrapolation from the D–T-burning Tokamak Fusion Test Reactor now under construction and scheduled for operation in 1981. At the other extreme, it was noted that fusion power is a technology in its infancy. Many options for possible fusion reactor systems and developments can be pursued over the next 30 years. Exploratory studies were made to discover fusion reactor characteristics and research directions that might lead to viable fusion transmutation systems in the next century.

Viewed in the long term, the studies lead to the conclusion that the transmutation of fission wastes in fusion reactors (probably specially dedicated facilities) will be technically feasible. For example, Figure 3 shows the toxicity of three fractions of the nuclear fission waste for both natural and fusion-enhanced decays over a period of millions of years. With transmutation, it appears likely that the toxicity can be reduced to an acceptable level (for instance, the level of a typical uranium ore of 0.2% concentration from which the wastes originate) in tens of years. Less than 1% of the energy generated originally in producing the fission wastes will be required for transmutation, and for the actinides there will be net energy produced. It appears that far less than 1% additional wastes will be produced; hence, the fusion transmutation process removes more wastes than it creates.

However, before the conclusion that a technology *can* be developed should be taken seriously, it is necessary to consider the technology in terms of the time scale to introduction, the complexity of the proposed system, the costs involved, the uncertainties in the process, and the need for the product. The studies made it clear that transmutation by fusion neutrons *is not a near-term option* for the disposal of radioactive wastes. It can only be considered a possible candidate for second-generation fission waste management schemes.

Ultimate disposal of radioactive wastes in geologic formation appears to be the most feasible waste management technique at this time. This conclusion is based on the technique's perceived effectiveness, its economics, and the short time required for its introduction. Geologic storage, however, is based on isolation of the radioactive wastes from the environment for hundreds of years, and therefore it is difficult to "prove" in a relatively short period that it is in fact an ultimate disposal technique. But we do have time to verify our choice of geologic formation for terminal storage. If we allow a 10-year cooling period for fission wastes prior to separation and transmutation, 60% of the wastes generated up to the year 2000 will not be ready for further processing until after that year. If for any reason our perception of the solution to the ultimate disposal problem has changed by that time, another option is available. The copious supply of 14-MeV neutrons from fusion can transmute the radioactive wastes; thus, fusion can provide society with a backup technology for an ultimate disposal method, should one be needed. *Program Manager: William Gough*

Figure 3 The decay rate of spent fission fuel is greatly accelerated by transmutation.



THERMAL-MECHANICAL ENERGY STORAGE

The only technical option an electric utility has for the storage of energy is conventional pumped hydro. However for many utilities a lack of suitable sites, combined with licensing and regulatory delays, has virtually eliminated this option. The Energy Storage Assessment Study, carried out by Public Service Electric and Gas of New Jersey for EPRI and ERDA, concluded that the only other energy storage options that clearly are technically and economically feasible for the near term are compressed-air storage (CAS), underground pumped hydro (UPH), and sensible-heat thermal energy storage (SHTES). The major obstacle to broad utility acceptance of these storage methods is the lack of the first commercial plant.

Two important objectives of the thermal-mechanical energy storage (TMES) subprogram are (1) to help overcome that obstacle through a major projects effort addressing CAS, UPH, and SHTES, and (2) to explore advanced TMES concepts and to support the major projects effort. These objectives are being pursued within a supporting R&D effort. Economic projections place flywheels (described below) and superconducting magnetic energy storage (SMES) in clearly uncompetitive positions relative to other storage technologies.

Major Projects

It has been conservatively estimated that 5% of the energy produced for load in the year 2000 could be provided from energy storage or load management or a combination of both. If an assumption is made that half of this 5% comes from energy storage and half from load management, the oil savings attributable to thermal-mechanical storage technologies could amount to 440,000 bbl/d.

Since CAS and UPH both require favorable geology (aquifer, hard rock, salt), as well as several of the most promising SHTES systems, are there geologic constraints precluding 40 GW by the year 2000? Estimates of suitable geology, combined with major load centers, show roughly 30% of the U.S. utilities (on a peak MW basis) as having access to *any* of the three geologies. This is 8–10 times the TMES capacity estimated previously; so these technologies are not site-limited.

The real limitation will be construction time, as shown by the following estimates of such time and of the dates of the first U.S. demonstration and commercial plants for these technologies:

	Construction Time (yr)	*First Demo Unit*	*First Commercial Unit*
CAS	4–7	1983	1986
UPH	5–10	1985	1988
SHTES	3–7	1982	1985

While several utilities have initiated studies of their own at specific sites, the uncertainties associated with such subterranean factors as geology and excavation costs, inherent hardware uncertainties associated with a first-of-a-kind facility, and uncertainties associated with regulatory and environmental approvals have, so far, been a major barrier to moving any of those options forward.

Major technical uncertainties relative to UPH include effects of pressure/temperature cycling on rock formation, reduction of construction time, accelerated shaft-sinking techniques, improved system-planning methods, and development of higher-head, single-lift, reversible pump turbines. The most important constraint on UPH is the construction time.

An important point regarding first-generation, or near-term, CAS systems is that these systems will require some firing with oil, although at a reduced level ($\frac{1}{3}$ to $\frac{1}{2}$, based on total energy supplied by the CAS system) from that required by a simple-cycle gas turbine. Technical questions requiring investigation include the change of the host formation (aquifer, salt, rock) properties in time with pressure/temperature cycling, increased compressor unit size, turbine and system design to utilize air pressures up to 100 atm, and impact on turbine design of mineral carry-over.

SHTES systems potentially feasible for the near term include hot-oil storage, feedwater storage below ground, and steam storage below or above ground. SHTES utilizing storage vessels is attractive because of its greatly reduced siting limitations relative to CAS or UPH. SHTES also offers the potential for retrofit applications. Higher storage efficiencies are possible with TES, since an intermediate conversion of thermal energy to electricity is eliminated.

Major technical uncertainties include stability of oil, heat loss to ground, pressure vessel design, and system integration. The greatest obstacle to SHTES is the fact that the system requires integration with a specific baseload plant instead of with the utility system.

Feasibility studies on each of the near-term systems have been carried out. One such study—Design for a Pilot/Demonstration Compressed Air Storage Facility Employing a Solution Mined Salt Cavern—is being conducted for EPRI by General Electric Corporate Research and Development. The study is intended to complement similar ones done by General Electric for ERDA on compressed-air storage in aquifers and compressed-air storage in conventionally mined hard rock caverns.

The feasibility studies have identified various technological problems, already discussed, and have concluded that before real progress toward commercialization can be realized, those technological issues must be addressed in a site-specific, utility-specific study at the level of a preliminary engineering design. Such a preliminary design study can help resolve the technological issues that have so far prevented any utility from taking a lead in the development of the energy storage technologies. If the study produces satisfactory results, it is anticipated that EPRI could set priorities for any R&D required to minimize technological uncertainties and that a participating utility could assemble the information required for the detailed design of a demonstration-scale storage project. Further, a broad cross section of EPRI members will gain an insight into the methodology required in establishing the technical and economic feasibility of a technology with some site-related aspects.

A list of utilities has been drawn up, including EPRI members and nonmembers, both public and private, interested in participating in a preliminary design activity. EPRI and ERDA will be jointly issuing a request for proposals this summer. Utility-led contract teams will be selected on a competitive basis.

Supporting R&D

In the supporting R&D area, small-scale projects will be initiated or continued for the investigation of advanced CAS, latent heat TES, and R&D as identified from the major projects. Second-generation, or advanced, CAS systems have as their objective operation at higher pressures with no oil. Major technical uncertainties include development of high-pressure, high-temperature heat exchangers, integration of CAS systems with gasification or liquefaction plants, development of coal-fired heat exchangers, and integration of CAS with thermal storage.

Latent heat TES systems still face more fundamental problems of storage material stability under cycling, heat exchanger material compatibility with heat of fusion material, and heat transfer at a moving phase boundary. Latent heat TES is being investigated as part of a project being carried out by Boeing Engineering and Construction. This project, a cooperative EPRI/ERDA research program, was initiated to expand the analytic base for high-temperature TES concepts and to enhance the technical base and concentrated design work of a current EPRI study on solar-thermal power generation. Two advanced technology TES systems, a phase-change energy storage system and a reverse thermochemical reaction energy storage system, are to be investigated in depth as part of this research program, and one near-term (sensible-heat) technology TES system is to be carried along as a benchmark.

Preliminary results show that direct storage of high-temperature thermal energy for the gas-cooled solar power plant is technically feasible. Technology development favors the sensible-heat device, cost considerations favor the phase-change device, and operational flexibility favors the thermochemical system. The ERDA-funded portion of the work will expand these studies for more detailed technical and economic trade-offs.

Flywheels

In June 1974 a project called Development of High-Density Inertial Energy Storage was begun. Carried out for EPRI by Wm. Brobeck and Associates in Berkeley, the project had as its objective determining key mechanical characteristics of multi-ring, fiber composite flywheels, as suggested by Post and Post in their article entitled "Flywheels," in *Scientific American,* December 1973.

The first year of the project was spent constructing the test facility and designing, constructing, and testing several two-ring fiber composite flywheels. Funds were provided for a second year (1975) to allow design, construction, and testing of several five-ring fiber composite flywheels to speeds of 22,000 rpm, the maximum capability of the test facility. Because of repeated experimental setbacks attributable to balancing the multicomponent system, no tests were run on a five-ring system.

Paralleling that experimental study were two broader studies. Besides the Energy Storage Assessment being carried out for EPRI and ERDA by Public Service Electric and Gas of New Jersey, Rockwell International was conducting a flywheel feasibility study for ERDA. These studies concluded that for near-term electric utility application a realistic cost estimate for a flywheel system would be $80/kW for the power-related costs and $200/kWh for the energy-related costs.

In order to establish technical and economic goals for the flywheel program, ongoing cost and design studies for utility lead-acid battery systems were used. Flywheels and batteries both possess characteristics of site flexibility and modularity, thus lending themselves to dispersed, rather than central, locations. In addition, these lead-acid cost and design studies are aimed at a utility system for the early 1980s. The cost and design studies estimate $80/kW and $100/kWh for utility lead-acid battery systems. Even at that cost the lead-acid battery did not emerge from the Public Service Study as a clear winner for the near term.

The combination of these experimental and economic findings has led to a decision by EPRI to discontinue support for a flywheel program until such time as the facts warrant a reexamination of the flywheel as a feasible energy storage system for electric utilities. *Program Manager: John Maulbetsch*

SOLAR HEATING AND COOLING OF BUILDINGS

EPRI's program in solar heating and cooling of buildings (SHACOB) has two basic objectives: placing SHACOB applications in perspective for the electric utility industry and ensuring that utility interests and requirements are integrated into the federal solar energy program.

With more electric power used for heating and cooling in new construction after the mid-1980s, utilities will have to be aware of the potential impacts of solar-assisted heating and cooling systems. The electric utility industry must accept a leading role in the development, demonstration, and promotion of those systems that show potential. Conversely, utilities must be aware of the adverse impact of various systems and operational modes in order to establish rates that reflect the cost of providing service to customers utilizing such systems. (Implementation of demand charge rates, such as that recently put into effect in Colorado, is an example of a response to the introduction of systems that pose negative impact on load management efforts and offer no capacity credit.)

Preferred Systems

The content and schedule of EPRI's solar heating and cooling program complement the federal government's development and demonstration program. The federal program is focused on the displacement of energy, while the EPRI effort is characterized by an overall economic approach to energy management and utilization.

The EPRI program seeks to identify "preferred" solar heating and cooling systems. The definition and development of preferred systems require a step-by-step approach to energy management that recognizes that the residential or commercial load center must be viewed as an integral part of a utility system. The process leading the consumer to the most suitable heating, ventilation, and air conditioning (HVAC) system is as follows: (1) implementation of energy conservation in building design; (2) improvement of HVAC component and system design; (3) integration of energy storage and use of off-peak power; and (4) solar augmentation. At each step of the process all options must be weighed on an incremental basis, with initial and operating costs compared with the cost of energy saved.

A system satisfies the criteria of a preferred system if it minimizes consumer cost while providing potential for utility load management, and thereby capacity credit. The solar-assisted heat pump with integrated storage is one concept that satisfies the preferred system requirements and, indeed, has something for everybody. There is a net reduction in electric power requirements compared to those for electric resistance heating. Also, along with the trend toward all-electric construction, there is a displacement of scarce resources, such as oil and gas, by less-scarce nuclear and coal. Finally, through storage of off-peak power, load management can be affected, and if the storage capability is reliable, the system possesses capacity credit. The end result is better energy management and lower cost to the consumer.

There are three parts to the EPRI program for developing, demonstrating, and evaluating preferred SHACOB systems: (1) experimental projects for demonstrating residential and commercial SHACOB applications; (2) requirement definition and impact analyses to place the SHACOB applications in perspective for utility service areas; and (3) materials and component qualification to verify the lifetime and performance of components. In practice, projects in the three segments are interwoven and the development of the overall program is an evolutionary process.

Program Status

EPRI is supporting instrumentation and monitoring projects on four utility-sponsored experiments. The projects involve solar water heating, solar-assisted heat pumps in commercial and residential structures, and utilization of off-peak electrical power. Three additional projects have been submitted for approval by the EPRI Board of Directors. These projects have two objectives: to acquire and communicate information on instrumentation methodology and cost so the benefits of experience can be of assistance to other utilities planning demonstrations, and to obtain performance and cost data on specific system concepts and operating modes for inclusion in the overall experimental program and impact analyses. Attractive features of these projects include the cost-benefit in supplementing existing projects and the management assistance supplied by the sponsoring utilities.

In a more controlled and intensive experimental program, Arthur D. Little, Inc., has recently completed the preliminary design phase of a project to build 10 homes with preferred solar heating and cooling systems. The project is now in the detailed design phase for the 5 experimental homes that will be built in service areas of Long Island Lighting Company and of Public Service of New Mexico. After construction and checkout, a two-year monitoring program will be conducted to qualify performance for the various system options and operating modes. In a parallel effort a project has been recently initiated for design, installation, monitoring, and evaluation of from 5 to 10 SHAC systems for commercial buildings. This program will lag behind the residential program by about one year.

In order to test the methodology for describing "preferred" systems for Long Island and New Mexico, 14 additional utilities were selected for exercising the computer codes. A wide variety of service area requirements were introduced to ensure that the methodology had generality and wide geographic application. During the next phase of this project the computer program will be further exercised and refined, and a user's manual will be developed to simplify its utilization. When completed, the program will be available to utilities for evaluating solar heating and cooling systems in their specific service areas.

Aerospace Corporation is taking the SHACOB systems defined in experimental projects and determining the requirements and impacts such systems can have on utility operations (RP553). The study will cover the entire United States and extend systems studies to evaluate regional and national impact as well. As projects progress, the feedback process between impact analyses and experimental efforts will be continuous.

Experience shows that the key to economic viability for SHACOB systems rests, first, on the recognition of life-cycle costing as a proper basis for evaluation and, second, on the development of consumer confidence in system and component performance and lifetimes. SHACOB systems must demonstrate reliable operation long enough to justify the necessary initial capital investment. Understanding of overall economics, then, demands verification of system reliability and component longevity. In response to this need a project, which has been recently completed (RP550), outlines the options and costs to implement a program of solar materials and components testing. The study results are presently under utility advisory review. Following reviewer input, a material and component test program will be defined and initiated.

Recognizing that in the 1985–1990 time period (when SHACOB systems may achieve commercial viability) the alternative energy source for climate control will be electricity, and confident that in the long run the marketplace will prevail, it will be the "preferred" systems that will make most sense to consumers and utilities. Solar-assisted systems represent one set of options, and these must be considered in conjunction with energy conservation in design, utility needs, alternative HVAC components, and storage in overall energy utilization context. *Project Manager: John E. Cummings*

R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

LIGHT WATER REACTOR FUEL ROD PERFORMANCE PROGRAM

The Light Water Reactor (LWR) Fuel Rod Performance Program integrates 19 research projects that range in scope from laboratory tests of Zircaloy cladding tube behavior under hypothetical LOCA conditions (*1*) to large-scale testing of prototypic fuel assemblies in operating power reactors. This program has been assembled over the last two years; a program planning document was issued as EPRI Special Report SR-25 in December 1975 (*2*).

Fuel performance limitations significantly affect plant availability, and fuel reliability affects fuel cost and, indirectly, plant maintenance cost and time. The overall goal of the LWR Fuel Rod Performance Program is twofold: (1) to develop both the data base and the analytic tools that can be used to increase plant availability and (2) to improve fuel rod reliability. Although LWR fuel performance is generally very good, the interactions between the fuel pellet and cladding tube can result in fuel distortion or leakage on rapid power increase. Fuel vendors have recommended limitations on the rate of power increases, both overall and in local power shaping. This remedy, while workable, is expensive in terms of lost plant output from the partial load operation during slow increase period (where otherwise the plant could be providing full power). This loss of output is estimated to range from 3 to 6% with fuels manufactured prior to 1974 (*3*). Because of basic assembly design changes that were recently introduced, the effect of these restrictions on future fuel manufacture and future plants is expected to be reduced to less than 2%. There is still a need for further improvement, since a 2% gain in the average capacity factor of nuclear plants represents $2 million to $4 million per reactor in annual replacement fuel costs.

A near-term goal of this program is to gain a sufficiently detailed understanding of the various interactions within the fuel rod to permit basic design modifications and/or changes in reactor operating strategies so as to do away with limitations such as those described above. Another objective is to make it possible to define and calculate steady-state fuel operating

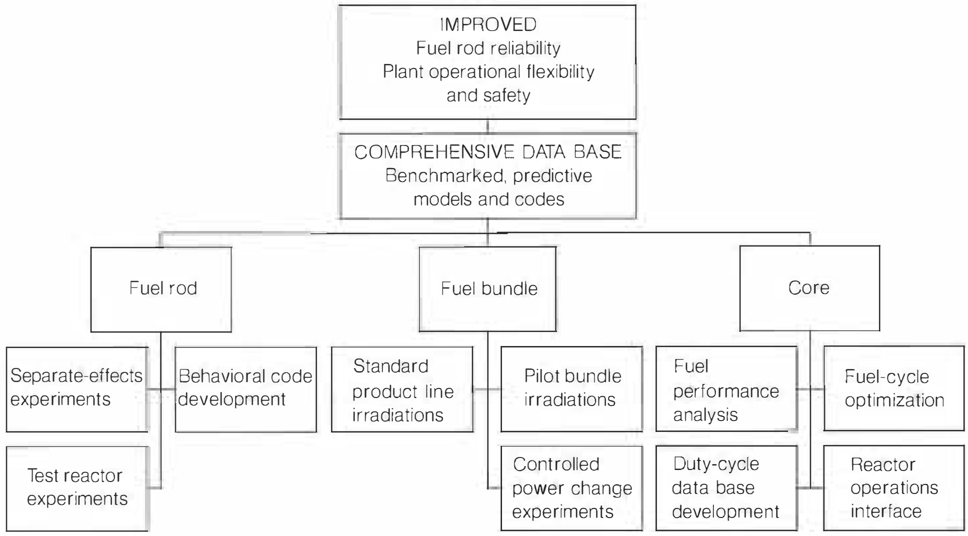
Table 1

CURRENT FUEL PERFORMANCE PROJECT LISTING*

Fuel Rod	
RP249	Zircaloy-Steam Oxidation Kinetics (WPI)
RP251	EPRI/MPC Zircaloy-LOCA Project (BNWL)
RP455	EPRI/NASA Cooperative Project on Zircaloy Stress Corrosion Cracking (SRI, NASA-Ames, MIT)
RP456	Zircaloy Inelastic Deformation Study (GE, SU, MIT)
RP396	Plutonia Fuel Study (BNWL)
RP508	UO_2 Cracking and Relocation Study (ANL)
RP216	Halden Reactor Program Membership
RP355	EPRI Test Program in Halden—IFA 435
RP507	Studsvik BWR Overpower Ramp Test (AB Atomenergi)
RP397	Fuel Rod Code Evaluation (CE, O'Donnell, SAI, Stoller)
RP829†	Determination and Microscopic Study of Incipient Defects in Irradiated Power Reactor Fuel Rods (BMI, GE, W, ANL)
Fuel Bundle	
RP510†	EPRI/GE Cooperative Project on BWR Fuel Performance (GE)
RP586	EPRI/CE Cooperative Project on PWR Fuel Performance (CE)
RP611	EPRI/W Cooperative Project on PWR Fuel Performance (W)
RP711	EPRI/B&W Cooperative Project on PWR Fuel Performance (B&W)
RP72-2	Plutonium Utilization in BWRs (GE)
RP306	EPRI/Exxon Project on Multiple Plutonium Recycle (Exxon)
RP497	Quad Cities-1 Plutonium Recycle Nuclear and Fuel Performance Measurements (GE)
Core	
RP509	Fuel Performance Evaluation (Scandpower)

*Projects are listed by title, RP number, and contractor(s). This information should be included in requests to EPRI for reports or additional data.
†Under negotiation.

Figure 1 EPRI fuel rod performance program.



conditions and energy content more reliably so as to provide a firmer basis for LOCA (loss-of-coolant accident) calculations. A longer-term incentive is that more quantitative understanding and control of interaction phenomena may eventually permit the use of higher linear heat generation ratings in the fuel. For example, an increase in the average linear heat generation rate from about 6 to about 8 kW/ft would permit increasing reactor output from 1300 to 1700 MWe without changing the size of the vessel (*3*). In addition, the resulting higher specific power (kilowatts per kilogram of fuel) would have a small but beneficial effect on the uranium supply required to provide inventory for a growing nuclear economy.

The Fuel Rod Performance Program, which consists of related research at the fuel rod, fuel bundle, and whole core levels (Figure 1), is limited to Zircaloy clad fuel. The three project areas are briefly described below. A current project listing is given in Table 1.

Fuel Rod Studies

Fuel rod studies are directed at providing a fundamental understanding of the interactions between the component materials (i.e., the fuel pellet and Zircaloy cladding tube) and the reactor environment, which can result in fuel distortions and eventually in failure. Primary emphasis is on pellet-cladding interactions that can lead to initiation and growth of cracks at the ID of the cladding. This work is expected to develop a predictive capability that will include the effects of design, operating, and materials parameters.

In addition to undertaking studies of materials limitations during nominal life operation, it is also necessary to obtain a more detailed understanding of phenomena occurring under hypothetical accident conditions. Uncertainties in both fuel and cladding properties have led to limitations on normal reactor operations, which sometimes result in derating of the reactor. The program here serves to supplement the larger federally sponsored program.

Research and development work in this project area logically falls into three subgroupings (Figure 1). Separate-effects experiments are underway to determine key parameters controlling the behavior of fuel (RP396 and RP508) and cladding (RP455 and RP456) under normal operating conditions. A material data base for hypothetical accident analyses (e.g., LOCA) is being developed under RP249 and RP251.

Test reactor experiments in the Halden (RP216 and RP355) and Studsvik R2 (RP507) test reactors are designed to study integral fuel rod behavior under conditions similar to those in power reactors, but with elaborate instrumentation to provide on-line monitoring of such parameters as cladding dimensional changes and fuel temperatures.

As might be expected, a large number of variables, both material- and environment-related, enter into fuel rod performance. Experience has shown that only a computer code is capable of handling these data in such an interactive manner that the key controlling variables can be determined. Thus, the fuel rod code is conventionally used as a mechanistic integrator of fundamental materials behavior and predicts the manifestations of different combinations of properties and environments. RP397 is conducting an evaluation of currently available fuel rod codes for application to LWR fuel performance. This study, considered a prerequisite for further development work, will shed light on the need for improvements in present fuel and cladding models and will guide future efforts in new model development.

Fuel Bundle Studies

All fuel vendors have with their utility customers some type of cooperative program of nuclear fuel performance surveillance. These individual data banks are company-proprietary. Only a limited part of the in-depth data on commercial fuel performance appears in the open literature. The fuel performance surveillance programs with fuel vendors will substantially increase the amount of detailed fuel performance data from large operating BWRs and PWRs that is available to the utilities. As Table 1 shows, EPRI has contracts with every major first-core or reload fuel vendor in the United States.

The gathering of detailed fuel rod performance data under prototypic conditions is essential input for the improvement of LWR fuel rod performance and reliability. The major objectives of this project area are (1) to provide benchmark data for the modeling of LWR fuel rod and fuel assembly performance; (2) to provide separate-effects data to link with laboratory and test reactor data; (3) to provide extensive high-quality data on fuel performance to help permit the identification of infrequent operative failure mechanisms; and (4) to demonstrate the reliability and safety of improved fuel designs or concepts.

The bundle projects are divided into standard product line bundle irradiations, where the emphasis is on obtaining statistics from large numbers of rods, and pilot bundle irradiations, in which fuel and cladding variables are introduced into special bundles for the purpose of studying separate effects under power reactor conditions. The latter includes irradiation of plutonium recycle fuel (*4*). All the projects have in common the following distinct phases of work: (1) detailed preirradiation characterization of the fuel rods and assemblies; (2) operational surveillance, which is conducted on the basis of reactor performance rather than at a set frequency; (3) extensive interim poolside examinations; (4) optional comprehensive postirradiation examination; and (5) correlation of observations with design and with operating history.

Core Studies

An eventual application of the fuel rod and bundle studies described here is to refine current fuel management patterns, taking fuel rod limitations into account quantitatively. The probability of fuel distortion or cracking should be included as a boundary condition in the fuel management models.

This program area is still in the preliminary planning stage. Four important aspects that will receive detailed examination have been identified:

- Fuel performance analysis
- Development of a duty-cycle data base
- Fuel-cycle optimization
- Interface with reactor operations

It is not practical to account for the behavior of 30,000–50,000 fuel rods in an LWR core at the level of detail afforded by an integral fuel rod model, due to excessive computer time requirements. Further, the ability of such codes to predict failure is currently not well demonstrated. At the other extreme, mechanism-independent, purely statistical approaches, while requiring considerably less computer time, appear to offer minimal guidance to the purchaser or operator of nuclear fuel. A simplified mechanistic model, calibrated to large bodies of power reactor data and offering estimates of failure probabilities based on operating history, appears to be the best vehicle for satisfying this analytic need. This is what is meant by fuel performance analysis. RP509 is an initial effort to assess the state of the art. To use this tool effectively, detailed information on the power and burnup history of individual rods must be obtained and stored. The development of this duty-cycle data base will involve extensive use of the process computer; in addition, there is usually an auxiliary computer to store all the bundle power history data and to convert the bundle data to individual rod data. Program projects are currently examining the state of the art with respect to duty-cycle data collection in bundle projects. A related effort, RP618, in the Safety and Analysis Department, is currently surveying existing process computer facilities and capabilities.

Once the power tracking and the predictive capability are developed, they can be incorporated into an operating tool for the guidance of reactor operators. This logic system would evaluate the change in local power shapes for any maneuver and the change in distortion or failure probability after the intended maneuver. Thus, core power maneuvers could be chosen that would achieve maximum energy output and at the same time assure an acceptably low fuel failure rate.

Future Emphasis

The foregoing is a brief overview of the structure of the EPRI LWR Fuel Rod Performance Program by project area. Future project starts will emphasize power reactor fuel studies in which improved fuel and/or assembly designs and revised operational strategies and/or fuel performance evaluation tools are evaluated. *Program Managers: J. T. A. Roberts, F. E. Gelhaus*

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4. "Nuclear Power Division Report," EPRI JOURNAL, No. 3 (April 1976) p. 32.

THERMODYNAMICS AND CORROSION

Corrosion in the steam-generating loops of pressurized water reactors, as well as in the primary loops of boiling water reactors, occurs just frequently enough to be a serious problem that requires a solution but not so frequently as to jeopardize the safety of the plants. The corrosion reaction is in effect controlled by a series of conditions, each of which must be satisfied before corrosion damage actually occurs.

The first such condition can be stated as a question: Can the metal react with water or with constituents in the water to form one of the dissolved species of the metal—usually an electrically charged particle known as an ion? Thermodynamics provides an answer to this question, as long as certain measurements have been made of the species involved in the reaction. The most fundamental of these measurements is the amount of energy required to raise the temperature of the species from some common reference temperature to the service temperature of the reactor loop. The tendency of the corrosion reaction to actually proceed is related to two major thermodynamic driving forces: (1) the heat given off when the reaction proceeds (the larger the amount of heat given off, generally the greater the tendency of the reaction to proceed); and (2) an increase in entropy of the products of the reaction relative to the reactants (entropy being related to the degree of disorderedness of the molecules: the greater the amount of increase in disorderedness in going from the reactants to the products, the greater the tendency of the reaction to proceed).

Both the entropy and the heat content of all species can be measured in a laboratory calorimeter, provided this is capable of reaching the temperature of interest. The temperature of interest in water-cooled reactors is 25°C to about 350°C. Because of the simplicity of operating calorimeters with water below 100°C, existing data are mostly for that region of temperature. For solid species, accurate data exist over the entire temperature range of interest. It is for the dissolved ions in aqueous solution at temperatures above 100°C that very few data exist. This is precisely where we wish to have thermal data for predicting the thermodynamic driving force of the corrosion chemical reactions.

EPRI has established a project (RP311-2) to perform calorimetric studies and to determine the thermodynamic properties of many common ions, including common condenser inleakage impurity ions in water solution at temperatures to 300°C. Because the heat measurements do not involve large quantities of heat, the calorimetric measurements must be sensitive to temperature changes of no more than a few tens of microdegrees centrigrade and must be performed in high-pressure autoclaves capable of withstanding over 1000 psi. (Professor James Cobble of San Diego State University has developed and used this calorimetric method; the EPRI program is under his direction.)

This program has been active for about 18 months and is already producing useful thermodynamic data for the cobaltous ion, Co^{+2}. Since the hydrogen ion concentration is so important to the corrosion process, additional data have been generated, using thermodynamic theory, for extrapolating measurements from room temperature up to higher operating temperatures in order to obtain the dissociation coefficients of the common amines used to control pH. These theoretical results have shown the limitations for pH control of cyclohexylamine and morpholine, as well as possible improvements that could be made by using piperidine and pyrrolidine. For example, at any given concentration of piperidine the high-temperature pH is 0.2 pH units higher than for a similar concentration of cyclohexylamine and 0.55 pH units higher than for an identical concentration of morpholine.

There are many species of interest even in the current reactors using only the iron-chromium-nickel alloys. One feature of this program tending to shortcut some of the total volume of measurements required is the active use of correlation and extrapolation techniques developed over the past two decades by Dr. Cobble. Thus, a few key measurements at specific temperatures permit the interpolation and extrapolation of a much wider range of conditions than have actually been measured. The more the coverage of the total matrix of conditions and ionic species with actual reliable experimental data is increased, the more accurate will be these extrapolations.

It is not always possible to operate a nuclear power plant in a regime in which the corrosion reactions are thermodynamically impossible. However, this program will give us detailed information on just where such regions and conditions are, so that we might approach them somewhat more closely than at present. *Project Manager: Thomas O. Passell*

RADIATION SURVEY OF NUCLEAR POWER PLANTS

Occupational radiation exposure in operating nuclear power plants is obviously of great concern to electric utility companies. One of the most influential factors in occupational exposure is the radiation fields, especially those associated with the reactor coolant system (RCS). The development of techniques of radiation control that retard the rate of buildup of these

Figure 2 BWR recirculation piping shutdown radiation levels, with data from seven reactors over four effective full power years, show the linear increase in the level as generation increases.

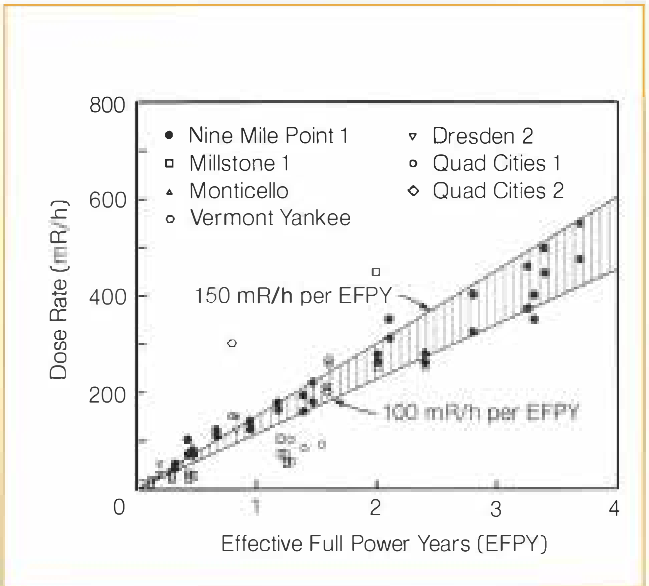
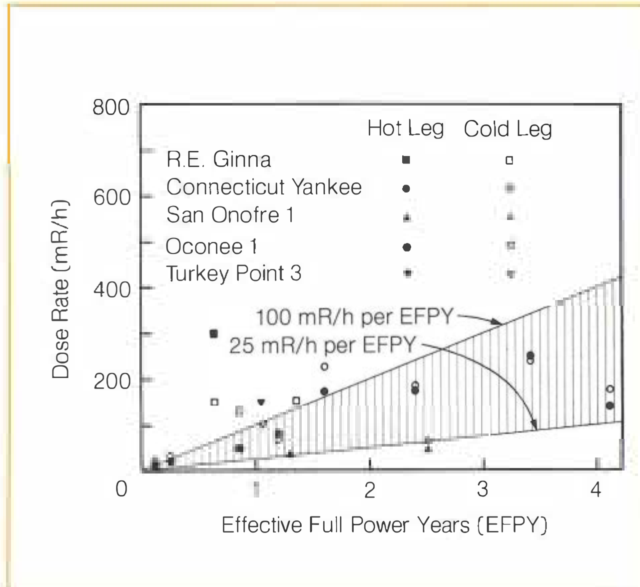


Figure 3 PWR primary system piping shutdown radiation levels, with data from five plants, also display a linear increase with time. The bandwidth is arbitrary, shown only to guide the eye.



radiation fields would simultaneously increase plant availability by increasing plant personnel availability and serve to reduce the cumulative radiation exposure to plant personnel.

As a first step toward establishing a research program on radiation control techniques, a survey of selected operating nuclear power plants was conducted by Nuclear Water and Waste Technology Inc. (NWWT) for EPRI. Twenty-three plants (10 PWR and 13 BWR), each with at least two years' operating experience, were visited to obtain relevant plant data and to discuss with plant personnel design and operating influences on radiation levels.

Efforts to define the trends of shutdown radiation levels at various locations around the RCS were complicated by the lack of radiation-field data taken at well-defined locations through the use of uniform techniques to allow for comparison among plants. Radiation-field data used here are associated with particular locations around the RCS and came from plants for which the effect of plant design and operations on radiation fields is considered reasonably typical.

For BWR plants, contact radiation fields on recirculation piping are shown in Figure 2. Radiation fields are seen as increasing linearly with energy generation. The shaded area, drawn as a guide to the eye, suggests that these radiation fields are increasing 100–150 mR/h for each full power year of operation. Note that the trend is greatly influenced by the amount of data from one plant, Nine Mile Point.

These are other conclusions derived from the survey of BWR plants:

- Activated corrosion products, primarily Co-60, are the principal contributors to the radiation fields.

- Prediction of the trends of these radiation levels was derived from two models, which show radiation levels increasing linearly with power generation and a constant deposition rate of Co-60 on pipe surfaces during power generation. These models predict recirculation piping radiation fields, respectively, of about 1200 and 1000 mR/h at 10 full power years and 1900 and 1200 mR/h at 15 full power years.

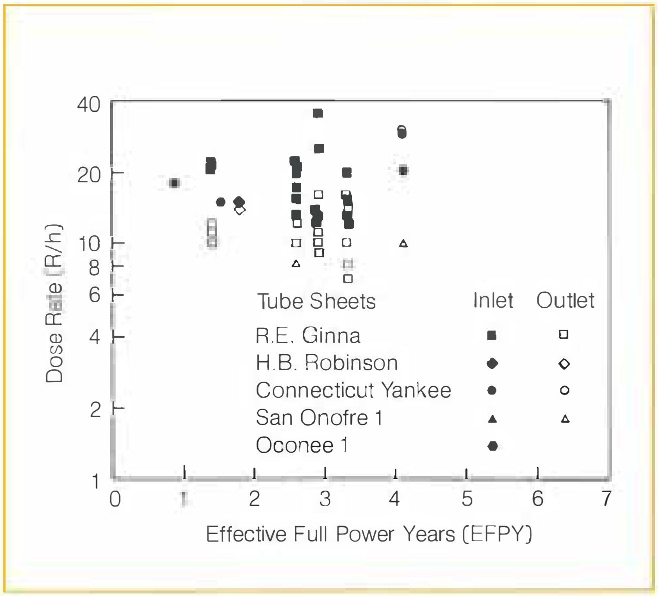
For PWR plants, radiation fields appear to be increasing linearly, as shown in Figure 3. A trend is more difficult to define for the PWR plants. The shaded area, again drawn as a guide to the eye, indicates this difficulty by the broad band of selected slopes, from 25 to 100 mR/h per full power year.

Steam generator tube sheet radiation levels rise rapidly to an equilibrium level of 10,000 to 30,000 mR/h, as shown in Figure 4. These have had significant effect on occupational exposure, due to their magnitude and the inspection and maintenance requirements on PWR steam generator tubes.

These additional conclusions were derived from the survey of PWR plants:

- Activated corrosion products are, again, the principal con-

Figure 4 Shutdown radiation levels for the steam generator tube sheets of the same five reactors as in Figure 3 appear to rise to an equilibrium level.



tributors to the radiation fields, with Co-58 and Co-60 sharing dominance.

□ Extrapolations predict steam generator tube sheet fields remaining at 10,000 to 30,000 mR/h and primary coolant piping fields stabilizing at 100 to 500 mR/h at 10 to 15 full power years of operation.

The need for further work is evident. Better definition of radiation-field trends and the improvement of the understanding of the mechanisms of radiation buildup will result in better prediction of radiation fields into the future. The development of techniques and equipment that can be used to improve control over radiation fields will result in reduction of the rate of buildup of these fields. These needs are cited in the report on the radiation survey (*1*) and in the proceedings of a recent workshop on system contamination (*2*). They are among the top priorities for research programs in the Engineering and Operations Department. *Project Managers: Robert A. Shaw, Dale L. Uhl*

References

1. *Primary System Shutdown Radiation Levels at Nuclear Power Generating Stations.* Palo Alto, Calif.: Electric Power Research Institute (1975), EPRI 404-2.

2. D. L. Uhl and R. A. Shaw. *Proceedings of the System Contamination Workshop.* Palo Alto, Calif.: Electric Power Research Institute, March 1976.

EPRI AND ERDA JOIN IN SPONSORING FUEL CELL SEMINAR

Some of the key supporters of U.S. fuel cell development at a recent seminar on the technology sponsored by ERDA and EPRI. Left to right: John Belding, director of ERDA's Energy Conversion Division; Robert Bell, director of research, Consolidated Edison Co. of New York; Fritz Kalhammer, director of EPRI's Energy Management and Utilization Technology Department; L. R. Lawrence, ERDA's manager for fuel cells; and Arnold Fickett, EPRI Fuel Cell Program manager.

The nationwide campaign to establish the fuel cell as a viable commercial electric power generator for utilities, industry, residences, and transport was placed in sharper focus at a recent three-day fuel cell seminar held in Palo Alto, California.

The first joint EPRI–ERDA fuel cell seminar brought together 100 delegates representing most of the country's major fuel cell development programs. The state of the art of fuel cell technology was assessed through a review of programs sponsored by EPRI, ERDA, the U.S. Army, individual gas and electric utilities, and other sectors of industry. Arnold Fickett of EPRI and L. R. Lawrence of ERDA are the fuel cell program managers for the cosponsoring organizations.

Lawrence predicted at the seminar that there will be a large number of fuel cell applications in the future: "The first major impact of fuel cell technology is expected in the early 1980s when first-generation phosphoric acid systems are incorporated into utility systems, replacing antiquated oil-burning steam plants which presently exist in many high-environmental-impact locations.

"Environmentally, fuel cell systems are completely acceptable and can be sited in residential or high-population areas, resulting in significantly reduced electric transmission losses."

According to Lawrence, "The American Public Power Association and the National Rural Electric Cooperative Association consider fuel cell systems an especially important option for the 5–27 MW range of small municipalities and rural communities.

"In the next 10 years, fuel cell technology promises to have systems which will convert oil or coal to electricity with a 40 to 50% efficiency. Scenarios can be drawn of fuel cells installed for baseload throughout the country by the year 2000."

Robert A. Bell, director of research for Consolidated Edison Company of New York, recommended a bold strategy for fuel cell development in his keynote address. "We should not wait for the final configuration of the fuel cell power plant before we go to demonstration. We should follow the pattern of Edison and establish the credibility of the technology early—establish a technology base on which we can build with further improvements. The fuel cell power plant is an important option for urban electric utilities—we need it now. An aggressive demonstration program should be the cornerstone of the nation's fuel cell development plan."

William Wood, power supply planning engineer for Public Service Electric and Gas Company of New Jersey, was another seminar speaker. He told the delegates that "fuel cells at $200 to $250 per kW capital cost, and 38 to 45% efficiencies, will have a significant market penetration, primarily for intermediate power generation. They will be constrained only by the future cost and availability of liquid and gaseous utility fuels."

Supplementary Environmental Controls

Although operating supplementary environmental control systems (SECS) have been shown to be a reliable and cost-effective means of meeting current air quality standards, their use is apparently limited (1) to transitional periods for meeting federal air quality standards and (2) to supplementing continuous air pollution emission control procedures when satisfying state standards or when continuous controls are inadequate or out of operation.

These were among the conclusions reached at a recent workshop on the subject sponsored by the Environmental Assessment Department. The workshop, attended by representatives from government agencies, industry, utilities, and universities, was coordinated by TRC, the Research Corporation of New England, and was held in Hartford, Connecticut.

SECS are emission control systems in which the quantity of emissions is varied according to the dispersion characteristics of the atmosphere. The systems, which include fuel switching and load shifting, utilize the atmosphere for waste disposal, while complying with ambient air quality standards. With SECS, smaller quantities of pollutants are emitted from a power plant during periods of poor atmospheric dispersion, while emissions are increased during periods of considerable atmospheric dispersion. Although the systems can reduce overall air pollution control costs to the utility industry, federal regulations are currently interpreted to prohibit their use as a permanent air pollution control strategy.

"One of the principal reasons for holding the workshop was to solicit suggestions for future EPRI research in the area of SECS," said Project Manager Ronald Wyzga. "It was felt that the highest research priority should be directed toward the use of SECS as a transitional control strategy and/or as a supplement to continuous emission control systems.

"With regard to the former, work is needed to specify and study SECS that would provide an optimum transition to continuous control procedures. With respect to supplementary uses of SECS, designs which include episode control procedures should be studied," Wyzga stated, adding that future work on SECS might include regional and systems approaches that consider the several emissions sources in a particular region.

The participants concurred that research efforts by the Environmental Assessment Department on the effects, conversion, and transport mechanism of air pollutants are important in providing a larger information base for future regulation-making. A basic question is whether the SECS will reduce the total public health effect or merely redistribute it. With more information, the total environmental impacts of SECS could be better evaluated and their role in air pollution control possibly reconsidered.

EPA's Herschel Slater (left) presents the regulatory point of view on supplementary environmental control systems to Daniel Hedden, Northeast Utilities Co., and E. M. Ilgenfritz, Dow Chemical Co., during a recent EPRI workshop.

Nuclear Pressure Vessel Safety

E. K. Lynn of the Nuclear Regulatory Commission gives a synopsis of pressure-boundary-related programs at NRC's Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Members of the EPRI-sponsored Nuclear Pressure Vessel Study Group met on June 22 and 23 to discuss research efforts in the United States and abroad to ensure the safety of nuclear reactor pressure vessels and piping. Nearly 30 experts in the field of pressure vessel safety from the U.S., Japan, France, and Great Britain participated in the meeting held at EPRI.

"A pressure vessel failure is a low probability–high consequence event," stated Karl Stahlkopf, Pressure Vessel Technology program manager. "There has never been a failure in the entire history of the industry. Research is being carried out in the U.S. and abroad to ensure the continuing safety and integrity of nuclear pressure boundary systems, and to improve the reliability and availability of existing systems through more accurate materials characterization and improved analytical procedures."

The Nuclear Pressure Vessel Study Group meets at six-month intervals, helping to guide EPRI's research efforts in this area.

Soviet Engineers Visit EPRI

Three Soviet experts in the field of controlling NO_x emissions from thermal power plants met at EPRI on June 18 to exchange technical information with staff in EPRI's Air Quality Control Program.

The specialists were members of the Soviet delegation to the Gaseous Emissions Subcommittee of the U.S./USSR Joint Project Group on Design and Operation of Air Pollution Reduction and Waste Disposal Systems for Thermal Power Plants. Their visit to the U.S. included meetings with energy specialists at Edison Electric Institute, the U.S. Environmental Protection Agency, the Southern California Air Pollution Control District, Southern California Edison Company's Redondo Generation Thermal Station, and the Tennessee Valley Authority.

Participants in the meetings discussed all technical phases of control of emissions of oxides from nitrogen, as well as areas and items of future cooperation.

George Hill, director of the EPRI Fossil Fuel Power Plants Department, briefs Soviet visitors to EPRI on the Institute's efforts to control NO_x emissions from thermal power plants.

"We discovered that the Soviets are tackling the problems along much the same lines as we are," stated Don Teixeira, project manager in EPRI's Air Quality Control Program, "even though it would appear that the U.S. is considerably ahead in technology development."

Another meeting of the Soviet-American committee is proposed for October 1976. Both sides will be striving to develop specific cooperative projects for approval at that time.

FBC Economics

A review of EPRI's fluidized-bed combustion (FBC) program was the focal point of a recent two-day meeting of equipment manufacturers, fluidization researchers, and the technical staff of the Fossil Fuel Power Plants Department.

The main topics examined were the hydrodynamics of fluidized beds, coal combustion and heat transfer, sulfur capture and waste handling, instrumentation and control, and commercial design of fluidized-bed boilers.

Project Manager Mike Maaghoul reports that from these sessions two important conclusions emerged. One is that additional research and development is required to reliably design a utility-size fluidized-bed boiler; the other concerns the possibility of improving FBC economics by regenerating the boiler's spent sorbent material.

The bed of an FBC boiler consists mainly of limestone, which reacts chemically with sulfur to form calcium sulfate. "The economic advantage of FBC boilers over conventional boilers is that desulfurization occurs in situ, without the need for postcombustion SO_2 control systems," Maaghoul says.

But what would the utility do with the calcium sulfate? "You have two choices: dispose or reuse," comments the EPRI project manager, adding that regeneration of calcium sulfate may be the better alternative.

Maaghoul remarks, "Due to diffusion limitations, only about one-third of the limestone reacts with the sulfur. The other two-thirds will continue to be wasted unless methods are developed for improving limestone utilization or for regenerating the calcium sulfate for recycling."

One of the main obstacles to designing and building a large commercial unit emphasized at this meeting is that there is not enough information on the design of the boiler's heat transfer tubes, and feeding and mixing phenomena in these units are not yet adequately understood.

According to Maaghoul, the above topics were discussed and either are now being examined in R&D projects or are likely to be examined next year under EPRI sponsorship. Maaghoul further reports that the meeting participants were optimistic that these problems could be resolved soon.

Coal-blending Seminar

Iowa Governor Robert D. Ray dicusses his state's coal research program at a recent EPRI/FEA seminar on coal blending and utilization in Des Moines.

Coal experts from federal, state, and local governments, as well as from industry and universities, participated in a June 16–17 seminar sponsored by the Federal Energy Administration and EPRI to examine the potential of mixing eastern and midwestern high-sulfur coals with western low-sulfur coals to produce environmentally acceptable fuels.

Although not a new technology, coal blending has recently gained attention as a way of meeting state emission standards. According to EPRI's Shelton Ehrlich, one of the key speakers at the Des Moines, Iowa, seminar, "Coal blending has the potential for allowing a utility to use some of the lower-cost, high-sulfur coals found in the East and Midwest. But while it may work for meeting state standards, it would not work for meeting federal standards."

In his speech, Ehrlich outlined some of the technical difficulties in blending coals. Specifically, he commented on problems in handling two or more separate coals, on the fact that western coals may easily ignite spontaneously, and on the inherent variability of coals, which makes blending an inexact art. He also remarked that pulverizing would be a problem and that precipitators may function inadequately when low-sulfur coals are used.

Ehrlich, program manager for fluidized combustion and coal cleaning, also cited the disadvantages of firing coal blends. "Two coals which individually would not result in slag, may, when fired together, cause slagging," he said. "Equally important, their combustion characteristics as a blend may be difficult to deduce from their individual characteristics."

Although there are many technical problems in blending coals, utilities have been employing this technology while working on other solutions. One of the presentations at the seminar was on two utility case studies, detailing their experience with coal blending. According to Ehrlich, a case history book on utility experience in blending coals may be undertaken jointly by EPRI and FEA as a result of the seminar.

Project Manager Thomas E. Browne of the EPRI Energy Systems, Environment, and Conservation Division also participated in the meeting. He described the work of the Energy Supply Studies Program in the area of coal supply economics.

Energy Exchange Agreements Signed

Two separate energy exchange agreements were recently negotiated between EPRI and the Federal Ministry for Research and Technology of the West German Federal Republic and Sweden's State Power Board.

Both agreements are for the exchange of energy information on research plans and results. The agreement with Germany is geared exclusively to research and development on the safety of nuclear power reactors.

The agreement with Sweden encompasses a broad range of energy research and development technologies, including nuclear power, electricity transmission, and efficient energy usage; it also provides for the temporary exchange of personnel. The State Power Board is responsible for Sweden's nationalized utilities.

Similar types of information exchange agreements, but of a more general nature, have been concluded with Great Britain's Central Electricity Generating Board and with Electricité de France.

Project Highlights

EPRI Negotiates 33 Contracts

No.	Title	Duration	Funding ($000)	Contractor/ EPRI Project Mgr.
Fossil Fuel and Advanced Systems Division				
RP531-2	A New Fluid Dynamic Collector Applicable to Electrostatic Precipitators: Proof-of-Concept Study	6 months	24.3	Flow Research, Inc. *W. Piulle*
RP630-2	Evaluation of Improved Process Control Capability for Flue Gas Desulfurization Processes	1 year	185.0	Southern California Edison Co. *K. Yeager*
RP635-1	Assessment of the Zinc-Bromine Battery for Utility Load Leveling	18 months	274.4	Gould, Inc. *J. Birk*
RP715-1	Evaluation of Alternative Processes for Making Clean Liquids from Synthesis Gas	4 months	54.4	Ralph M. Parsons, Inc. *K. Yeager*
RP716-1	Corrosion Chemistry in Low-Oxygen Activity Atmospheres Characteristic of Gasified or Incompletely Combusted Coal	2 years	177.0	Lockheed Missiles & Space Co., Inc. *R. Jaffee*
RP719-1	Improvements in SO_2 Sorbent Utilization in Fluidized-Bed Coal Combustors	9 months	377.6	Babcock & Wilcox Co. *M. Maaghoul*
RP781-3	Comparison of Fine Particulate Measurement Techniques for Source Testing in the Utility Industry	9 months	19.9	KVB *R. Carr*
RP782-1	Full-Scale Demonstration of NO_x Destruction in Fuel-Rich Burners	3 months	115.2	Babcock & Wilcox Co. *D. Teixeira*
RP785-1	Characterization of Low Sulfur/Alkaline Ash Western Coals for Flue Gas Desulfurization Processes	6 months	75.0	Arthur D. Little, inc. *K. Yeager*
RP791-1	Study of Brine Treatment	7 months	21.0	Lawrence Livermore Laboratory *P. LaMori*
RP836-1	Future Utility NO_x Control Requirements	7 months	87.7	Greenfield, Attaway & Tyler, Inc. *K. Yeager*
RP843-1	Development of Channel-Mounted Rossow Probe for Open-Cycle MHD Generators	6 months	26.3	Utah State University *P. Zygielbaum*
RP846-1	Geothermal Heat Exchanger Test	6 months	99.7	Ben Holt Co. *V. Roberts*
Nuclear Power Division				
RP697-1	Theoretical and Experimental Analysis of Residual Stresses in Reactor Components	2 years	199.9	Cornell University *T. Oldberg*
RP701-1	Evaluation of Near-Term BWR Piping Remedies	2 years	875.0	General Electric Co. *R. Smith*
RP702-1	Development of an Ultrasonic Instrument to Measure Residual Stress	1 year	29.9	Bonitron, Inc. *K. Stahlkopf*
RP812-3	Analysis of Fluid Structure Interaction in a BWR Pressure Suppression System	2 months	17.8	Marc Analysis Research Corp. *J. Carey*

Follow-on Survey on Utility Solar Research

A second survey to identify utilities that are either sponsoring or planning solar research projects was recently completed at EPRI. It carries forward a similar effort made last year, when EPRI identified 53 utilities as the sponsors of 220 individual solar research projects. These projects are in addition to the utilities' support of the EPRI Solar Energy Program.

John Cummings, manager of EPRI's Solar Heating and Cooling of Buildings Program, comments that although the results of the new survey have not yet been analyzed, the study served "to update the status of last year's projects and to identify new projects or projects that were missed in the original effort."

According to Cummings, "the surveys are important in helping utilities plan their solar energy projects, in shaping the EPRI Solar Heating and Cooling of Buildings Program, and in educating the general public and the federal government on the extensive solar activities being sponsored by individual electric utilities." Even though this year's survey is complete, Cummings hopes that utilities will continue to keep him informed on their solar energy plans and results.

The survey requested information on planned or active projects in these areas: (1) solar heating and cooling demonstration projects, (2) performance and impact modeling and evaluation of these projects, (3) insolation and weather data, (4) solar-related projects such as heat pump evaluation or thermal storage evaluation, and (5) legislative and regulatory effects.

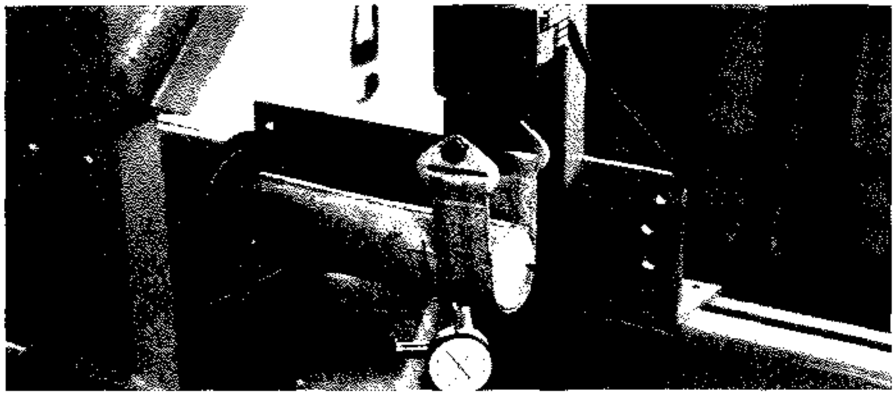
The final report based on the second survey will be published and distributed at the end of the year.

No.	Title	Duration	Funding ($000)	Contractor/ EPRI Project Mgr.
RP820-1	Evaluation of Operational Techniques for Reduction of Radiation Levels in LWRs During Maintenance	6 months	56.9	Nuclear Services Corp. *D. Uhl*
RP824-1	On-Line Vibration Diagnostics for Power Plant Machinery	3 years	363.4	Shaker Research Corp. *R. Pack*
RP827-2	Analysis Support of Dosimetry Measurements in the Reactor Cavity of LWRs	16 months	29.9	Radiation Research Associates *F. Rahn*
Transmission and Distribution Division				
RP281-3	Fault Current Limiters—Executive Summary	3 months	2.0	I-T-E Imperial Corp. *R. Kennon*
RP763-1	Development of Coherency-Based Dynamic Equivalents as an Aid for System Planning	17 months	175.9	Systems Control, Inc. *T. Yau*
RP794-1	Laser Detection of Voids and Contaminants in Polyethylene-Insulated Power Cables	20 months	168.4	United Technologies Corp. *R. Steiner*
RP808-1	SF_6/Oil Dielectric for Power Transformers	26 months	150.0	Westinghouse Electric Corp. *W. Johnson*
RP851-1	Development of a Power Pole from Fly-Ash-Derived Foamed Glass—Phase II	31 months	1585.7	Environmental Control Products, Inc. *R. Tackaberry*

No.	Title	Duration	Funding ($000)	Contractor/ EPRI Project Mgr.
Energy Systems, Environment, and Conservation Division				
RP434-1	Electric Utility Rate Design Study	4 months	10.8	Energy Utilization Systems, Inc. *R. Uhler*
RP488-1	Development of Methodology for Predicting the Demand for New Goods With an Illustrative Application to Residential Heat Pumps	14 months	35.3	Charles River Associates, Inc. *R. Crow*
RP799-1	Electric Field Effects on Large Animals	2 years	1125.4	Battelle, Pacific Northwest Laboratories *H. Kornberg*
RP800-1	Evaluation of a Polycyclic Organic Material Sampling System	19 months	42.0	IIT Research Institute *A. Stankunas*
RP801-1	NO_x Interferences in the Measurement of Ambient Particulate Nitrates	10 months	79.4	Radian Corp. *A. Stankunas*
RP805-1	Mathematical Models for Atmospheric Pollutants	9 months	74.7	Battelle, Pacific Northwest Laboratories *J. Karaganis*
RP854-1	Particle Chromatographic Analysis of Fly Ash	1 year	22.9	Clarkson College of Technology *A. Stankunas*
RP877-1	Documentation of Data and Literature Relevant to the Assessment of the Effects of Thermal Power Plant Cooling System on Aquatic Environments	18 months	75.0	Atomic Industrial Forum *R. Goldstein*

Waste Products Into Power Poles?

Cantilever test on a section of a foamed-glass pole to measure flexural characteristics.



The first power poles made of industrial waste products may be used by U.S. electric utilities within the next few years if manufacturing techniques being developed by EPRI are successful.

Researchers at ECP, Inc., Los Angeles, recently began work on a $1.5 million project sponsored by EPRI to develop a continuous process for producing power poles made of scrap glass and fly ash materials. According to EPRI's Robert Tackaberry, who will be managing the 32-month project, these "foamed-glass" poles are expected to be considerably cheaper than wood, concrete, or steel poles.

"Foamed-glass poles would conserve on wood consumption and provide an excellent use for two major industrial waste products," said Tackaberry. He adds that the ultimate objective of the project is to construct a pilot plant and produce a limited number of foamed-glass poles for field evaluation.

Transients on Transmission Systems

Recent research in fast protective relaying and in current limiters has indicated a strong need for better methods of discriminating among switching surges, line faults, and other disturbances, asserted Stig Nilsson, a project manager in EPRI's Transmission and Distribution Division.

Discussing a new project awarded to Westinghouse Electric Corp., Nilsson commented that further qualitative and quantitative analysis of high-frequency signals occurring on high-voltage transmission lines is necessary to improve discrimination techniques. Consequently, Westinghouse researchers will be designing, installing, and supervising the operation of high-speed monitoring systems in order to obtain permanent records of the high-frequency voltage and current signals.

According to Nilsson, those data will then be correlated to determine the frequency spectrums and waveform characteristics of the various kinds of transmission line disturbances.

The $631,000 project involves two monitoring stations, one for a 500-kV system and another for a 138-kV system. Both will be installed in substations of Florida Power and Light Co.

Project results are to be used in planning future research on ultrahigh-speed relaying, on the development of current limiter controls, and in the evaluation of insulation stresses in lines and substation equipment.

Electric Energy Use and Regional Economic Growth

Under EPRI sponsorship, a prototype model for determining the relationships between electric energy use and regional economic growth has recently been developed and tested for the Buffalo metropolitan area. The Research Foundation of the State University of New York was the contractor, with James Harris Savitt the principal investigator.

According to Robert Crow, manager of EPRI's Energy Demand and Conservation Program, the model will assist EPRI technical staff in developing more detailed models concerning electric energy use and regional economic growth. "This model is very important in planning our research on regional forecasting," Crow said, "and also potentially useful to individual utilities as a source of ideas for their own forecasting purposes."

Crow stated that within three years EPRI will probably have developed consumption forecasting models for multistate regions covering the entire country.

Each month the JOURNAL publishes summaries of EPRI's most recent reports. Supporting member utilities receive copies of reports in program areas of their designated choice. Supporting member utilities may order additional copies from EPRI Records and Reports Center, P.O. Box 10412, Palo Alto, CA 94303. Reports are publicly available from the National Technical Information Service, P.O. Box 1553, Springfield, VA 22151.

New Publications

Energy Systems, Environment, and Conservation

EPRI EC–144 THEORETICAL, NUMERICAL, AND PHYSICAL TECHNIQUES FOR CHARACTERIZING POWER PLANT PLUMES
Topical Report

Systems Applications, Inc. (SAI) and Meteorology Research, Inc., are conducting a research program to determine under what conditions ozone forms in power plant plumes. The initial steps were reviews of current knowledge of plume chemistry, physics, and mathematical modeling and analyses of past field studies of plumes. It became apparent that a formal document integrating these topics would serve a useful purpose. SAI therefore prepared such a synthesis, which appears in this report. Its intent is to identify existing problems in the measurement and modeling of reactive plumes and to point out areas in which further work would increase an understanding of power plant plumes. *Systems Applications, Inc.*

EPRI 262 SULFUR DIOXIDE INTERFERENCES IN THE MEASUREMENT OF AMBIENT PARTICULATE SULFATES
Final Report, Volume II

Ambient levels of atmospheric sulfates have been linked with health problems in urban areas. However, existing data are based to a large extent on results of the analysis of filters used to measure total atmospheric particulate loadings.

The primary objective of this program was to establish quantitatively the extent to which sulfur dioxide is converted to sulfate during Hi-Vol particulate sampling employing glass-fiber filters. A secondary goal was to determine the amount of interference of sorbed, but unoxidized, SO_2 in the sulfate analytical method. Experiments were conducted under closely controlled laboratory conditions.

The results of this study show that a significant part of sulfate measured by the Hi-Vol filter techniques may be an artifact resulting from conversion of SO_2. Further, the contamination is to a large extent a function of the weather at the sampling site. To put the sulfate question into perspective, it is recommended that existing data banks be examined in light of this work so that the significance of potential contamination from SO_2 conversion artifacts can be determined.

The remainder of the report summarizes the experimental techniques employed and the results of the study. Appendixes provide extensive documentation of all data. *Radian Corp.*

Fossil Fuel and Advanced Systems

EPRI SR–39 THE PROCEEDINGS OF THE NO_x CONTROL TECHNOLOGY SEMINAR, SAN FRANCISCO

On February 5 and 6, 1976, EPRI sponsored a conference in San Francisco on the status of technology for control of oxides of nitrogen from power generation facilities. Coal-fired steam generators, gas turbines, and synthetic fuel NO_x emissions were covered during the two-day seminar. Representatives of electric utilities, regulatory agencies, academic institutions, research organizations, and other industries were present.

The purpose of the seminar was threefold: (1) to acquaint the utility industry with stringent NO_x emission standards for fossil-fueled power plants currently under consideration by regulatory bodies; (2) to evaluate the current state of the art for NO_x control; and (3) to assess future technical options for NO_x control and, where possible, to present their economic consequences.

EPRI AF–158 COMPARATIVE STUDY AND EVALUATION OF ADVANCED CYCLE SYSTEMS
Phase 1 Report

A number of advanced energy conversion cycles are being proposed to increase generating efficiency and, in some cases, to reduce the cost of electricity. These new concepts are being put forward by organizations with widely varied backgrounds, using a diversity of approaches and assumptions for predicting performance, costs, and development requirements.

This Phase 1 report covers the initial work on a study undertaken to analyze a number of proposed advanced systems on a common basis, using uniform technical and economic assumptions. In this study, special emphasis is being given to the viewpoint of the utility industry. The results should permit an assessment of the relative merit of these advanced systems, as well as a prediction of potential benefits to the nation and to the utility industry upon implementation of the systems. This effort should help accelerate development of one or more of the advanced systems to meet the nation's electric energy requirements by the turn of the century.

A total of 19 advanced systems were studied in the screening process. In addition, 2 conventional systems were analyzed to serve as reference cases against which the advanced systems could be compared. The fuels studied are coal, oil, and nuclear. The 19 advanced systems are grouped into the following categories: open cycle (5 systems), closed cycle (8 systems), and direct energy conversion (6 systems). *General Electric Co.*

EPRI EM–166 DEVELOPMENT OF LITHIUM–METAL SULFIDE BATTERIES FOR LOAD LEVELING
Progress Report

An investigation of lithium-sulfur batteries was initiated at Rockwell International in November 1968 with a company-funded study. This study was significantly augmented by support from the Edison Electric Institute and the Tennessee Valley Authority, starting in 1972. Elemental lithium and sulfur electrodes were used in a molten LiCl-KCl electrolyte with a melting point of 352°C. Early experiments disclosed serious fundamental problems associated with the volatility of elemental sulfur at the 400°C operating temperature and with the solubility of polysulfide reaction products in the electrolyte. Both led to rapid capacity loss of the positive electrode. This prompted a study of alternative electrode materials, which revealed the excellent electrochemical properties of the transition metal sulfides in the molten salt electrolyte. Iron and copper sulfides were selected for intensive investigation on the basis of their low cost and ready availability. As the work progressed, emphasis was placed on development of the lithium–iron sulfide battery, in view of the higher energy density and lower cost achievable.

The research and development efforts described in this report will be continued, with emphasis on scaling up electrodes and ceramic separators to a size required for prototype load-leveling modular cells. Systematic parametric studies such as those initiated with lithium-silicon negative electrodes will also be conducted with positive electrodes. Increasing attention will be paid to the selection of lightweight, low-cost structural components and to the use of preparative and assembly methods adaptable to volume production of low-cost, high-energy density batteries. *Rockwell International*

EPRI FP–173 MODELING THE GAS–PHASE KINETICS OF FUEL–NITROGEN REACTIONS
Final Report

A mathematical model has been developed for the premixed gas-phase kinetics of the conversion of fuel nitrogen to nitric oxide. This model is based on two assumptions: (1) that the combustion kinetics can be modeled by the quasi-global rate mechanism and (2) that the kinetics of the fuel nitrogen can be accounted for by considering all the fuel nitrogen to react to form a reactive, nitrogen-containing intermediate compound (such as CN, NH, or N atoms) on the same time scale as the combustion reactions of the carbon and hydrogen in the fuel. This intermediate is called the model compound. Detailed kinetic steps are then used to model the reactions of the CO-to-CO_2 conversion and the reactions by which the reactive nitrogen-containing intermediate forms nitric oxide. Equally important are the reactions by which this reactive nitrogen intermediate forms stable compounds such as N_2, and thus does not form nitric oxide.

Although direct comparison of the computations with actual combustors is not possible, the computed results give predicted trends that are in accord with experimental observations. Further work is recommended to (1) match the computations to experimental data on premixed flames to test the validity of the model for quantitative results and (2) use the simplified model for studies of fuel-nitrogen conversion in liquid and solid fuels. *KVB Engineering Co.*

EPRI ER–183 CLOSED–CYCLE, HIGH–TEMPERATURE CENTRAL RECEIVER CONCEPT FOR SOLAR ELECTRIC POWER
Interim Report

This interim report presents the results of a study on the technical feasibility of a high-temperature central receiver in a solar plant employing closed-cycle helium as a heat transport fluid. Feasibility was examined in terms of system life, efficiency, cost, and technological requirements. These considerations are implemented in the conceptual design of a preferred receiver and its components for utilization in a solar plant of 100 MW electrical power output. The rationale is provided for the configuration, equipment arrangement, and material choices. A thermal cycling test simulating a 30-year lifetime of the receiver heat exchanger at temperatures to 816°C (1500°F) and at 34 bar (500 psi) helium pressure confirmed the material choice. A preliminary design of a model receiver, appropriately scaled to 1 MW of thermal energy into the receiver, is presented as a candidate for early test.

The report also contains system and supporting subsystem definitions for employing the preferred central receiver in a solar plant, as well as recommendations for further development efforts. The work to be performed during the remainder of the contract period is included in these recommendations.

A 36-page summary of the report is available, EPRI SY-32. *Boeing Engineering & Construction*

EPRI 418 THE INTERACTION OF ELECTRICAL DISTRIBUTION SYSTEMS WITH BATTERIES AND FUEL CELLS
Final Report

An assessment of the operational features of energy storage and conversion systems connected to a distribution substation bus is the objective of this project. The investigation was performed on a hybrid computer, using a detailed simulation of a composite energy storage and ac distribution system. For portions of the study the representation was similar to the configuration anticipated for the Battery Energy Storage Test (BEST) facility. Both line- and force-commutated converter systems were considered with lead-acid batteries, advanced batteries, and fuel cells as the dc sources. Computer results presented in this report of steady-state and transient operation permit evaluation of the performance and design requirements with respect to harmonic filtering, power factor control, dc source interface, converter control, and stand-alone operation.

In regard to system operation, the only significant difference among the sources appears to be the internal resistance. The studies performed in this investigation indicate that there should be no major difficulty in operating these sources on a utility network, interfacing the sources with the utility through either line- or force-commutated converters. In most cases conventional control techniques may be employed directly. This investigation indicates that satisfactory operation with line- or force-commutated converters is also possible for common ac system disturbances. *Purdue University*

Nuclear Power

EPRI NP–120 HTGR FRACTURE TOUGHNESS PROGRAM
Final Report

The primary pressure boundary components of the high-temperature gas-cooled reactor (HTGR) must meet the toughness requirements of Section III of the ASME Boiler and Pressure Vessel Code (K_{IR} curve, Section G). However, the materials used in the HTGR are not the same as those used to generate the K_{IR} curve of the ASME Code. The present program was carried out to provide sufficient fracture toughness data for typical production heats of HTGR materials in order to determine the adequacy of the K_{IR} curve for HTGR applications. Five heats of HTGR materials were tested over the temperature range of -200 to +550°F. The HTGR materials studied were A508-1 forging, A537-1 and A537-2 plates, and a manual metal arc weldment in A537-2 plate (both weld metal and heat-affected zone).

This report represents an effort to present well-documented HTGR fracture toughness data, along with the complete history for each heat of material (i.e., mill test reports and welding history, metallography, chemistry, archive and specimen drawings). A statistical analysis of the data was performed, following the guidelines established in the EPRI Light Water Reactor Fracture Toughness Program. All fracture toughness data generated for the HTGR materials fell above the K_{IR} curve, except at very low temperatures not representative of service conditions. For all the HTGR materials studied, except A508-1 forging material, the K_{IR} curve appears to be too conservative. *Effects Technology, Inc.*

EPRI NP–121 FRACTURE TOUGHNESS DATA FOR FERRITIC NUCLEAR PRESSURE VESSEL MATERIALS
Final Report, Volume I

Eight types of nuclear pressure vessel steels and weldments (totaling 50 heats) have been studied by three testing laboratories. New testing and data analysis procedures were established to deal with the dynamic fracture toughness measurements. Approximately 20,000 test results were obtained and filed in a computer data bank. Archives of photographic and other documents, broken specimens, and additional material from each heat were also set up. A preliminary round-robin program established that there was no bias among laboratories, that some laboratories showed less experimental scatter than others, and that real differences existed among the various fracture toughness tests.

The methodology developed in the program for obtaining and statistically analyzing a large quantity of fracture toughness data represents a significant step toward formulating a statistically based K_{IR} curve. However, improvements in the statistical treatment of the data and in the elastic-plastic analysis of dynamic toughness data are required before a statistically well-defined K_{IR} curve can be developed. *Effects Technology, Inc.*

EPRI NP–132 URANIUM RECOVERY FROM SEAWATER
Final Report

An experimental study of electrolysis of seawater did not reveal a practical method for recovery of uranium. An examination of alternative methods for recovering uranium indicated that at the present time three processes with low environmental impact are feasible. These are solution mining, extraction from phosphoric acid, and adsorption from seawater. Commercial implementation has been shown to be feasible for the first two methods, which are in the production stage. Recovery from seawater by adsorption is being actively pursued in Japan, but it has not been developed to a commercial state. A processing rate of 80 tons of seawater per day has been achieved, using titanic acid and active charcoal adsorbent; however, this amounts to less than 100 g of U_3O_8 per year. The objective of the development program in Japan is to extract about 3 t/yr by 1990. *Westinghouse Electric Corp.*

EPRI NP–142 DEVELOPMENT STATUS AND OPERATIONAL FEATURES OF THE HIGH-TEMPERATURE GAS-COOLED REACTOR
Final Report

This study investigated the maturity of HTR technology, its possible technical problems, and the prospects of introducing large HTR power plants into the market. The report presents the problems of introducing and closing the thorium fuel cycle. Finally, it discusses the state of development of advanced HTR concepts for electricity production, the direct-cycle HTR with helium turbine, and the gas-cooled fast breeder.

The study deals exclusively with program work and with results gained during development of HTR systems. Development results from British and French Magnox reactors, as well as from AGR systems, are cited only in special cases. In particular, the operating experiences from Magnox reactors are referred to as an aid in evaluating the design of large HTRs.

The authors of this study are convinced that the HTR must be considered a safe and reliable system, with low environmental impact, and that it should be further developed. *Gesellschaft für Hochtemperaturreaktor-Technik mbH, Bensburg, Germany*

EPRI NP–146 THERMOGRAPHIC IMAGING OF NUCLEAR FUEL RODS
Final Report

A novel thermographic imaging technique for the nondestructive testing of nuclear fuel rods has been demonstrated—a technique that can sense the gap spacings between the metallic cladding and the uranium oxide pellets within the rod. The principle utilized is to electrically heat the metallic cladding in a time that is short compared with all thermal relaxation times and then to observe the differential thermal patterns on the surface of the cladding as they rapidly develop and later fade away. These patterns can be correlated with different gap spacings, with a spatial resolution on the order of the cladding thickness. *Stanford Research Institute*

EPRI NP–148 FULL–SCALE TORNADO–MISSILE IMPACT TESTS
Interim Report

Approximately half the tests scheduled in the EPRI/Sandia Tornado-Missile Program have been completed. This interim report was issued to disseminate the results of the initial tests as quickly as possible, in order to satisfy the needs of utilities and architectengineers now engaged in plant-licensing procedures. The findings are presented with a minimum of interpretation.

The initial tests indicate that existing power plant walls are adequate for the most severe conditions currently postulated by regulatory agencies. The tornado-missile test velocities represent conservative design assumptions. Predicted missile velocities will be reduced as outstanding issues associated with the maximum wind speed, realistic aerodynamic coefficients, and the nature of a tumbling trajectory are clarified.

Another fundamental question is whether some of the postulated missiles can, in fact, become airborne. Such issues are being pursued under other EPRI contracts. This test program is being sponsored by EPRI under the EPRI/ERDA Memorandum of Understanding, May 1976. *Sandia Laboratories*

EPRI NP–149 TRANSIENT CRITICAL HEAT FLUX DURING FLOW REVERSAL
Key Phase Report

This report presents the results of an investigation of transient critical heat flux (CHF) during flow reversals. Some characteristics of a pressurized water nuclear reactor were simulated by a test section consisting of an 8 ft × 0.435 in vertical tube communicating between two plena. Freon-113 at about 200 psia was used as the working fluid to simulate high-pressure water. The time and the location of CHF between flow reversals were established experimentally. A separate program verified a steady-state CHF correlation that was originally established by Bowring for water and adapted for Freon-113 by means of the method of Ahmad. Several CHF and non-CHF runs have been made, involving flow reversals or flow stoppage. They are completely reported so they can be used to test a computer code being developed to predict when and where CHF is expected to occur. *Massachusetts Institute of Technology*

EPRI NP–150 FUTURE NEEDS FOR DRY OR PEAK SHAVED DRY/WET COOLING AND SIGNIFICANCE TO NUCLEAR POWER PLANTS
Final Report

A nuclear plant cooling system evaluation has been conducted partly for the purpose of assessing the potential need for, or usefulness of, developing new nuclear system–power-cycle combinations that might be better suited to dry-cooling-tower applications, e.g., higher steam temperatures, Brayton cycles. In order to have a comparative array, the study evaluates the costs and water consumption of three cooling systems: dry, wet, and peak shaved dry/wet with separate towers.

These three cooling systems were matched to four kinds of nuclear power plants. Present nuclear generating stations in the U.S. use light water reactors (LWR), either the boiling or the pressurized water reactor type. Stations using the high-temperature gas-cooled reactor (HTR) or the liquid-metal-cooled fast-neutron breeder reactor (LMFBR) are under development in the U.S. and overseas. These all use conventional steam turbines (ST). The HTR alternatively can circulate its helium coolant through a gas turbine (GT) with heat rejection by any of the cooling methods. The four kinds of nuclear power plants evaluated in this study, then, encompass the LWR, the LMFBR, the HTR-ST, and the HTR-GT.

To evaluate environmental cooling differences, a selection was made of three representative U.S. sites that had typically high summer dry-bulb temperatures but substantially different wet-bulb temperatures. All three (Lubbock, Texas; Raleigh, North Carolina; and Reno, Nevada) were near potential load growth centers, and were inland where water limitations are present. *General Electric Co.*

EPRI NP–151 CRITICAL HEAT FLUX IN FLOW REVERSAL TRANSIENTS
Key Phase Report
Volume I—Theory and Experiment
Volume II—Analytical Techniques

A large inlet break loss-of-coolant accident (LOCA) in a pressurized water reactor would cause the flow through the core to reverse within milliseconds. Currently approved analysis methods conservatively assume that vapor blanketing of core heat transfer surfaces occurs upon the first reduction to zero flow. The result is that these surfaces are thermally insulated and none of the stored thermal energy is removed from the core. This investigation produced a self-consistent physically based procedure for calculating when the vapor blanketing or critical heat flux (CHF) conditions actually do develop in a constant pressure rapid flow reversal transient. The method uses steady-state CHF correlations with transient predictions of local fluid conditions and is shown to adequately predict the CHF level, time, and location in high-pressure Freon-113 flow reversal transients.

The homogeneous two-phase model is shown to be adequate for analysis of rapid flow reversal transients, and a small but versatile computer program is included for either pressure-drop forced or inlet-flow forced one-dimensional simulation of such complicated constant pressure rapid flow transients. *Massachusetts Institute of Technology*

EPRI NP–154 TORNADO MISSILE RISK ANALYSIS
Topical Report 1

The ability of tornadoes to generate and sustain wind-driven missiles is considered to be a potential hazard to the safe operation of nuclear power plants. Current NRC criteria require that safety-related structures be designed to resist a range of hypothetical missiles traveling at maximum credible velocities. Because of the uncertainties associated with the wind intensity, occurrence of tornadoes, and characteristics of missiles, this "worst-case" deterministic analysis of the effects of the tornado-induced missiles results in an overly conservative structure design that may not be justifiable on the basis of the actual risks to plant safety. A probabilistic assessment of the tornado missile risk is therefore in order.

The uncertainties inherent in natural phenomena cannot be eliminated, but they can often be quantified. The objective of this project is to develop a probabilistic formalism for characterizing the effects of tornado-generated missiles on plant safety. This report summarizes the state of the art and discusses the R&D efforts needed to accomplish the stated objective. *Carolina Power & Light Co.*

EPRI NP–163 A MONTE CARLO ANALYSIS
OF A CHALK RIVER EXPERIMENT ON CROSS SECTIONS
OF FISSILE NUCLIDE
Final Report

The accurate determination of thermal neutron parameters is clearly of crucial importance for thermal reactor calculations. The measurements at Chalk River of alpha (the capture-to-fission ratio) and fission cross sections of ^{233}U, ^{235}U, and ^{239}Pu at thermal energies represent some of the most precise work to date in determination of these parameters. The experiment involved placement of samples of mixed uranium and plutonium isotopes in a special irradiation facility in the NRU reactor and measurement of pre- and postirradiation sample composition by mass spectrometric techniques. The thermal neutron parameters can then be determined, provided that estimates of neutron flux spectra in the samples are accurate.

Monte Carlo calculations can be used to determine accurate neutron spectra at the sample positions and thus to assess the thermal parameters of interest. The Monte Carlo approach allows the number of calculational approximations and assumptions to be minimized. *Mathematical Applications Group, Inc.*

EPRI NP–167 EVALUATION OF THE NEUTRON
CROSS SECTIONS OF ^{235}U IN THE
THERMAL ENERGY REGION
Final Report

This report is a continuation of EPRI's program in upgrading the "Evaluated Nuclear Data File—ENDF/B" to a level where it can become acceptable as a national standard for thermal reactor applications.

One of the problems confronting the ENDF/B library has been the difficulty of specifying a self-consistent set of thermal cross sections for the fissile nuclides ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu. Since these cross sections are interrelated through various experiments, previous attempts to derive such a set consisted of least-squares fitting of all the available experimental data. The discrepancies encountered in these analyses indicated the need for (1) reviewing the interpretation of the results obtained and the procedures used in a few of the most important experiments and (2) reevaluating the energy dependence of the cross sections in the low energy range (below $\sim$ 1 eV) in addition to their values at 2200m/sec.

EPRI's program in this area was initiated with the development of a nonlinear least-squares fitting technique for determining the energy dependence of cross sections. The capabilities of this technique have been extended under the present project and applied to the evaluation of the ^{235}U cross sections. The technique has been incorporated into a computer code—SIGLEARN—described in the topical report EPRI NP–168. *Battelle, Pacific Northwest Laboratories*

EPRI NP–168 SIGLEARN: A PROGRAM FOR
SIMULTANEOUS LEAST–SQUARES FITTING OF THERMAL
NEUTRON CROSS SECTIONS AND RELATED RATIOS
Topical Report

The computer program SIGLEARN was written to assist in the evaluation of the shapes of neutron cross sections of fissile nuclides in the thermal energy region. Specifically, it employs the method of nonlinear least squares to fit simultaneously up to seven different types of data for a single nuclide. The program is a special adaptation of the general-purpose nonlinear least-squares program LEARN, which uses the Adler-Adler formulation for σ_f and σ_c and the Breit-Wigner multilevel formula for σ_s. In addition to adjusting the free parameters and calculating the associated covariance matrix, the program performs a statistical evaluation of the quality of individual data points and the relevance of parameter subsets.

This report, which is the documentation of the computer program, consists of three substantive sections. Section II, the application section or user's manual, is directed to the person concerned with the execution of the program. Section III, the problem definition section, is directed to the person concerned with the mathematical models and algorithms employed in the program. Section IV, the programming information section, is directed to the programmer concerned with the implementation, maintenance, and modification of the program. *Battelle, Pacific Northwest Laboratories*

Transmission and Distribution

EPRI 7813–1 DEVELOPMENT AND FIELD TRIAL OF
VI–LN2 CRYOCABLES
STAGE 1: 138-kV SINGLE–PHASE TERMINATION
Final Report

This report describes the development and field trial of the first cryocable termination intended for 138-kV underground power transmission lines cooled by liquid nitrogen and thermally and electrically insulated by a common vacuum space and solid dielectric conductor supports.

The field trial proved that liquid nitrogen can be transferred from a grounded metallic LN2 transfer line to the high-voltage conductor of a 138-kV transmission system. It further demonstrated that an air-insulated high-current conductor can be passed from ambient temperature to $-194°C$ through the termination within a distance of only 3 ft.

It is now confidently expected that the vacuum-insulated LN2 cryocable will not require superinsulation and that the electrical insulation will also satisfy all thermal insulation requirements. Consequently, the vacuum-insulated LN2 cryocable will be structurally similar to three-phase SF_6 insulated cables, but the aim is to make it very much more compact. Specifically, this program was designed to measure ac losses in available samples of Nb_3Ge and to determine under what conditions the losses can be reduced to 10 $\mu W/cm^2$ at $\sim$ 15°K. *Underground Power Corp.*

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