Ten Options for Clean Coal

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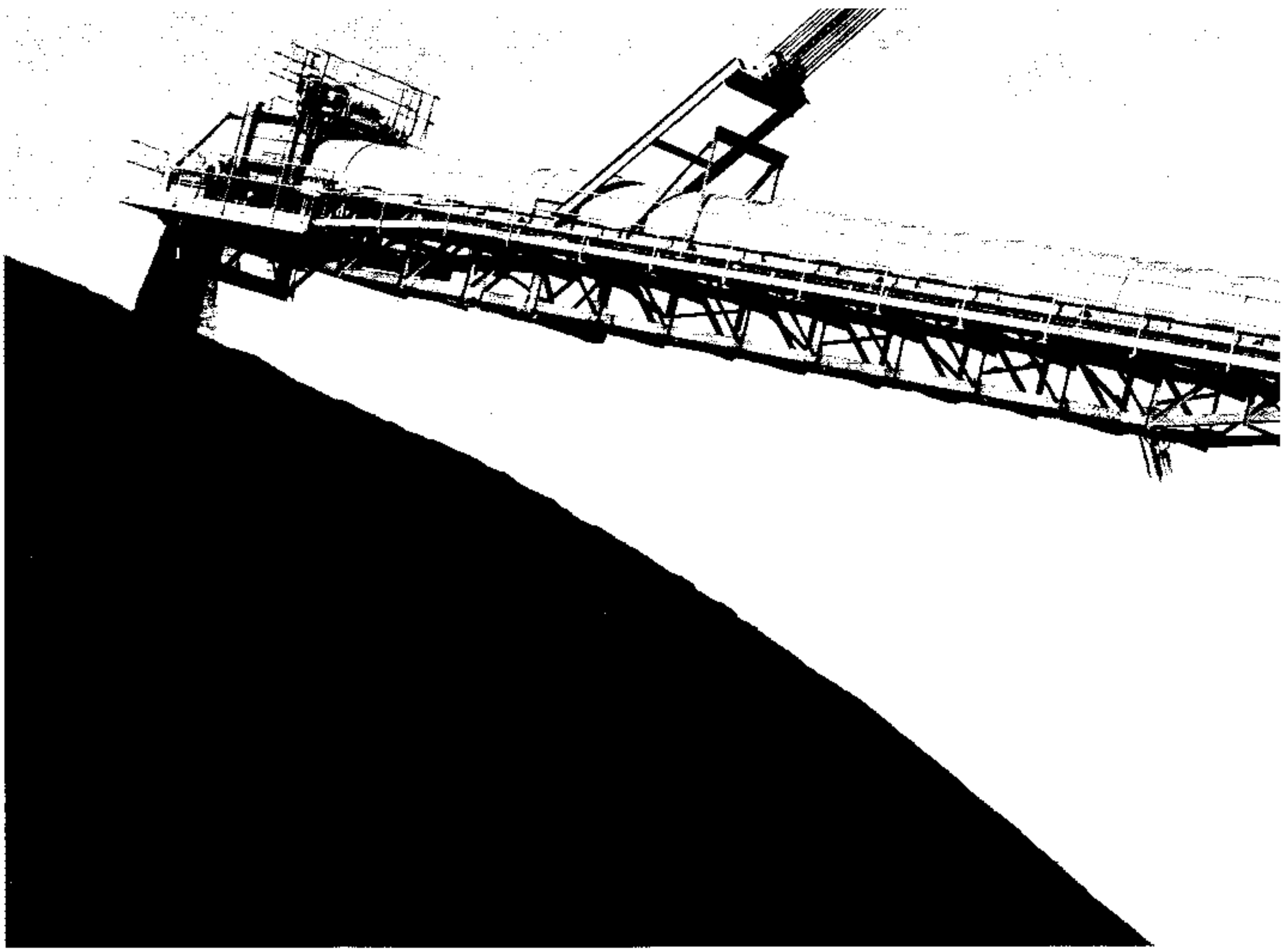

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COVER: Coal in abundance for boiler fuel—but how to cut its sulfur content, how far, and at what cost?

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R&D STATUS REPORTS

DEPARTMENTS

R&D Success Begins With R&D Priorities

When EPRI began, there was no alternative to relatively subjective judgment in allocating our R&D resources among the competing power generation, transmission, and distribution technologies. Together, we and our advisory committees relied on our personal professional responses to questions like, What is needed by the industry? and, What proportion of the R&D budget should we plan to spend on this?

Our approach also relied heavily on the competence and experience of the technical staff, which was just being drawn together when EPRI's first program plan was in development. But during 1975 the Fossil Fuel and Advanced Systems Division began looking for a quantitative way to rank the benefits of competing technologies. Its work took the form of an analytic effort—just one of several planning and analysis activities in the division—and focused first on an economic comparison of the technical approaches to coal utilization.

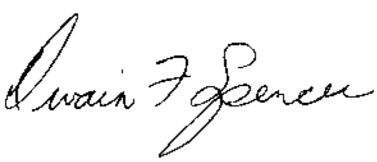
This year, as part of a division reorganization in May, a Power Plant Requirements and Analysis Program was formally established in the Advanced Fossil Power Systems Department. The express objective of program manager René Loth is to assess the relative benefits of various power generation technologies being pursued by the division. Loth's program includes: (1) utility systems analysis, (2) process evaluation and cost estimation, (3) advanced fossil power systems reliability, and (4) critical resource assessment. All these analytic components share a single element—the use of accepted techniques from electric utility operations and planning practice. And they share a goal—to estimate the potential market penetration of new power generation technologies.

This structuring of analytic efforts in the Fossil Fuel and Advanced Systems Division will help us to communicate more effectively with our advisory committees and thereby to establish R&D priorities with a new level of confidence. Our limited R&D

resources may therefore be focused on the alternatives shown most likely to be commercially available and economically attractive between, say, 1985 and 1990. On the other hand, we may very consciously make an R&D allocation specifically to improve the prospects of a technology that otherwise seems to be out of the running. Either way, the ability to set R&D priorities in a consistent way is itself an R&D success and should prove to be a key to later success in specific research.

The leading feature article in this issue of the JOURNAL reviews our first results, a busbar cost-ranking of clean coal utilization technologies. René Loth and I developed the approach, using information drawn primarily from EPRI-sponsored projects. We recognize that this analysis omits many factors that would be included in a truly complete evaluation, but its value lies in its consistent approach to busbar energy cost, despite the many variables and assumptions behind even that single factor.

Even this "first cut" has assisted us in revising our priorities in coal conversion and related power generation research. In addition, the methodology is now being extended to include analyses of generation expansion on representative utility systems.



Dwain F. Spencer, Director
Advanced Fossil Power Systems Department
Fossil Fuel and Advanced Systems Division

Authors and Articles

Electric utilities are confronted with a bewildering array of technologies for cleaning and converting coal. As a fuel for generating electricity, coal has potential for being used in at least two dozen ways, varying from direct firing of low-sulfur coal to burning of low- or medium-Btu gases from processes still being developed.

The variables that underlie these technologies are legion. A yardstick is needed to evaluate them and serve as a guide to coal R&D on behalf of the utilities.

□ This month's cover story, "Clean Coal: What Does It Cost at the Busbar?" (page 6), details the design, elements, and application of such a yardstick, all of which are the aim of a research project in EPRI's Fossil Fuel and Advanced Systems Division.

The article was prepared by JOURNAL features editor Ralph Whitaker, with close assistance from Dwain F. Spencer, director of the Advanced Fossil Power Systems Department.

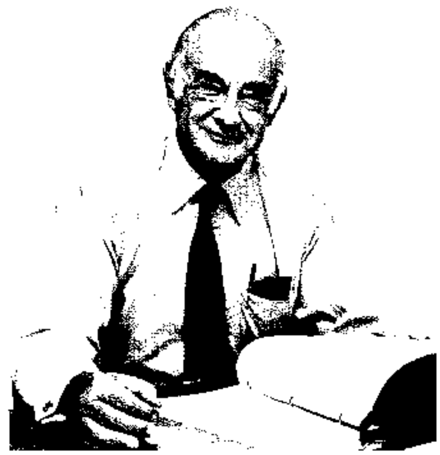
□ Both the history and the use of gas-insulated underground transmission cable are short: barely 5 years and 4 circuit miles. Eighteen U.S. utilities, however, have gas cable installations, and it is expected that their experience will stimulate others.

The development of gas-insulated cable systems capable of transmitting large blocks of electric power is the goal of a research project under way in EPRI's Electrical Systems Division. In "Gas-Insulated Cable Research Aims for Versatility" (page 14), Ralph Samm, manager of the Underground Transmission Program, reviews the performance considerations of gas-insulated cable and the developmental status of its major elements: gas, conductor, spacer, and enclosure.

"Taking full advantage of gas-insulated transmission," says Samm, "depends on successful design coordination of all components into an operating system."

Samm joined EPRI in 1974 as a project manager and was appointed to his present position the following year. Samm had been project manager of research and development at I-T-E Imperial Corp. in Greensburg, Pennsylvania, for 16 years before coming to EPRI. He has an MBA from the University of Pittsburgh and a BS in electrical engineering from Johns Hopkins University.


Samm


Comar

□ Cyril L. Comar, director of EPRI's Environmental Assessment Department and a pioneer in the use of radioactive materials for biological research, recently prepared an EPRI report aimed at clarifying the controversial issues surrounding the use of plutonium. The overview that prefaced the report, "Plutonium: Facts and Inferences," appears, slightly abridged, on pages 20–24.

Comar presents statistical data and offers analyses—based on experience since the mid-1940s in both nuclear power and weapons development and testing—on aspects of plutonium use such as potential releases from a nuclear power industry; behavior of plutonium in the biosphere; its predicted effects on human beings; differences and relationships between toxicity and hazard; and the potential for malevolent use of plutonium from nuclear power installations.

Comar held responsibility in the late 1940s for national programs dealing with radioactive fallout. More recently he chaired a National Academy of Sciences study of effects of low-level radiation on human populations. He is a member of ERDA's Nevada Applied Ecology Group Advisory Plutonium Committee and of the Scientific Review Panel for the Inhalation Toxicology Research Institute, Lovelace Foundation for Medical Education and Research.

Before joining EPRI in early 1975, Comar was professor and head of the Department of Physical Biology and director of the Laboratory of Radiation Biology at Cornell University. He was also director of the Cornell Energy Project. Earlier he served as chief of biomedical research at the Oak Ridge Institute of Nuclear Studies. He holds the title of professor emeritus, Cornell University.

Comar has a doctorate in agricultural biochemistry from Purdue University, has published more than 200 scientific papers, and belongs to more than a dozen professional societies.

Clean Coal: What Does It Cost at the Busbar?

If you're working with a coal-burning electric utility today, you could be looking into as many as two dozen ways to use coal as a fuel. They vary from the direct firing of low-sulfur coal to the burning of low- or medium-Btu gases derived from processes still in development.

In between those extremes is a spectrum of both generic and proprietary approaches:

- Intermittent generation controls to cut the volume of sulfur dioxide emissions when ground level concentrations get too high
- Filters and scrubbers to clean combustion products before they go up the stack
- Washing and chemical cleaning schemes to remove sulfur, as well as particulates, ahead of the combustion process
- New combustors and combustion processes that minimize the release of sulfur compounds
- Liquefaction processes (like those for gasification) that convert coal's heating value to an entirely different, clean, efficient form

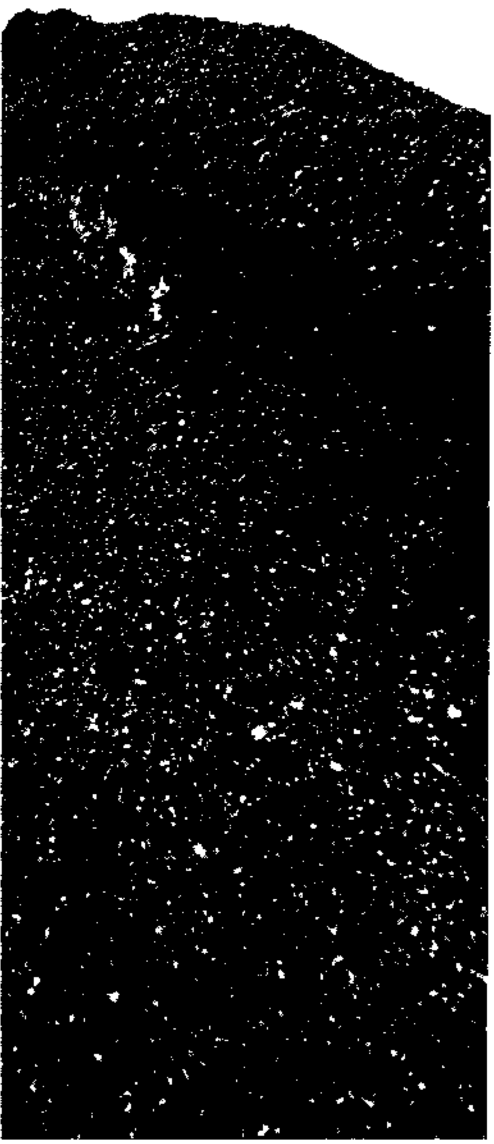
But is there a best way to use coal? Which way? How do we decide? And what do we do about it?

Too many variables

Measuring the state of the art in coal technologies is difficult. For one thing, differences between processes tend to make any comparison a matter of "apples and oranges"—because of the subtleties of chemistry that govern feedstock requirements, efficiencies, and throughputs. Then there are the differences in the states of development of candidate processes that defy easy or precise pre-

We need a way to evaluate coal fuel technologies, using the fewest possible variables. Sulfur criteria for coal, process, and environment are one set of variables. Plant capital, O&M, and fuel costs are another. Together, they permit consistent comparison of busbar power costs for 10 major clean coal options.

□ An EPRI state-of-the-art feature



diction of time and cost to commercialization, land and other resource requirements, operability, reliability— and even the very probability of development success.

Equally important are the number and range of what economists call exogenous variables, those that originate outside the R&D community but bear significantly on the practical economic potential of any approach to coal cleaning or conversion. One such factor is the resource base itself—our reserves, their character (especially their sulfur content), and their geographic distribution. Another factor is the coal industry and its technologies and capabilities for growth in mining and transportation. Together, the two factors will influence the quality of coal and the price electric utilities will pay for it.

In addition, of course, there is the electric utility industry, with all its own variables in system load characteristics, growth, reliability, capital and operating costs, and fiscal capability of taking on new or modified generating plants. Regulation enters the analysis, too, not only in affecting revenue requirements but in setting environmental standards for coal-burning plants.

Selecting a yardstick

The list of variables goes on. However, a yardstick is necessary to guide R&D efforts on behalf of utilities. Designing and applying that yardstick, in a first-cut, screening exercise, has been the aim of a technical analysis conducted by EPRI's Fossil Fuel and Advanced Systems Division during the past 15 months. The methodology and conclusions of that work are summarized here.

What follows, then, focuses on the yardstick, its construction, its precision, and its application. The measurement unit is busbar electric power cost, figured in 1975 dollars and expressed in mills/kWh. Distinctions are not made between and within individual coal technologies, other than to name them and to characterize them by their sulfur removal capabilities.

Initially, a list of two dozen alternatives was drawn up. However, in many instances—notably coal cleaning, dry alkali/bag filters, and several regenerative scrubbing processes—the available basic data were inadequate for valid analysis. So the pioneer evaluation was necessarily limited to 10 options (Table 1). As the study is updated (at least annually), however, many of the others will be incorporated.

Because all the candidate technologies are seen as options for limiting SO_2, even low busbar power costs would be meaningless if the options could not reasonably be expected to meet environmental standards. EPRI's work, therefore, also had to include some assessment of future sulfur removal requirements, based on projected coal utilization, environmental standards, and coal quality.

The remaining stages of the study were devoted to estimating the capital costs for coal cleanup or conversion plants to meet the calculated sulfur removal requirement and then computing busbar power costs for each candidate technology as it might be employed in both baseload and intermediate generation modes.

Sulfur criteria

National energy consumption is expected to rise from 70 quads (quadrillion Btu) in 1975 to 170 quads in 2000. (With greater efficiency and the resultant conservation, the latter figure would be 150 quads, a value frequently used in energy growth estimates by EPRI.) Considering only the coal used for electricity generation, the need will increase from 11 quads in 1975 to 30 quads in 2000. This growth implies an increase in coal consumption by electric utilities from 400 million tons in 1975, to 900 million tons in 1985, and to 1500 million tons in 2000.

Based on a 3% annual replacement rate for coal-fired power plants, a capacity equivalent to 300 million tons (of 1975's 400 million) will have to meet what are called new-source performance standards (NSPS) in the year 2000—that is, control of sulfur emissions to at least the present upper limit of 0.6 lb/10^6 Btu. Of course, the capacity growth represented by 1100 million tons will be similarly governed. Thus, by the turn of the century, more than 90% of U.S. utility coal-fired plants will be subject to NSPS levels.

More stringent controls

But what is the likely level, or stringency, of sulfur control? Of course, it is not certain what action various federal, state, and local agencies engaged in environmental regulation will take. But several present and probable strategies were considered in the study, with particular respect to SO_2 and derivative compounds:

- New-source performance standards
- State implementation plans for primary ambient air quality
- Possible new national ambient air quality standards
- Limited and controlled growth provisions within the Environmental Protection Agency's (EPA) policy for preventing significant air quality deterioration
- Potential sulfate control standards

NSPS at 0.6 lb/10^6 Btu sulfur in coal is a likely upper bound on control requirements. The next three strategies listed are projected to result in a sulfur limit of about 0.4 lb/10^6 Btu. Although much less certain, control of sulfates could further reduce sulfur emission levels to about 0.2 lb/10^6 Btu (and also call for control of precursors such as trace metallic catalysts and ammonia). In sum, a reasonable expectation is that sulfur levels must be controlled, on average, to 0.2–0.4 lb/10^6 Btu by the year 2000.

It should be noted that today's strategies and standards apply only to the direct firing of coal. There are no formal emission regulations for coal conversion processes or for power plants fueled by their products. However, in at least one case (Lurgi dry ash gasification and cleanup trains for synthetic natural gas [SNG] production), EPA is considering even more stringent requirements that would call for emission levels comparable to those from the resource replaced (natural gas). The implication is that separate control requirements might be placed, for example, on a gasification or liquefaction plant (considered as a refinery) and on a power plant fired with synthetic gas or petroleum-type fuel. Certainly, this would add significantly to the processing costs for fuel conversion. However, in its study EPRI adopted for each conversion process a range of sulfur removal capability that can achieve the 0.2–0.4 lb/10^6 Btu sulfur level also assumed for direct-fired plants.

Coal quality and sulfur removal

Annual production of 1500 million tons of coal by the year 2000 is an assumption of the study. The logistic implications for production, processing, and transportation are neglected. So is the competing or overlapping demand for perhaps 850 million tons of coal to be used in synthetic fuel production (SNG, solvent-refined coal, low- and intermediate-Btu gas, and petroleum-type fuels). Some of these would be available to electric utilities, but production "splits" have not been estimated. The focus is simply on the sulfur quality of the coal.

Perhaps 100 million tons of low-sulfur eastern coal will be available to utilities each year, and from 300 to 600 million tons of low-sulfur western coal. Low-sulfur coal is considered to be less than 0.5% sulfur by weight; it runs about 8000 Btu/lb, so its sulfur quality can be expressed as being about 0.6 lb/10^6 Btu. It is thus considered capable of meeting today's new-source performance standards without sulfur control measures.

The balance of the coal expected to be needed in the year 2000 will be about 800 to 1100 million tons each year. It will be high-sulfur (2.5–3%) coal, running about 12,000 Btu/lb and, therefore, between 2 and 2.5 lb/10^6 Btu. Today's utility coal (overwhelmingly the high-sulfur variety) averages a sulfur content of about 2.4 lb/10^6 Btu. Assuming the same average in 2000, the sulfur removal requirement is 83–92% to attain likely regulatory levels of 0.4 to 0.2.

Of the estimated 1500 million tons of coal in the year 2000, some 150 million tons will be burned by the 10% of power plant capacity still exempt from emission controls. Of the balance, some 350–650 million tons will be low-sulfur coal requiring only minimal beneficiation. This leaves 700–1000 million tons of high-sulfur coal likely to need extensive cleaning or conversion. The average sulfur removal requirement for that coal is in the range of 80–90%.

Stated simply, 80–90% removal of sulfur will be sufficient to meet projected SO_2 standards between now and 2000. This is extremely significant because it implies that flue gas desulfurization with today's wet alkali scrubbing process will remain adequate throughout the same period. (Wet alkali scrubbing carries with it, of course, the need for either a sludge ponding area or some means to dispose of wet slurry.)

Estimating capital costs

The yardstick of direct comparison of alternatives takes shape in the dollar estimates of total power plant cost (Table 2). Consistency is the key, yet it is difficult to achieve when estimates come from different sources (as in this study)—even though many of the sources are conceptual design studies performed under EPRI sponsorship:

- Gasification, by Fluor Engineers and Constructors, Inc.
- Solvent-refined coal and petroleum-type fuels, by Ralph M. Parsons Co.
- Low-Btu gasification, by Combustion Engineering, Inc.
- Direct coal firing with wet alkali scrubbing, by Ebasco Services, Inc.

Other basic data came from a number of individual manufacturers. Notably, the estimates for atmospheric fluidized-bed combustion were supplied by General Electric Co. from its preliminary report on the National Science Foundation's Energy Conversion Alternatives Study (known as ECAS).

The estimate for a coal-fired plant with wet alkali scrubbing (and on-site sludge ponding) was used for normalization: Ebasco's estimate was compared with others by Combustion Engineering and by General Electric (for ECAS). This estimate assumed the use of eastern coal with 3% sulfur content, and all basic plant cost estimates fell within a range of 2%.

Table 2 also lists design heat rates assumed to be attainable in baseload

Table 1
TEN CLEAN WAYS TO BURN COAL

Method	*Sulfur Removed (%)*
Direct firing, pulverized low-sulfur coal	none
Direct firing, pulverized high-sulfur coal with wet alkali scrubbing and on-site sludge disposal	80–90
Direct firing, pulverized high-sulfur coal with regenerative scrubbing (using hydrogen produced on site) and reduction of gas to elemental sulfur	90–95
Direct firing, pulverized coal in a fluidized bed at atmospheric pressure with dry limestone added to the bed	80–90
Direct firing, pulverized solvent-refined coal	70–90
Liquid firing, petroleum-type fuel	90–95
Low-Btu gas firing (100–150 Btu/scf) after gasification in moving-bed, dry ash Lurgi gasifier and Selexol process for acid gas removal	>95
Medium-Btu gas firing (∼300 Btu/scf) after gasification in slagging moving-bed gasifier and Selexol process for acid gas removal	>95
Low-Btu gas firing (100–150 Btu/scf) after gasification in atmospheric, two-stage entrained gasifier and Stretford process for acid gas removal	>95
Medium-Btu gas firing (∼300 Btu/scf) after gasification in pressurized, two-stage entrained gasifier and Selexol process for acid gas removal	>95

Table 2
CAPITAL COSTS FOR TEN CLEAN WAYS TO BURN COAL

	Heat Rate (Btu/kWh)	*Base Cost ($/kW)*	*Contingency (%)*	*Uncertainty (%)*	*Total Cost** ($/kW)*
Conventional Steam Plants					
Low-sulfur coal	9,000	290	+10	±10	375–460
High-sulfur coal with alkali scrubbing	9,500	PP: 290 SR: 50 340	+10 +20	±10 ±20	485–625
High-sulfur coal with regenerative scrubbing	10,000	PP: 290 SR: 150 440	+10 +20	±10 ±20	575–740
Atmospheric fluidized-bed combustion	9,500	PP: 340	+20	+25, 15	450–665
Solvent-refined coal	9,000 BC:[d] 10,000	PP: 290	+15	±15	375–500
Petroleum-type fuel	9,000 BC: 13,400	PP: 190	+10	±10	250–300
Low-Btu gas, moving-bed, dry ash Lurgi process	BC: 13,600	PP: 190 SR: 390 580	+10 +20	±10 ±15	760–1,000
Medium-Btu gas, slagging-moving-bed process	BC: 11,300	PP: 190 SR: 255 445	+10 +20	±10 +25, −15	585–800
Low-Btu gas, atmospheric, two-stage entrained process	BC: 10,600	PP: 190 SR: 210 400	+10 +20	±10 +25, −15	525–710
Medium-Btu gas, pressurized, two-stage entrained process	BC: 9,800	PP: 190 SR: 155 345	+10 +20	±10 +25, −15	490–600
Combined-Cycle Plants					
Petroleum-type fuel	7,500 BC: 11,200	PP: 160	+15	±15	185–250
Low-Btu gas, moving-bed, dry ash Lurgi process	7,500 BC: 9,500	PP: 160 SR: 335 495	+15 +20	±15 ±15	650–875
Medium-Btu gas, slagging moving-bed process	7,500 BC: 9,100	PP: 160 SR: 215 375	+15 +20	±15 +25, −15	490–695
Low-Btu gas, atmospheric, two-stage entrained process	7,500 BC: 8,400	PP: 175 SR: 180 355	+15 +20	±15 +25, −15	460–650
Medium-Btu gas, pressurized, two-stage entrained process	7,500 BC: 8,150	PP: 160 SR: 130 290	+15 +20	±15 +25, −15	375–530

** Includes IDC and startup at 30% (except 22% for combined-cycle petroleum-type fuel plant).
PP = power plant.
SR = sulfur removal system.
BC = basis coal (coal conversion and power generation).

operation. (For intermediate load operation, as in daily cycling, the heat rate was assumed to be 5% higher.) Other vital assumptions were:

□ Conventional steam plants—2400 psi, 1000°F superheat, 1000°F reheat conditions

□ Combined-cycle plants—2200°F gas turbine inlet temperature and 16:1 pressure ratio, coupled to a 2400-psi, 1000°F steam bottoming cycle

Base capital cost for each plant is given in mid-1975 dollars per kilowatt. In each case, this figure consists of total construction cost, including contractor's overhead and fee, land cost, and owner's head office costs. It excludes contingency, escalation, and interest during construction. A contingency was then added, the amount depending on the degree of definition—for example, 10% for a coal-fired plant but 20% for a stack-gas scrubber.

The accuracy of estimates was considered separately and a range, or band, of uncertainty was assigned. Understandably, wider bands of uncertainty were linked with the less well-defined options that are still in early development. By adding or subtracting uncertainty figures, upper and lower capital cost estimates were obtained. Interest during construction, together with startup costs, was applied to each of these plant costs at a rate of 30%. (The combined-cycle option using petroleum-type fuel is an exception; a rate of 22% was used because of a significantly shorter construction period.) The total cost column in Table 2 gives the probable range of capital requirements for each plant.

Capital costs for the solvent-refined coal and petroleum-type fuel options do not include increments for their respective coal liquefaction plants. Costs associated with the liquefaction processes are incorporated in the fuel costs.

Estimating busbar power cost

The ultimate unit of measurement on this yardstick of coal utilization technologies is mills/kWh, the busbar cost of power from each candidate. Values were calculated for both baseload operation (at 0.65 capacity factor) and intermediate or cycling operation (at 0.35 capacity factor).

Busbar cost comprises both fixed and variable charges. A fixed charge rate of 18% per year was applied to the range of capital costs derived for Table 2. (Current utility experience varies around the U.S. between about 15% and 22%.) This covers interest on debt, return on equity, depreciation, insurance, and federal, state, and local income and property taxes.

Variable charges include the costs of fuel, chemicals, and operation and maintenance. Two levels of coal cost were investigated, $\$1/10^6$ Btu and $\$2/10^6$ Btu, but only the former, which is representative today, was used in the computations for Figure 1. (An exception is the case of direct-fired low-sulfur coal, estimated to cost $\$1.25/10^6$ Btu because of delivery charges.) Raising the coal cost across the board would increase plant fuel expense by varying amounts, depending on the heat rates of the different options.

Fuel costs for the solvent-refined coal and petroleum-type fuel options are based on high-sulfur feed coal at $\$1/10^6$ Btu, but they also include plant charges for liquefaction. Recent cost estimates for such plants are $\$2.50–\$2.75/10^6$ Btu and $\$3.50–\$3.75/10^6$ Btu, respectively.

Chemical costs were found to be negligible for most plants (0.1–0.2 mills/kWh), except for the coal-fired plant with wet alkali scrubbing and the atmospheric fluidized-bed combustion plant. In the latter case, for example, stoichiometric requirements for sulfur removal are uncertain but range between 0.3 and 0.6 ton of limestone per ton of coal. Since the cost of limestone itself varies from $5/ton to $20/ton, the resulting range of chemical cost becomes significant, and two levels were computed for use with the high and low busbar cost estimates, respectively.

Operation and maintenance costs were estimated on the basis of plant complexity, ranging from 2 mills/kWh for direct coal firing (without stack-gas scrubbing) to 4 mills/kWh for a combined-cycle plant with coal gasification. For intermediate cycling service, all operation and maintenance costs were assumed to be 0.5 mill/kWh higher than for baseload operation.

Reading the yardstick

It is perhaps no surprise that direct-fired low-sulfur coal comes in with the lowest busbar power cost for both baseload and intermediate operation: 25–28 mills/kWh and 36–41 mills/kWh, respectively. Nor is it unexpected that high coal costs tend to favor options with lower heat rates—generally, the combined-cycle plants.

But the most telling conclusion of the study, to date, intimately related to projected emission standards and foreseeable needs for sulfur removal, is that direct firing with wet alkali scrubbing, a technology almost fully developed today, is the second most attractive baseload option, at 28–34 mills/kWh with high-sulfur coal.

Other findings (all apparent in Figure 1) are: (1) busbar power costs for baseload operation are in the 25–40-mill range, except for Lurgi low-Btu gas and petroleum-type liquids fueling conventional steam plants; (2) regenerative scrubbers, advanced gasifiers (beyond the Lurgi), and atmospheric fluidized-bed combustors are all comparable for use with conventional steam plants—and only slightly more expensive than plants with wet alkali scrubbing—for either baseload or intermediate duty; (3) only the combined-cycle versions of advanced gasification processes show promise of being less costly than low-sulfur coal; (4) combined-cycle plants using petroleum-type fuels and medium-Btu gas from advanced gasifiers have comparable costs for intermediate service; (5) atmospheric fluidized-bed combustion looks attractive in baseload operation, but there is significant uncertainty in its economic performance.

Using the yardstick

The payoff from this study is not the economic benefit that any utility can get by adopting the "winning" coal technology. The payoff is in the better shaping of R&D emphasis in EPRI's direct coal utilization and coal conversion programs. Six examples suggest the ramifications:

□ New funding is being allocated to research on scrubbers, because they are the most economically attractive prospect for plants that must comply with tighter SO_2 emission standards.

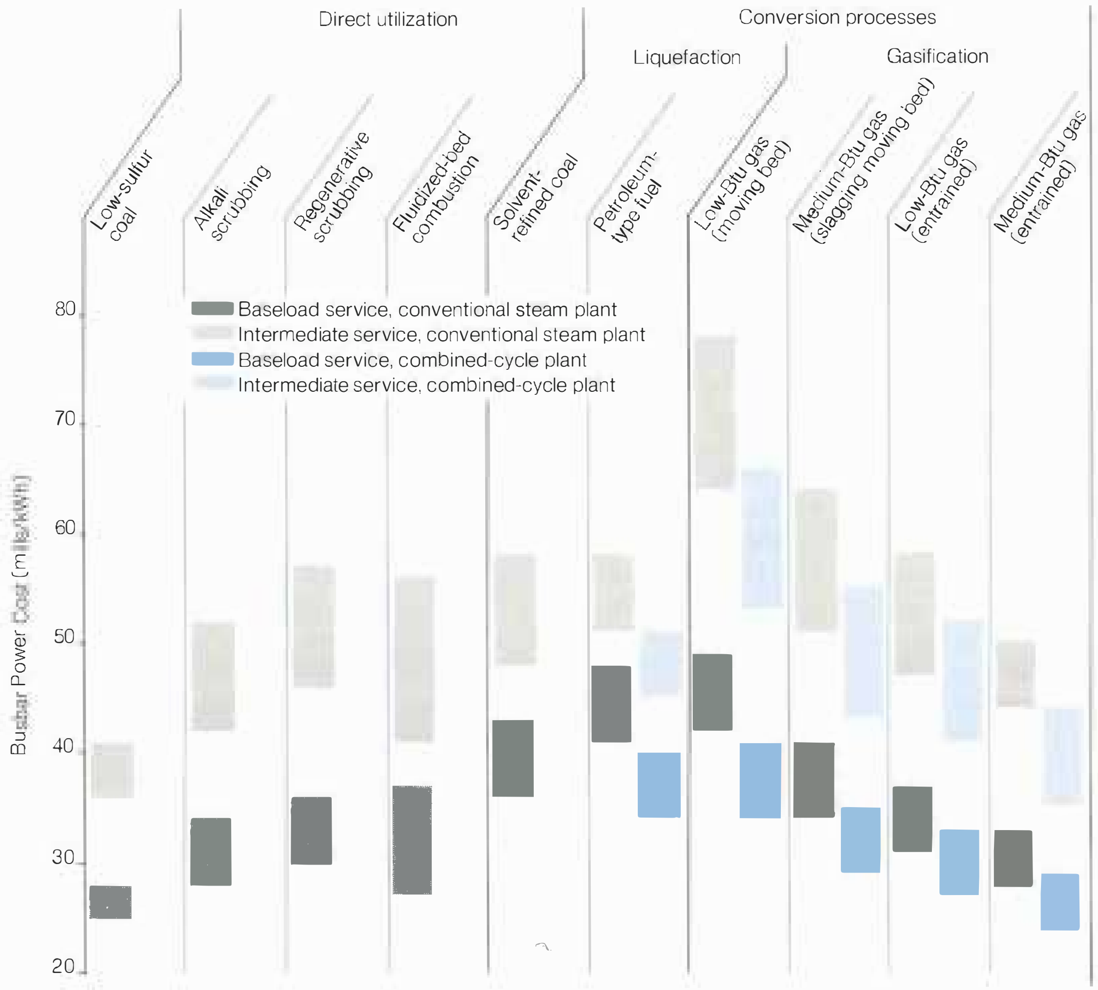


Figure 1 The ranges of busbar power cost for coal fuel technologies are most easily compared in groups: four options for direct coal firing,two liquefaction processes, and four gasification processes. In each group, the present—or most nearly developed—option is at the left. Thus, among the direct-firing options, each results in successively more costly power than power from low-sulfur coal without controls. Among the gasification processes, however, the more advanced—and, at the moment, more uncertain—versions produce markedly cheaper power.

Reliable operating procedures for wet alkali scrubbers (to overcome corrosion, fouling, and plugging) should improve their availability and cut maintenance charges by one third. For regenerative scrubbers, which require less land area for waste disposal, the aim is to develop practical process alternatives meeting a range of utility needs. (Different process by-products are salable in different regions.)

□ More attention is being given to total plant requirements, all the way from raw coal to busbar energy. It's a system view rather than a narrow focus on one or another coal conversion technology. And it is particularly pertinent for solvent-refined coal and petroleum-type fuel processes. For example, EPRI is exploring how such fuel processing costs might be cut by modifying gas combustors and gas turbines so they can accept lower quality fuels.

□ Two major coal liquefaction processes, H-Coal (Hydrocarbon Research, Inc.) and Donor Solvent (Exxon), are getting the thumbs-up sign to produce both utility fuel oil and gas turbine fuels. EPRI plans major funding to support the operation of large pilot plants (250–600 ton/day) for both these processes. In contrast, major pilot plant support is not planned for any other process that yields petroleum substitutes from coal.

□ Coal gasification integrated with a combined-cycle plant remains a high priority because of the need for operating experience with this technology. Three coal gasification schemes are taking favored positions for further EPRI R&D attention: the slagging moving-bed gasifier (British Gas Corp.) and the partial-oxidation entrained gasifier (Texaco), both for combined-cycle plant application, and the atmospheric, two-stage entrained gasifier (Combustion Engineering, Inc.) for fueling a conventional steam plant. Research efforts on other advanced gasification systems are being cut back.

□ EPRI's fluidized-bed combustion research is now focused on the atmospheric-pressure process, and a test facility is being built. The pressurized FBC concept is being minimized.

□ The importance of reliable gas-steam combined-cycle power plants is newly evident and getting attention. One major new effort for EPRI has been the work with utilities and suppliers toward demonstration of an air-cooled gas turbine that can operate in the temperature range of 2100–2300°F.

Is cost the only yardstick?

The seeming simplicity of EPRI's "first cut" at analyzing coal technologies suggests the question whether cost is the only yardstick. The answer is yes, but only because it is so nearly universal a way to recognize many variables. A better question seeks to clarify the cost of *what.*

This article—and up to now the EPRI analysis it portrays—has focused on the cost of one factor alone: sulfur removal. The criterion for the various options was only their design capability to meet projected sulfur control levels of 0.2–0.4 lb/10^6 Btu with coal having a 2.5–3.0% sulfur content (2–2.5 lb/10^6 Btu).

What must be emphasized is that many other important variables, and their inevitable effects on costs, have knowingly been omitted in the interest of simplicity and so that an R&D guidance scale could be quickly assembled. One example is NO_x control. What will be required? How widely? When? By what process means and at what cost?

Similar questions can be asked about siting restrictions, cooling water requirements, and waste disposal, to name a few. Always, the bottom-line question is "At what cost?" As more of these variables are researched and included in the estimates, the busbar power costs will change, and perhaps even the relative ranking of options.

Despite their favorable ranking on the basis of sulfur removal cost, wet alkali scrubbers may not retain their advantage as other coal technologies show the need for less land area, or a smaller volume of cooling water, or as they exhibit lower overall heat rates (which some already do).

Mid-term commercialization (that is, between 1985 and 2000) is now the earliest foreseen for even the most promising coal options. Today's simple screening, based solely on the cost of sulfur removal, enables a more focused, efficient allocation of R&D funds. As the cost implications of other factors are included, the resultant fully documented research will reveal the best choices for clean coal utilization.

Modeling future capacity

The existence of consistent, directly comparable cost data for coal conversion technologies enables some interesting modeling, too. It's one thing to use the figures for direct comparison of isolated plants. But it would be more meaningful to see the effects of utility system interaction. EPRI is therefore using its study data as inputs to a half-dozen representative utility system models that will expand in generating capacity by selecting the technologies that yield minimum incremental power costs. Since these expansion models closely simulate utility systems throughout the United States, it should be possible to better assess the potential for each technology in a future national generation capacity.

The modeling should also help to answer a perennial question about R&D leverage. The new coal conversion and power generation technologies, as selected by the operation of the expansion models through some period of time, can be identified and assessed, and their total economic benefit to the national energy picture can be estimated. Comparing the benefit to the R&D cost gives the leverage, another tool for figuring priorities and establishing funding—possibly for the next annual updating of this benchmark study of clean coal and what it costs at the busbar.

Gas-Insulated Cable Research Aims for Versatility

by Ralph Samm

Design refinements, better materials performance, and fabrication in longer segments will reduce the installed cost of gas cable and increase reliability. That's when applications of gas cable at greater distances and at smaller power and voltage ratings will be possible.

□ An EPRI program feature

Gas-insulated transmission cables have a short history: barely 5 years of use and only a little more than 4 circuit miles in operation. But these cables, from 100 to 3300 ft long, are on 18 electric utility systems, and more than a third of the total length has been added just this year (Table 1).

Although surveys tell us that the use of underground transmission will grow slowly in the next several years (perhaps 100–125 circuit miles annually), the proportion of gas-insulated systems is expected to increase as utilities gain confidence from their operating experience and a better perception of the most economical applications. Economy, of course, is the motive, and it is found today in higher power ratings, simpler installation, easier maintenance, and lower operating cost—all in comparison with high-pressure oil-filled cables.

Understandably, gas cable technology is still undergoing major developmental change. The EPRI-sponsored research program has as a goal gas-insulated systems that can transmit large blocks of electric power—functionally equivalent to overhead lines in the EHV (345–500 kV) and UHV (≥765 kV) range. Part of the program therefore concerns the most logical sequence for technical improvements in today's systems, with cost reduction a major objective. Another research focus is the development of flexible cable enclosures. This article briefly reviews the system performance considerations of gas-insulated cable and the developmental directions of major components: the gas, the conductor, the spacer, and the enclosure.

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The system

The basic gas-insulated cable is schematically simple: a hollow aluminum conductor (or three conductors) symmetrically positioned at intervals by spacers within a grounded sheath. Rigid sections 40–60 ft long are factory assembled and sealed for shipment, then evacuated (to remove moisture) and filled with a dielectric gas after installation. Conductors mate (sliding contacts) when cable sections are butt-welded together in the trench.

The isolated-phase (one-conductor) configuration has been in commercial service in the United States since 1971. The three-conductor design has recently been developed for transmission systems in this country; however, it is already in substation use in Japan and in Europe (France, Germany, the Netherlands).

At present, gas cables compete mainly at the higher voltages (345 kV and above), higher power ratings (2000 MVA or more), and shorter lengths ($\frac{1}{2}$ mi or less). Compared with other cables they are physically large, due to dielectric considerations. But they have an inherent self-cooling capacity to match overhead line ratings, and still higher voltages are accommodated simply by scaling up in size; dielectric losses are negligible, and forced cooling, easily added and maintained, could more than double the self-cooled ratings. A first approach to gas cable cooling is the use of water pipes to remove heat from the cable enclosure.

Size, materials costs, and manufacturing costs today tend to make gas cables

Table 1
GAS-INSULATED CABLE EXPERIENCE

Utility	*Cable Rating (kV)*	*3-Phase Circuit Length (ft)*	*Installation**	*Year Energized*
Cleveland Electric Illuminating Co.	362	450	A	1971
Cleveland Electric Illuminating Co.	362	450	A	1972
Consolidated Edison Co. of New York, Inc.	362	520	U	1972
Potomac Electric Power Co.	145	210	A	1972
Public Service Electric and Gas Co. of New Jersey	242	600	U	1972
New Orleans Public Service, Inc.	145	150	A	1972
Southern California Edison Co.	242	550	U/A	1973
Potomac Electric Power Co.	145	520	A	1973
Duke Power Co.	242	2200	O	1974
American Electric Power Co., Inc.	145	1600	U	1974
Arizona Public Service Co.	242	370	A	1974
Commonwealth Edison Co.	362	1900	A	1974
Boston Edison Co.	362	630	U	1974
Central Illinois Light Co.	362	1100	A	1975
Bonneville Power Administration	550	700	U	1975
Hawaiian Electric Co., Inc.	145	150	A	1975
Quebec Hydro-Electric Commission	800	100	A	1975
Arizona Public Service Co.	242	300	O	1975
The Hydro-Electric Power Commission of Ontario	242	2300	A	1976
American Electric Power Co., Inc.	145	2000	U	1976
Public Service Co. of New Hampshire	362	3300	A	1976
British Columbia Hydro and Power Authority	550	1760	T	1976

Source: *Guide to the Use of Gas Cable Systems.* Final report prepared by I-T-E Imperial Corporation, Greensburg, Pennsylvania, September 1975. EPRI 7825.

*A = Above ground
U = Underground
O = Open trench
T = Tunnel

expensive per unit length, so—everything else being equal—they are most advantageous over short distances where overall economy is preserved by their simple, inexpensive terminations and the absence of costly pressure maintenance equipment.

Although gas-insulated cables and substations differ as applications, and therefore in some operating conditions, the basic technology is common to both. Concepts and hardware are frequently interchangeable. For example, gas-monitoring systems (to measure density and moisture content) and terminations being developed for substations will have direct application to cables. Similarly, flexible cable enclosures, low-cost insulating spacers, better contamination control, and components for higher operating temperatures under development for gas cables will improve the technical and economic performance of gas substations.

The gas

The dielectric gap between conductor(s) and grounded sheath is filled with SF_6 gas compressed to 22–45 psig (2.5–4.0 bars) maximum. Other gases and mixtures are being investigated, but gas system designs in the near term depend on the qualities and technology of SF_6.

Initially, gas cables were designed for an operating stress at the conductor of 60–80 kV/in, less than one-third the stress on an oil-paper–insulated cable. This conservatism was directed by the requirement that a system maintain dielectric integrity at operating voltage even if a leak caused complete loss of gas pressure. Early cable designs were severely penalized by the resultant materials costs.

With better control of both factory and field welding techniques, which lowered the incidence of leaks, the pressure-loss criterion was eliminated. Systems now operate at 45 psig with an operating stress of 80–100 kV/in.

But even in attaining these stress levels, new problems were encountered. Inherent in any compressed-gas system are small conductive particles that act as contaminants, reducing the dielectric strength of the gas below its theoretical level under absolutely clean conditions. Interestingly, under some conditions of contamination the dielectric withstand value peaks near 45 psig and then falls off at higher pressures. Better and cleaner factory and field assembly techniques are making higher stress levels possible. So are methods to immobilize (trap) the particles. Development now under way is aimed at a 120-kV/in operating stress.

Particle control to allow operation at higher pressures is not necessarily the ultimate answer. Dewpoint temperature must also be considered. SF_6 at 45 psig has a dewpoint of −40°C (−40°F). Therefore, in areas where temperatures are expected to go this low, the operating pressure must be limited. Fortunately for most systems, underground temperatures remain above −40°C, and higher pressures can be planned. Alternative designs with lower pressures must be used where systems come to the surface (or for systems built entirely above ground).

Other qualities of SF_6 influence cable design, particularly for surface application. SF_6 is very stable up to 150°C, and it has excellent convective heat transfer characteristics. The present maximum temperature limit for a gas cable conductor is 105°C (hot spot), but the differential from conductor to enclosure does not exceed 25°C. Buried cable is limited also to a 70°C maximum enclosure temperature (to minimize earth drying and possible thermal runaway). This means a nominal conductor temperature of 95°C (allowing 10°C for a hot spot in the sliding contact).

A surface system (or one that is forced-cooled) can dissipate heat more readily. Therefore, its conductor temperature may rise above 105°C without the enclosure temperature running above 70°C. Subject to limitations in other cable components, the conductor could even approach 150°C. An air-cooled enclosure might then exceed 100°C, and for safety, such a system would need to be isolated from human access. But forced cooling would hold down the enclosure temperature under otherwise comparable circumstances.

Two further useful characteristics of SF_6 (as with most gases) are its dielectric constant of just over 1.0 and dielectric loss of nearly 0.0. The near-unity constant results in low capacitance and, therefore, low-charging current. With the combination of low-charging current and negligible dielectric loss, a conductor can be more fully loaded.

The conductor

Present practice for rigid systems calls for the use of an extruded tubular aluminum conductor. Skin-effect considerations limit its wall thickness to between 0.5 and 0.75 in; heavier walls are not cost-effective. Also to be taken into account are expansion and contraction of the 40–60-ft-long tube. This varies between 0.5 and 1.0 in and is successfully controlled by sliding plug-in contacts for operation up to 105°C. Because gas maintains its integrity to 150°C, research is in process to uprate the capacity of these connectors.

An alternative to the extruded conductor is one incorporating stranded aluminum. Such a design is being developed for use in a flexible gas-insulated enclosure. The stranded-aluminum segments are held in place by a very thin corrugated copper sheath. A design trade-off will be made between a conductor compliant enough to contain its own expansion, and one rigid enough not to sag between spacers. This is not seen as a problem.

A third alternative for the conductor is either a thin rigid tube or a flexible tube filled with sodium (for lower cost) and sealed in manufacture so that no field handling of sodium would be required. This conductor is being studied under EPRI sponsorship, and if the manufacturing problems can be overcome, a less expensive and less energy-intensive conductor should result.

The spacer

Gas cable designs today usually call for either a conical spacer or a post spacer

(Figure 1) to hold the conductor(s) away from the ground sheath. The material is either a cycloaliphatic epoxy or a bisphenol epoxy. Cycloaliphatics have the advantage of being arc resistant during low-power flashovers (i.e., power levels normally associated with testing). Bisphenol spacers, however, can be coated with arc-resistant materials. They also offer the advantage of a lower dielectric constant than cycloaliphatics and a coefficient of expansion more closely matching that of aluminum. Heavy, cast spacers normally require inserts at the inner diameter for voltage-stress relief.

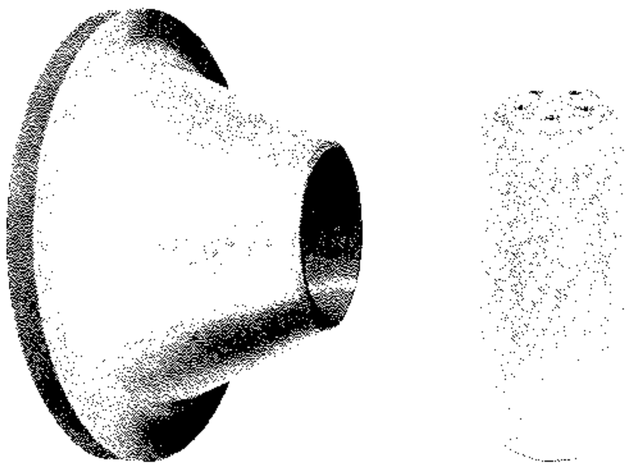
Spacers of both materials are under continuing development in sponsored research. But because they are limited to approximately 120°C maximum operating temperature, higher-temperature materials are being investigated in the hope that better advantage can be taken of the properties of SF_6.

A novel approach is the thin-sectioned low-dielectric-constant spacer (Figure 2) developed under contract for the flexible gas-insulated cable system. In this instance, the spacer is made in two identical halves that are snapped together around the continuous conductor during factory assembly. One of the prime considerations is low cost, since many more spacers must be used per unit length. In accomplishing this objective, other advantages accrued. For example, the thin wall of the spacer creates very little field distortion; therefore, the stress gradient on the insulator surface is uniform. This, in turn, gives better dielectric withstand values for a given size. Arc-resistant materials (those not requiring the use of coatings) and materials capable of operating at higher temperatures are problems still under investigation.

The enclosure

For voltage ratings of 345 kV and below, extruded aluminum enclosures are available (usually a wall thickness of 0.25 in); however, a price penalty is incurred due to the costly extrusion process. Maintenance of dimensional stability is the major problem with large-diameter thin-

Figure 1 Conical spacer can act as a hermetic barrier and to localize contaminants from fault arcs. Post spacer is cheaper for large diameters because less material is needed. Typically three posts are fitted to a collar on the conductor.



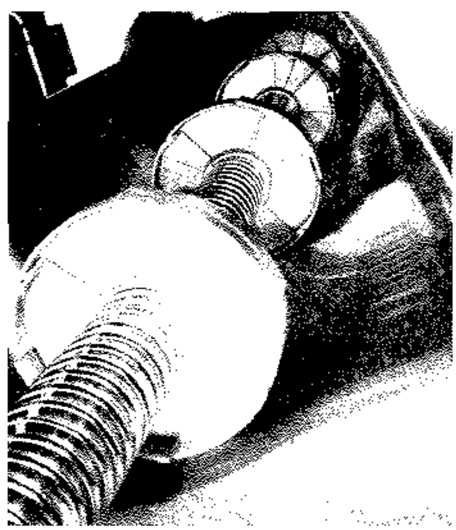


Figure 2 Low-dielectric-constant spacers snap on flexible cable before dies shape the enclosure for welding and corrugating.

Figure 3 Large-diameter enclosure consists of three identical segments, each with preassembled conductor and posts.

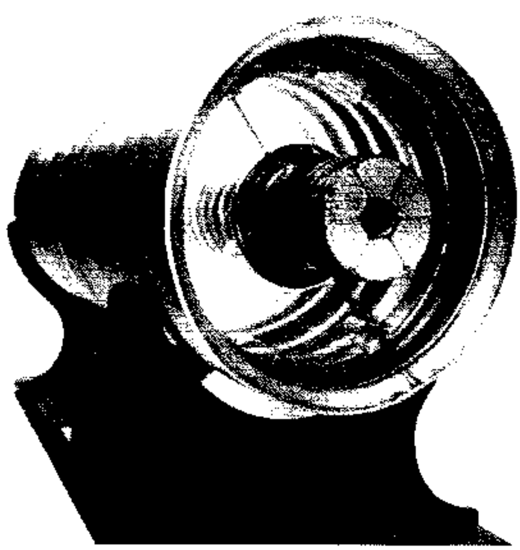


Figure 4 Corrugations create flexibility in a long cable section after enclosure has been wrapped around spacers and conductor and sealed with a continuous weld.

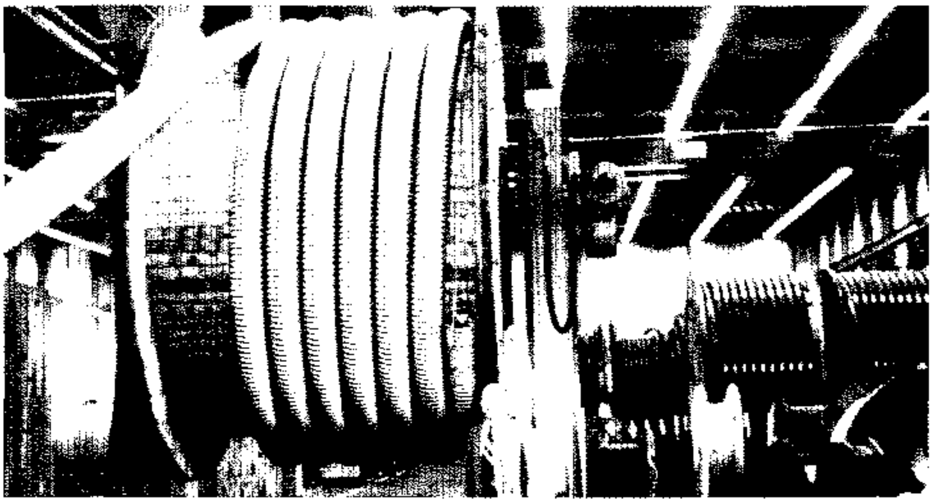
wall aluminum shapes. On the other hand, the advantages of an extruded enclosure are that both high-strength and high-conductivity alloys can be used. Essentially these are the 6000 series heat-treatable alloys. The requirement for conductivity needs no further explanation. High strength is necessary because the system, normally buried at a modest ambient temperature (20°C) and completely constrained by the earth, is operated at 70°C and thus experiences a 50° temperature differential. Unable to expand, it must withstand all stresses internally. The weakest link in a rigid system is normally the weld-annealed region where the sections are joined.

An alternative to the extruded enclosure is one formed from aluminum strip rolled and welded in a helix. This spiral welding procedure, as well as the base material, is less expensive; however, aluminum strip is not available in heat-treatable alloys. To gain a moderate degree of strength, lower-conductivity alloys must be used. This poses a trade-off for designers in their choice of materials and techniques.

For voltage levels above 345 kV or for three-conductor systems that require large-diameter enclosures, a reasonably good solution is an extruded segmental enclosure (Figure 3). Because of the dimensional stability of this design, there is less waste from deformation during handling, and the manufactured cost is about one-third less than for single extrusions. While the welding required to convert three segments into a completed enclosure adds to the cost, the lower materials cost more than compensates. Another advantage is that heat-treatable high-conductivity alloys are available for fabricating this enclosure.

Beyond these rigid cable enclosures lie flexible designs with the potential features of lower installed cost and greater reliability. They should enable gas-insulated systems to compete at lower voltages, greater lengths, and smaller power ratings. For example, a 345-kV flexible gas cable (Figure 4) now under EPRI-sponsored development is expected

Figure 5 Flexible gas cable prototype for EPRI-sponsored research has a diameter of ~12 in (300 mm). This cable is 120 yd (110 m) long.



to be at least 25% cheaper on an installed-cost basis—even at only 1000-MVA ratings, where conventional high-pressure oil-filled cables have the edge today.

The aluminum strip used to fabricate flexible cable (by a continuous process that forms the strip into a cylinder and welds a single longitudinal seam) has a relatively low strength but good conductivity and welding properties. The corrugated configuration is also compliant and thus adaptable to the stresses of temperature cycling when constrained by backfill in the trench.

Reliability will be enhanced by the use of long, factory-tested lengths (300 ft for 345-kV cable versus 60 ft for its rigid counterpart) requiring fewer field joints. Field welding is not only costly but also affords many more opportunities for contaminants to enter the cable enclosure.

The feature of flexibility also produces major economies in shipping and handling costs (Figure 5). The manufacturing process calls for continuous fabrication with lower-cost materials, and lengths are limited, in practice, only by the overall diameter of the shipping reel flanges.

Coordinating the elements

Gas cables must be viewed as systems. They offer high capacities, equal to those of overhead lines, but at a cost premium. However, they are simpler and easier to operate, and for many installations they are less costly than oil-filled cable. R&D is directed toward making gas cable systems more economical and reliable. Because the cost of terminations, pressure maintenance, and cooling is already minimal, reductions in cable cost will make longer systems attractive.

SF_6 gas has advantages and disadvantages as a dielectric. Its advantages are (1) near-unity dielectric constant, (2) practically zero dielectric loss, (3) good heat transfer characteristics, and (4) high thermal stability. Its disadvantages are (1) dielectric degradation with contaminants present and (2) high dewpoint temperatures above 45 psig.

Extruded aluminum conductors used today are limited by thermal-mechanical considerations at operating temperatures that are otherwise feasible (above 105°C). Sodium-filled tubing is being investigated as an alternative to the flexible stranded-aluminum conductor, which will comply with the thermal forces.

Cast epoxy spacers are heavy, expensive, and have nonuniform surface-stress gradients. Innovative designs incorporating thin walls, different materials, and less expensive manufacturing processes should overcome these problems.

The gas cable enclosure, normally an extruded aluminum tube, is a major expense item in the system. Spiral-welded tubing made from aluminum strip offers some relief, and extruded segments are less expensive for larger diameters. In terms of both cost and performance, the major breakthrough is expected to be a flexible, corrugated-aluminum enclosure.

Taking full advantage of gas-insulated transmission depends on successful design coordination of all components into an operating system. Today's individual applications are the proving ground, and the firsthand experience of 18 electric utilities should be the basis for wider acceptance.

Plutonium: Facts and Inferences

by Cyril L. Comar

Plutonium has become an emotionally charged word, triggering in the public mind fears of nuclear disaster. Scientific evidence, however, indicates that plutonium as a "hazard" is no more dangerous to human health than other chemicals we have learned to deal with.

This overview of what we know and can infer about plutonium is drawn from a recently published 164-page EPRI report, "Plutonium: Facts and Inferences" (EA-43-SR). The scientific review, intended to help place the plutonium issue in clearer perspective, was prepared by Cyril L. Comar, director of EPRI's Environmental Assessment Department. Major contributors were Waldemar B. Seefeldt, William J. Mecham, and Martin J. Steindler of the Argonne National Laboratory; Bernard Cohen, University of Pittsburgh; Gwyneth Howells, Central Electricity Research Laboratories, United Kingdom; and Newell Stannard of the University of Rochester Medical Center.

Every so often a word or phrase captures the public imagination as the embodiment of deep-seated apprehensions. "Plutonium" is now such a word. It triggers fears of nuclear warfare and annihilation, of humanity's manipulation by technology, of growing terrorism, and of the loss of civil liberties. It arouses frustrations with inadequate political and economic processes as well as anxiety about laying a health burden on present and future generations.

A basic question is whether society should create plutonium for industrial purposes, given that it is toxic and could be hazardous if enough were to be deposited in the bodies of workers or the general public. Today's power reactors, which are fueled by uranium, create plutonium internally as an inevitable by-product of their energy production, so two additional questions arise: Is plutonium the limiting safety factor in nuclear power? And is the industrial use of nuclear power justified at all, in terms of its biological risk as compared with the risks in producing electricity in other ways or the risk of having electricity and energy shortages?

Isolated statements can be made that are true in a limited sense but misleading as a basis for public opinion and public policy. For example: it may be true that a single pound of plutonium could deliver millions of doses of lung cancer–inducing radiation. This statement is misleading because of the ease of controlling plutonium and because experience has shown that only a minute fraction of any uncontrolled plutonium could conceivably get into human lungs. It is comparable to the statement (also true) that the amount of arsenic imported annually into the United States is sufficient to cause more than a billion human fatalities—a statement that ignores the fact that arsenic, however lethal, cannot and does not kill people who are not exposed to it.

In the opposite vein, it is also literally true that, although about five tons of plutonium have already been released to the biosphere from nuclear weapons, not one case of lung cancer ascribable to plutonium has been recorded. This statement may be equally misleading as proof, because present radiobiological theory, interpreted conservatively, would predict some increase in worldwide cancer rates as a result of such plutonium exposure, even though the increase might be too small to show in our medical statistics.

The broad decision about whether to develop nuclear energy for power production must therefore take many complex issues into account: the comparative environmental and health costs of various modes of electricity production; the possible health costs of inadequate electricity; demand patterns; the availability of resources; and the timing of bringing new energy sources into production. Our task here is not to explore those issues. Rather, it is to set forth a fair representation of facts about plutonium as one component of nuclear energy that has become a special focus of public concern. These facts should lead to a more realistic understanding of plutonium risks and should offer some guidance in reaching policy decisions about comparative risks in energy production.

Role and chemistry

Shortly after its discovery, plutonium was found to undergo fission with thermal neutrons. Knowledge of this fact spurred tremendous efforts to produce it in large quantities for military purposes. Of broader significance for societal purposes, however, is that plutonium is central to the use of nuclear fission for producing electricity and that it has other uses in industry and medicine.

The element plutonium is a silvery-white metal, atomic number 94 in the actinide series. There are at least 16 different isotopes of plutonium, of which the four most important are: plutonium-238 (half-life, 86.4 years), plutonium-239 (half-life, 24,390 years), plutonium-240 (half-life, 6580 years), and plutonium-241 (half-life, 13.2 years).

Plutonium-238 is very useful as an isolated power supply: in space, for communications in remote locations, for cardiac pacemakers, for artificial heart devices. About 40 kilograms of plutonium-238 have already been specially produced for such purposes. It is not a significant component of normal nuclear fuel.

Plutonium-239 is the most common plutonium isotope, being abundantly produced in reactors. A light water reactor contains about 600 kilograms; the liquid metal fast breeder reactor proposed for commercial operation would contain about 3000 kilograms. And over 200 tons of plutonium-239 have been processed for weapons purposes.

In its assorted applications, plutonium is composed of varying percentages of the different isotopes, the higher ones being produced by the action of neutrons on plutonium-239 in the reactor. Reactor-grade plutonium is roughly 70% plutonium-239 and 20% plutonium-240, whereas weapons-grade plutonium is roughly 93% and 7%, respectively. Generally, the longer the fuel is utilized in the reactor, the higher the proportion of plutonium-240 produced and the less suitable it is for weapons purposes.

Several characteristics of plutonium are important in determining its biological impacts. First, plutonium emits alpha radiation, which penetrates matter poorly. So it is not a hazard as long as it is outside the body (the radiation does not penetrate the outer layer of dead skin). But plutonium is highly carcinogenic when deposited in or on living tissue. Second, plutonium usually exists as plutonium dioxide, a compound that tends to be highly insoluble in water and in body fluids. Third, plutonium tends to adsorb onto undigested food and other materials, which causes it to be poorly absorbed from the gastrointestinal tract, and also to migrate very slowly in soil. Fourth, plutonium, unlike many other carcinogens, is easily detectable both in the environment and in living things so that any needed protective action can be anticipated and implemented. Finally, plutonium, because of its long physical half-life, must be regarded as a permanent contaminant, as are many other stable industrial chemicals that pollute the biosphere.

Toxicity and hazard

The public has been told, "Plutonium is the most toxic substance known to man." *Toxicity* is a medical term defined as the inherent capability of a substance to produce injury once it reaches a particular tissue within the body. In this sense, plutonium is certainly highly toxic. However, of greater importance to human beings is not toxicity but, rather, a more inclusive property called *hazard.* The hazard of a substance takes into account not only its toxicity but its availability—the extent to which the substance can actually reach individuals and have its toxicity take effect. For plutonium, the factors that determine its hazard are the amount that is handled, the effectiveness in preventing its release from the time of production through waste storage, the degree to which environmental and biological processes tend to determine the exposure of human beings to that which may be released, and finally, its toxicity.

Toxicity and hazard are not necessarily closely related. The hazard of highly toxic materials can be maintained at low levels by proper means. Conversely, materials that are only moderately toxic can represent great hazards if handled carelessly or if their toxicity is unrecognized. The hazard of ingesting plutonium is much less than that of ingesting other equally toxic substances, because plutonium is so poorly absorbed from the gastrointestinal tract and because the penetrating power of its radiation is so low. For example, it may be surprising, but plutonium taken by mouth is relatively innocuous because so little is absorbed into the body and, being mixed with intestinal contents, it cannot appreciably irradiate the tissues as it passes through the tract. Swallowing plutonium, then, is much less hazardous than swallowing ordinary chemicals such as various compounds of cyanide, lead, and mercury or radionuclides such as iodine-131 and strontium-90. Inhaling plutonium or being injected intravenously with it is just about as hazardous as the same procedures would be with various compounds of cyanide, lead, and mercury—and much less hazardous than with so-called supertoxics, such as botulinus toxin and others produced by biological processes.

These comparisons are made, not to justify an exposure to plutonium in light of the hazards of other chemicals, but rather to emphasize that society has learned to protect itself against harmful substances and must continue to be vigilant in the improvement of public health procedures. It is also important to note that the effects from plutonium are not manifest for many years, whereas those from many other toxic substances are apparent immediately. This is not to say that a premature death delayed for 15 years or so is any less deplorable than an immediate death, but the lack of immediate effects does reduce the suitability of plutonium for terrorist or criminal purposes.

The long-term effects of plutonium are of greater concern than immediate toxicity. It is difficult to compare plutonium with chemical carcinogens because of a lack of data on them and the absence of standard methods for estimating their long-term toxicity. But there is little question that inhaled plutonium would rank on a weight basis with the chemical carcinogens now recognized. Recent conservative extrapolations (indirectly derived and admittedly imprecise) suggest that inhalation of 1 microcurie of plutonium-239 could cause roughly a 1% incidence of induced cancer, with lung cancer being about twice as likely to occur as either skeletal or liver cancer. Expressed in other ways, it could be assumed that if 100 persons each inhaled 1 microcurie of plutonium-239, one person might die from plutonium-induced cancer; or it could be assumed that one radiation-induced cancer might occur for each 100 microcuries of plutonium-239 inhaled by the general population.

Estimates of possible genetic effects have been made on the basis of observations that systemic plutonium-239 can become deposited in the testes and ovaries. These estimates involve large uncertainties, but the genetic effects per unit of plutonium-239 deposited within the body appear to be equal to or lower than the direct carcinogenic effects. It is important to note here that our numerical estimates of risk from low-level radiation are considered upper limits, and useful for comparative policy purposes rather than as quantitative predictions of actual effect.

Applications

Military Over the past 30 years or so, there has been a great amount of industrial experience in handling large amounts of plutonium, mainly in connection with weapons production and to a lesser extent with the nuclear power cycle. Billions of dollars have been invested to produce tons of the metal, to utilize its energy, and to manage its degradation products.

Military operations have included separation of plutonium from spent uranium fuel, its conversion to oxide and fluoride, reduction to metal, metal fabrication, scrap recovery, and large-scale shipping. More than 200 tons (200,000 kilograms) of plutonium have been processed and about 8000 shipments made. Experience indicates that inadvertent releases from processing in facilities designed to handle radioactive material can be kept at low levels.

Two accidents involving nuclear weapons have been reported. At Palomares, Spain, in 1966 two weapons accidentally dropped from a United States plane were detonated by high explosives on impact, and plutonium was dispersed over 1200 acres. Near Thule, Greenland, in 1968 a United States bomber crashed, causing four weapons to burn and leave plutonium-contaminated debris and fuel scattered along a path about 700 meters long. Extensive cleanup operations were performed in both cases, and large quantities of contaminated material were shipped to the United States. Despite these accidents, the concentrations of plutonium in the bodies of villagers near Palomares and the levels of plutonium in the air at Thule remained considerably below the exposure levels permitted in the U.S. for workers who come into contact with radioactive materials.

Commercial Estimates of the plutonium that would be released into the environment by an expanding civilian nuclear power industry are of great importance. The estimates summarized later in this overview are based on actual operating experience, where it exists, and on detailed analytical studies, where it does not, as in the case of certain hypothetical accident situations.

In fuel reprocessing, plutonium compounds recovered from spent uranium fuel are converted into plutonium oxide. During the conversion process, minute particles of plutonium oxide could be carried by the gases given off. All off-gases are therefore passed through several high-efficiency particulate-air (HEPA) filters in series. The performance and reliability of these filter systems have been intensively studied. There are operational data available from two government plants and one commercial plant, which operated for seven years until it was closed in 1971 for expansion and improvement of procedures.

In fuel fabrication, plutonium oxide is ground into a fine powder, blended with uranium oxide powder, granulated, pressed into pellets, and machined for loading into fuel rods. Most operations are carried out in airtight glove boxes, the air from which is passed through a series of HEPA filters. Operating data for this phase are available from government facilities and six commercial plants.

Observations are also available from the 13 most serious plutonium-handling accidents that have occurred in the past 30 or so years. In all these cases plutonium releases have been kept below a level that would constitute any observable or expected health risk. Two reasons for such low health risks are that burning plutonium produces large particles, which tend to settle out rapidly in the vicinity of release; and that the airborne particles tend to adsorb onto nearby surfaces. The performance of air-cleaning systems is recognized as the main safeguard in maintaining or improving this effective record of containing releases.

Because there have been no major plutonium-handling accidents, it is necessary to rely on theoretical studies for prediction of possible consequences. Accordingly, eight detailed analytic studies have been made, covering reprocessing plants, mixed-oxide fuel fabrication plants, transportation risks, and the liquid metal fast breeder reactor.

Releases from the routine operation of reactors are almost exclusively gases and volatile materials. Since plutonium is not volatile, its release from a reactor could occur only under extreme circumstances. A serious reactor accident (an occurrence of admittedly low probability) could be a major source of plutonium releases, although the strontium, iodine, and cesium isotopes released at the same time would pose even greater hazards than the plutonium, especially in the near and intermediate future. The principal danger in a reactor accident is that portions of the fuel would melt, releasing radioactive materials as a vapor or as an airborne dust. Since plutonium compounds have high melting points and low vapor pressures, they would be the least likely to be released.

Statistical estimates of probable plutonium releases from reactor accidents are based upon three factors: the fraction released, the probability of an accident, and the average amount of plutonium in the reactor. We have estimated the first two items using the Rasmussen report on reactor safety (Atomic Energy Commission, WASH-1400, 1974). The release fraction cited by that report has not been questioned; the accident probabilities have been criticized, but we consider it doubtful that they could be in error by more than a factor of ten. The estimates we present are based on the Rasmussen study, scaled by plutonium content. Because there could be errors in both directions, these estimates seem to be reasonably conservative.

Waste management

A major public concern is whether plutonium releases might occur thousands of years from now from current waste storage. It is possible to estimate the chance that buried waste could ever reach the surface. The calculations take into account such matters as the probability of contact between waste and groundwater, the rate at which waste could be leached, the rates at which water and waste could move through the ground (including atypical situations such as the formation of artesian wells), the impacts of meteorites or volcanoes, the data on the observed entry into the biosphere of naturally occurring alpha-emitters in soil, and possible random mining operations carried out by future societies. These scenarios assume no watching, no special attention, no keeping of records, and no deliberate choice of areas that are arid and of low volcanic activity for repositories—all of which are measures that would tend to reduce the chances of exposure of future societies. This method of estimation has not, of course, been tested, but it appears to be reasonably based and, it is hoped, could be made more definitive long before large amounts of waste were produced by the nuclear power industry.

It should be noted that the hazard from radioactive waste will be dominated in the first hundred years by strontium-90 and cesium-137, for the next few thousand years by americium isotopes, and after 30,000 years by radium. Although the discussion here focuses on plutonium, the principles generally apply to radium as well. We have assumed, in accordance with present regulations, that the waste would be converted into an insoluble solid (for example, a borosilicate glass) and then buried at a depth of about 600 meters.

Plutonium in the biosphere

Present knowledge of the movement of plutonium in the biosphere comes from observation of relatively large amounts released from weapons and of lesser amounts released from points near the ground. The latter are more relevant in regard to releases from nuclear power facilities. The observed behavior of these releases is in accord with the known physicochemical properties of plutonium.

Plutonium particles in the air are rapidly deposited by rain and dry precipitation onto the earth's surface—onto soil, water, and living organisms. Particles that land in bodies of water usually settle to the bottom in sediments. Of course, both these particles and the ones that land on the soil can be stirred up and resuspended, thus becoming an additional source of exposure. Particles can land on vegetation and be swallowed by grazing animals, but the amounts that do are relatively small. For example, following an accidental release of plutonium from a military fabrication plant at Rocky Flats, Colorado, 96% to 98% of the plutonium deposited near the plant was found in the soil, 1% to 3% was found in plant roots and litter, and only a small amount on standing vegetation.

Plutonium is strongly adsorbed onto soil. Therefore, it migrates slowly, and experiments indicate that only 0.1% of the plutonium deposited in soil is expected to be leached. Two apparently contrasting developments highlight this characteristic. In Gabon a natural reaction producing plutonium-239 from uranium-rich deposits was found to have occurred some 1.8 billion years ago, and the migration of the plutonium during its 24,000-year half-life has been shown to have been less than 1 millimeter. At Maxey Flats, Kentucky, plutonium in small amounts was found in test wells several hundred meters from surface trenches in which it had been buried in a primitive manner by a waste-disposal contractor. The mechanisms of this latter movement are not yet clear, since there is the possibility of contamination by the drilling and testing apparatus. If migration occurred, it would probably be accounted for by seepage through fractures.

Plants take up very little plutonium from soil, with the concentration in plants ranging from one one-thousandth to one one-hundredth-thousandth of that in soil. In contrast, plants living in the water take up much greater amounts. The higher an organism is in the aquatic food chain, however, the lower its concentration of plutonium tends to be.

Plutonium in human beings

There are three major routes by which plutonium can reach human beings: ingestion via the food chain, inhalation of airborne or resuspended particles, and subcutaneous contamination of wounds. Ingestion is not a significant hazard because of the cumulative dilution in transfer from soils or water to food. In addition, ingested plutonium is very poorly absorbed from the gastrointestinal tract. Contamination of wounds is not likely. Thus, the route of most importance is inhalation.

A great deal of work has been done on respiratory physiology, and although the behavior of inhaled plutonium is complicated by many variables, some generalizations can be made. About 40% of inhaled plutonium is lost immediately by exhalation. The retained material is deposited in various parts of the respiratory system, depending on the size of the plutonium particles. Except for those very fine particles that get to the deepest part of the lungs, the particles are removed from the lungs by ciliary action and transferred to the gastrointestinal tract, from which they are excreted.

Quantitative estimates

To understand the overall significance of possible plutonium releases from a full-scale nuclear power industry, it is helpful to relate the amounts already handled, stored, and released from weapons activity to the actual exposure produced in the population and then to project similar comparisons for civilian nuclear power. Such data are presented in the table, expressed in microcuries rounded off and written without exponents, for ease of comparison.

More than 500 billion microcuries (μCi) of plutonium have been released to the earth's biosphere, primarily from weapons fallout. The amount of plutonium handled industrially to produce those weapons is guessed to be about 15,000 billion μCi.

As a result of the 500 billion microcuries of plutonium released, each person in the United States inhaled (during the year of highest levels—1963) about 1 one-hundred-thousandth of a microcurie, ingested (1972) about 2 millionths of a microcurie, and acquired a body burden

(1964) of about 4 millionths of a microcurie. The body burden is roughly a factor of 10^{17} less than the amount released.

Inhalation of about 1 microcurie of plutonium-239 is estimated to cause a 1% incidence of cancer. Therefore, the amount of plutonium inhaled during the peak year (1963) is about a factor of 100,000 less than that which could cause a 1% incidence of induced cancer; or, expressed another way, the amount inhaled during the peak year could cause only about a 0.007% increase in the normal incidence of cancer.

The plutonium handled in a nuclear power economy will depend upon the types of reactors in operation. Amounts range from about 150 billion microcuries (per 1000-MWe plant per year) for light water reactors without plutonium recycle to 700 billion microcuries for liquid metal fast breeder reactors. It will be a long time before the commercial handling requirements for a full-scale nuclear power industry will equal that required for weapons production.

More important than amounts handled are the estimates of release of plutonium from a nuclear power industry. The major routine releases will occur from reprocessing and fabrication plants. Experience so far indicates that such releases have been about 1000 microcuries per 1000-MWe plant per year. Through improved technology we can now reduce these releases by factors of 50 to 100. Statistical estimates of releases from catastrophic reactor accidents (events that are highly improbable) give values that range from 10,000 microcuries per 1000-MWe plant per year for light water reactors to 50,000 for liquid metal fast breeder reactors. It is clear that these estimated releases are far surpassed by the release of 500 billion microcuries of plutonium that has already occurred from weapons fallout.

PLUTONIUM IN THE ENVIRONMENT
(estimates in microcuries)

Amount Processed		
Military purposes	15,000,000,000,000	
Nuclear power production	Negligible by comparison	
Releases to Date (since mid-1940s)		
From weapons fallout	500,000,000,000	
From space equipment burnup	17,000,000,000	
U.S. Population Exposure		
Inhaled (per person/per year)		
1963 (peak year)		0.000012
1972		0.000001
Ingested in diet and water (per person/per year)		
1972 (New York City)		0.000002
Body burden (per person)		
1964 (peak year)		0.000004
1973		0.0000025
Health Effects		
Amount of plutonium-239 (inhaled, per person) that could induce a 1% incidence of cancer		[illegible]

Malevolence

The possible diversion of plutonium for malevolent purposes is more difficult to treat than the subjects discussed so far because human behavior and motivation are involved.

A fundamental question is whether the existence of reactor-grade plutonium makes it easier for terrorists to achieve their objectives. There are differences of opinion as to how difficult it is to build a plutonium bomb. But most would agree that the terrorist would be better off stealing a bomb, or at least stealing plutonium that was produced for military purposes, than attempting to build a bomb with reactor-grade plutonium. Furthermore, dispersing stolen plutonium as a toxic agent would be largely ineffective because it lacks an immediate, dramatic impact. Even those exposed persons who eventually developed cancer would not be likely to do so for several decades. Other than capitalizing on public panic, it is fair to say that any terrorist objective could be more readily achieved by using other substances and other means.

Benefit or bane?

In general, predicting possible effects from plutonium rests upon several bodies of knowledge that tend to support and complement each other. These include: (1) known physical, chemical, and biological properties, from which predictions of plutonium behavior are generated; (2) actual behavior of fallout plutonium and that released in the weapons industry, which fits the predictions; (3) a lack of observed effects in known exposed populations, which does not signify zero effect but which does place an upper limit on any error in our present understanding of the relationship between exposure and effect. Thus, although plutonium should in no way be discounted as a hazard to human health, it does not critically limit nuclear power safety and is not uniquely hazardous or more difficult to control than many other substances that are safely and commonly handled in our industrial society. The broader policy decision about nuclear power should be based on the judgment as to whether or not it provides a net benefit to society.

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FOSSIL PLANT PERFORMANCE AND RELIABILITY

This new program was initiated because of the major contribution to total power generation that will be demanded from conventional power plants over the next two decades. The program incorporates and will build on a series of projects that were formerly part of the Advanced Systems Department.

At this stage, effort is concentrated on designing a program that will fit the short- and medium-term needs of the electric utilities, provide an essential interface with federal programs, and encourage and assist vendors to augment and direct their research efforts in directions beneficial to the power generation industry in general. The EPRI program will concentrate on generic deficiencies in operation, design, and material areas and will focus on the need for more effective contributions from the vendors rather than displace their present contributions. Some new projects have been identified and planning studies for other projects are under way.

The most important event in the past six months has been the completion of a series of informal meetings to discuss reliability problems with representatives of some 30 utilities operating fossil-fired units of 600 MW and up. There are more than 80 units of this size in operation in the United States. These are representative of plants that will be carrying the bulk of the load during the next 20 years. However, it is recognized that the contribution of smaller units, especially in the near term, will be equally important and the discussions at these meetings covered their problems as well.

These informal meetings were useful in providing an updated and more detailed description of plant performance than could be obtained from data published by the Edison Electric Institute. These data, which have been widely quoted, indicate that for the 10 years 1964–1974, the average availability was 65% for units over 600 MW and about 80% for smaller units. The data produced by the regional meetings indicated 69% average availability and 15% forced outage rate for units over 600 MW, not counting fractional year shakedown periods. In general, therefore, plant maturation has not produced major improvements. A significant feature was the wide scatter in range of performance—forced outage rates varying 5–35% and availabilities 50–90%. This suggests that there is a good possibility of achieving average levels of availability on the order of 80% for the large units. Such an achievement would be worth a capital saving of some $3 billion on the basis of existing capacity and a further $20 billion on new capacity over the next 15 years at projected growth rates. Against these savings must be set the cost of incorporating measures to improve reliability. The research program must of course identify, evaluate, and, where appropriate, justify these measures.

Discussions have also been held with ERDA and other federal organizations. Part of their interest in performance and reliability stems from the administration of the many regulations applying particularly to nuclear plants and increasingly to fossil-fired plants. But there are indications that there would be federal support for research oriented toward achieving engineering and operating improvements. Thus, although a large part of the federal concern is in compiling performance data, federal research activity may become more direct.

The short-term approach to the Fossil Plant Performance and Reliability Program will be to identify major problems on existing plants, to trace their underlying causes, and to design research tasks that will eliminate them. The longer-term approach will attempt to minimize the impact of new problems or the repetition of old ones by providing a better basis for plant and component specification, test, and quality assurance.

Design is the responsibility of the vendor, but any EPRI-sponsored work on the solution of problems must influence design. Also, the development of better design depends on the completion of feedback loops between the user and the supplier. Providing good interfaces for communication between these two is therefore an essential part of the research approach.

Obtaining information to pinpoint problem causes is not easy. Both national (EEI, for example) and utility in-house records mainly provide statistics that indicate the availability of units or components. This assists management in ensuring that generating reserves are adequate in setting up maintenance schedules, in ordering new plants, and in identifying operating deficiencies from whatever cause. Some manufacturers have good confidential in-service performance records, but these are not accessible to EPRI. At this stage, therefore, there are several small studies filling this data gap, following up leads such as those provided by informal meetings and by other utility contacts. In this kind of work, and indeed in all reliability-related topics, a close contact is maintained with EPRI's Nuclear Power Division since there are many common interests.

A survey of boiler feed pump outages has been completed, and others will be initiated on feedwater heaters, corrosion protection of inoperative units, and coal pulverizers. The Nuclear Power Division's surveys of valve problems and condenser leakage incidents have provided other inputs. In the case of the feed pump survey, certain generic design faults were discovered and successfully corrected by vendors (or by the utilities themselves in several instances), with financial benefits many times greater than the cost of the survey.

Developments in electronics and instrumentation afford ways in which normal plant supervision systems may be extended to provide an early indication of plant deterioration, thus preventing major damage or permitting better maintenance planning. Techniques such as measurement of noise due to discrete failure events (acoustic emission) or vibration patterns from operating machinery have not been widely used by electric utilities. These techniques can be applied to leak detection, wear detection, fatigue damage detection, and other phenomena. Two such projects are under way: one is exploratory; the other is directed specifically at the detection of water entering steam turbines.

Many utilities are suffering from the effects of enforced changes in coal supplies which, in many cases, have led to an increase in boiler fouling rates and, in extreme cases, slagging. In a contract with Battelle, Columbus Laboratories, the mineralogical constitution of coal impurities is being studied to identify reaction sequences that are responsible for deposit bonding mechanisms. The subject of boiler fouling has been under review for some time by an ASME research committee, with which EPRI has a cooperative understanding. It is expected that further projects will evolve.

Also related to the subject is an experimental study by Foster-Wheeler Energy Corp. on improved materials for boiler superheaters and reheaters that is aimed at solving both gas side and steam side corrosion problems. Corrosion on the steam side of boiler tubes leads to the detachment of scale (exfoliation), which in turn causes severe erosive damage to valves and turbines. The Foster-Wheeler study has demonstrated the importance of relatively wide swings in temperature in initiating exfoliation, which will clearly be an increasingly severe problem in cycling plants. The British Central Electricity Generating Board has also made an intensive study of the exfoliation mechanism, mainly in relation to gas-heated nuclear boilers. The results of this and other unpublished data will be made available to EPRI through a technical planning study.

A project just starting with Westinghouse Electric Corp., Babcock & Wilcox Co., and Commonwealth Edison Co. is a comprehensive study of the effects of thermal cycling in relation to stresses induced in turbines during startup. The tests will use a range of controlled start cycles that will include the effects of boiler superheat bypasses and variable steam pressures.

An important class of materials studies concerns fundamental improvements in alloy formulation or production. A new way of producing high-strength alloys for generator end rings is being explored at the University of California at Berkeley and shows considerable promise for this critical component. Another contract at the University of Pennsylvania is aimed at improving pressure vessel steels by reducing the embrittlement due to impurity inclusions.

There are several projects whose objectives are to improve the data base underlying the design of major plant items. A good example (again in the materials area) is an effort to correlate and condense the existing data on creep rupture that are scattered over a wide range of temperatures and test durations and are often difficult or impossible to relate to realistic component lifetimes.

An RFP has been issued for work to provide long-term fatigue data relevant to turbine blade materials in realistic simulations of the steam turbine atmosphere, which include active deposited salts. Steam condensation in turbines contributes to the mobility of corrosive species. There is also a prospect of minimizing thermodynamic losses due to condensation if nucleation can be controlled. Westinghouse is studying the onset of condensation in the laboratory under conditions simulating those in the turbine to provide better design data for the industry.

An increase in plant size and a trend to higher fluid pressures have led to a situation where the structural integrity of condensers has become critical. A project at the University of Pennsylvania, now almost completed, will provide improved structural design concepts both for the use of designers and for the assessment of safety margins on existing and tendered plants. *Program Manager: Donald Anson*

PARTICULATE CONTROL

A principal constraint on the firing of pulverized coal in utility boilers is the collection and disposal of large quantities of fly ash. Traditionally, the electrostatic precipitator (ESP) has been used by electric utilities. However, the ESP has shown technological limitations in satisfying new demands that have been placed on it. Whereas a collection efficiency of 95% was formerly satisfactory, some new regulations require an efficiency in excess of 99.5%. At the same time, the shift toward low-sulfur coal leads to a low-conductivity ash that seriously interferes with precipitator performance. These two factors result in precipitators that are large and expensive, whose efficiency cannot be accurately predicted, and whose reliability is seriously reduced, causing outages and increasing requirements for purchased power.

EPRI has examined possible technological improvements or alternatives to the ESP in a search for a fine-particle removal apparatus with high efficiency and low energy consumption. This screening has narrowed to two technologies—improved conventional ESPs and the fabric filter— for further consideration for broad utility use.

The fundamental objective of the research is to reduce the size and cost of particulate control apparatus and to increase its collection efficiency and reliability. Much of the development effort will be performed by the Public Service Co. of Colorado at the EPRI–utility industry Particulate Control Development and Evaluation Center. This $4 million facility is capable of testing particulate control devices at temperatures of 300–1800°F and at flow rates of 5000–50,000 ft³/min.

A second portion of the EPRI effort is directed at demonstrating fabric filtration for the high-efficiency collection of particulates. This technology has shown the potential to provide a more reliable and less costly particulate control alternative, particularly for the combined problems of fine-particulate control and high-resistivity fly ash.

Particulate Control Development and Evaluation Center

EPRI is establishing a pilot plant facility to evaluate and develop advanced concepts in particulate control under utility operating conditions. This facility, scheduled for start-up in early 1977, will include 10,000 ft^3/min and 35,000 ft^3/min precipitator pilot plants, a high-temperature gas cleanup test facility, and an adjacent laboratory building to support test sections. The facility will be located on Unit 4 at the Arapahoe Station of the Public Service Co. of Colorado.

The first ESP-related technology selected for evaluation will be a high-intensity ionizer developed by Air Pollution Systems, Inc., under contract to EPRI (RP386, RP725). The first hot gas cleanup or filtration device selected for testing will be a high-temperature metal felted-fabric filter developed by Brunswick Corp.

The facility will be under EPRI management, although an on-site facility manager, Kaiser Engineers, will be responsible for technical support and program coordination to ensure the flow of technical data between EPRI and the project participants. Combustion Engineering, Inc., will act as construction manager and will be responsible for the design of the facility. All precipitator hardware will be supplied by Western Precipitation Division of Joy Manufacturing. The host utility will provide the site for the pilot plant and the sidestream on which the testing and evaluation of ionizers, precipitators, and filters will be conducted.

Figure 1 depicts test sections of the facility. Unit 1 will be a

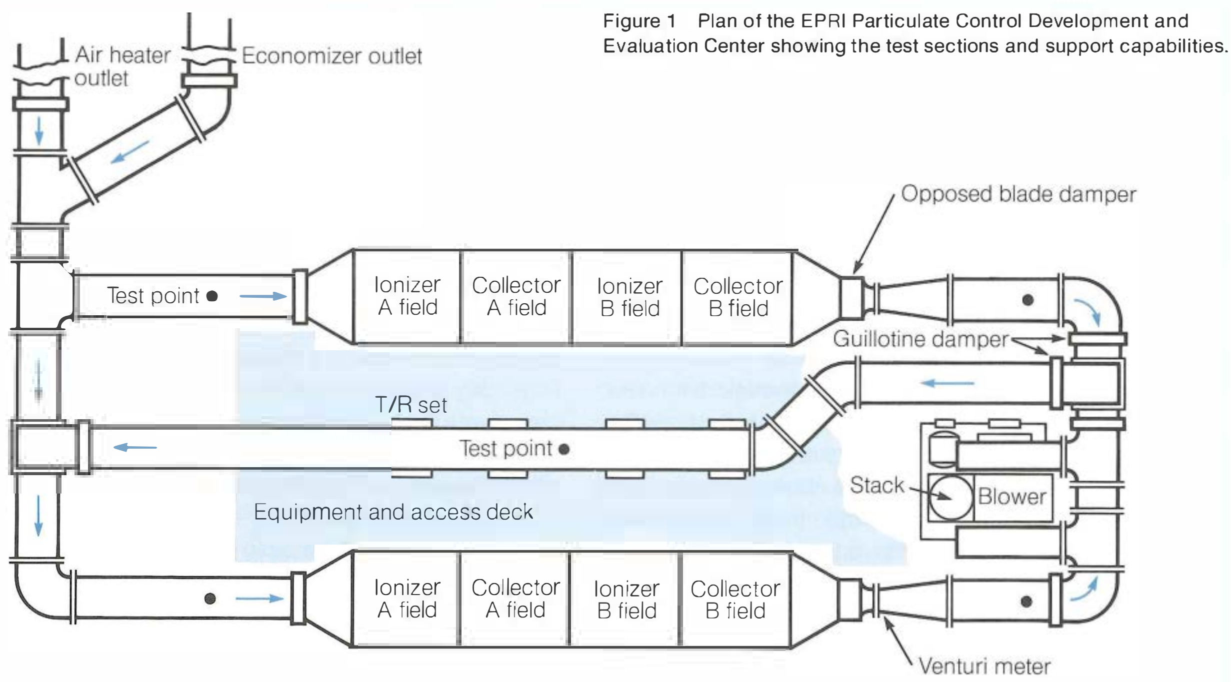
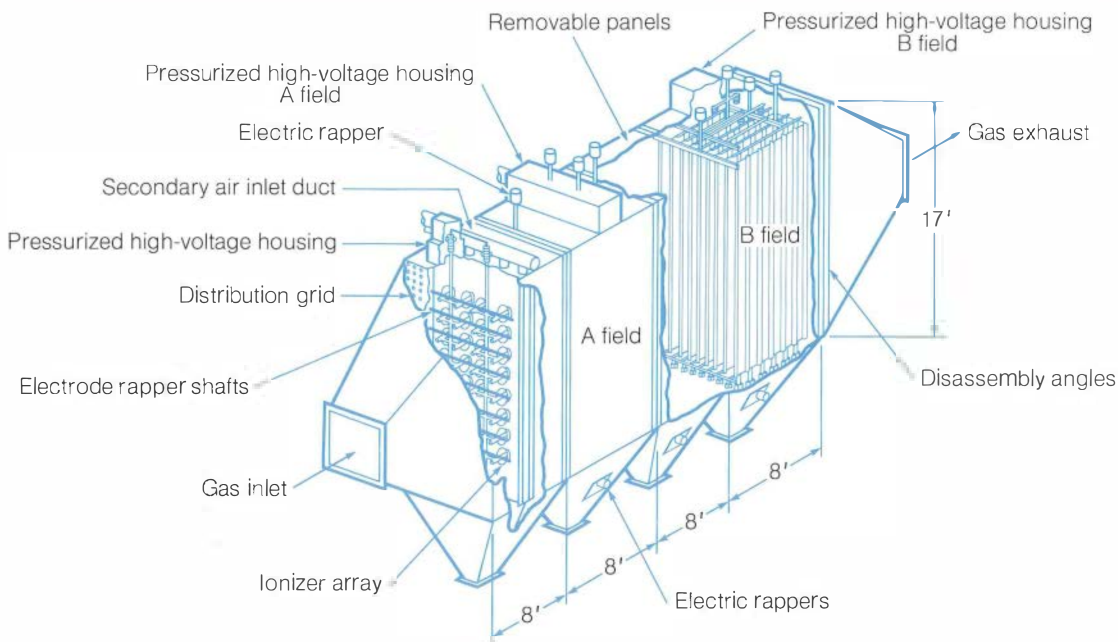


Figure 1 Plan of the EPRI Particulate Control Development and Evaluation Center showing the test sections and support capabilities.

Figure 2 Conceptual view of the high intensity ionizer attached to a typical utility electrostatic precipitator installation.



nominal 10,000 ft^3/min pilot plant with two precipitators, each rated at a nominal 5000 ft^3/min and capable of operating either in a series or in a parallel mode. The internals of the collectors will be flexibly arranged so that the spacing of the plates and the types of the electrodes can be easily changed to reflect various commercial or developmental precipitator configurations. The arrangement of ductwork and dampers will permit operation of the collectors in series or in parallel over a temperature range of 200–750°F.

Unit 1 will be used primarily as a technology screening tool, whereby a wide range of operating conditions can be considered quickly and at relatively low cost. Also, when the two 5000 ft^3/min precipitators are operated in parallel, the scatter of test results due to random fluctuations in boiler performance and fly ash composition can be identified and compensated for. This will greatly reduce the test time necessary to achieve a desired confidence level in the test results.

Unit 2 will have two identical precipitators at a nominal 35,000 ft^3/min. These will operate in series arrangement only. The cleaned gases will be returned to the suction side of the boiler induced-draft fan. This unit will be directed primarily to the prototype evaluation of promising collector hardware systems.

The laboratory building will house the control room, instrumentation monitoring, data acquisition/reduction center, and a physical/chemical measurement laboratory. An extension of the laboratory building will house the high-temperature gas cleanup pilot plant, Unit 3. This unit will be capable of test section temperatures up to 1800°F and gas flows up to 10,000 ft^3/min. The facility will support gasification and other high-temperature research. The facility instrumentation will measure dust concentrations, gas velocity, and composition in real time. The sampling and measurement procedures will be automated and capable of functioning as part of the on-line data logger. The results can then be transmitted to the in-house computer where data reduction also will be accomplished in real time.

High-Intensity Ionizer Development

Air Pollution Systems, Inc. has developed a high-intensity ionizer array as the first stage of a two-stage ESP (Figure 2). Physically separating the functions of ionization and particle charging from collection has the potential to improve ESP performance and reliability, particularly for applications in which the dust is highly resistive.

The high-intensity ionizer, as the first-stage ionizing and particle-charging device, also provides the possibility of significant improvement in ESP economics due to the following:

- A high degree of electric charging at a high gas stream velocity
- The effective charging of the fine-particulate fraction

- Relatively small anode (ground) surfaces that can be easily maintained in an ash-free condition. This protects the charging stage against the phenomena of back corona and excessive sparking problems often associated with low-sulfur western coals, as well as with many eastern coals.
- The reduced size of the collector stage due to reduced sparking and back corona. This enables the collector to achieve higher migration velocities.
- Reduced energy consumption

Successful laboratory development of this device has been completed, as has the first phase of verification testing on a coal-fired utility slipstream at the TVA John Sevier Power Plant. These tests were conducted at a gas flow of 2000–4000 aft^3/min, using both run-of-station (2.2–2.5% sulfur) and low-sulfur (0.8%) coal, both from Appalachia. The ionizer was attached to a three-stage pilot precipitator. The collection efficiency (total particulate mass) of the pilot precipitator without ionizer for the run-of-station and low-sulfur coal was 98% and 92%, respectively. In both cases, use of the ionizer reduced total particulate mass penetration by 50–60%. At the present time, an 800-hour test phase has been initiated at TVA to examine the mechanical and electrical reliability characteristics of the ionizer. To date no problems have been encountered during either startup or steady-state operation.

The potential cost-effectiveness of the high-intensity ionizer has been examined for EPRI by Kaiser Engineers. This evaluation has been made by comparing the estimated costs of conventional ESPs with those of precipitators equipped with the ionizer. In both cases the collector systems were designed to operate at 99.5% efficiency on a nominal 700 MW coal-fired power plant. Cost comparisons were made for both new and retrofit installations. The results indicate cost savings from the high-intensity ionizer to be in the range of 30% for new installations and 50–70% for retrofit installations, depending primarily on the physical difficulty associated with performing the retrofit modification.

While these results are encouraging, confirmation of the commercial potential of the ionizer must be based on completion of the orderly development program established for this device. Of particular importance will be the prototype scale (35,000 aft^3/min) tests in the EPRI Particulate Control Development and Evaluation Center. This development effort is scheduled for completion by autumn 1977.

Nucla Baghouse Evaluation

EPRI has recently completed a detailed field performance and engineering study of the fabric filter baghouses installed at the Nucla Station of the Colorado Utah Electric Association Inc., (RP534). This project has been conducted with Meteorology Research, Inc., and Stearns-Roger, Inc. The detailed results were presented at the July 13th EPRI Fabric Filter Workshop in Denver, Colorado, and the Air Pollution Control Association's 1976 national meeting in Portland, Oregon. The baghouses are of Wheelabrator-Frye manufacture, with a nominal air-to-cloth ratio of 2.8 in six compartments, using fiberglass fabric bags with a silicone-graphite coating. Normal pressure drop is 4.0 in H_2O. During shake reverse air cleaning, the pressure drop increases to 6 in H_2O.

The performance measurements conducted on the Nucla baghouse included total particulate emissions, emissions as a function of size from 0.04 μ to 10 μ particle diameter, size-dependent trace element emissions, plume opacity, and effect of boiler and fuel variations on baghouse performance.

Opacity measurements at the baghouse outlet, using a nephelometer, indicated that under stable boiler operating conditions, visibility in the stack exceeded 13 mi. This converts to a collection efficiency of 99.92% or greater. Unlike electrostatic precipitators, this efficiency is essentially independent of particle size and composition. Under the worst conditions, opacity was 1% or less (an invisible plume). The majority of the emissions occurred during the cleaning portion of the operation cycle.

As evaluated by Stearns-Roger, the baghouse reliability over the past two and a half years has been greater than 99%. Specifically, noninterference with boiler operation has been 100%; ability to produce a clean stack, 99.4%; and compartment reliability, 99.8%. The most troublesome maintenance items have been bag replacement, control systems, dampers, and actuators. The bag failure problem that was experienced during startup has been solved by installation of thimble flow straighteners in the cell plate. This has resulted in a bag life expectancy of at least two years.

The Nucla study also revealed areas where additional development may have a large payoff to the utility industry. Specifically, a more quantitative air-cloth versus efficiency curve is desirable. This will provide utilities a design basis and will provide data for cost-benefit trade-offs between capital and operating cost. For example, lower air-cloth ratios on the order of 2.0 would minimize cleaning cycles and thus minimize emissions. Although capital cost may be somewhat higher for this approach, maintenance costs may be reduced and bag life increased significantly. This was substantiated when the Nucla baghouse was operated at an air-cloth rate of 1.87. Under these conditions the baghouse never required cleaning; that is, the filter cake appeared to reach an equilibrium thickness and then shed naturally.

Based on these considerations, a fabric filter test module is planned for the EPRI Particulate Control Development and Evaluation Center. This module will be designed to evaluate baghouse design factors, bag filter materials, cleaning mechanisms, and technology for the dry removal of sulfur oxides. Also, to supplement the Nucla results, we expect additional field tests on new fabric filter installations for coal-fired boilers. These new installations will come on-line in 1977 and will more closely approximate modern utility boiler design and size. *Program Manager: Kurt Yaeger*

FLUIDIZED-BED COMBUSTION

Sulfur dioxide emissions from coal combustion can be greatly reduced when coal is burned in a fluidized bed of SO_2 absorbing material. The efficient gas-solid contacting in a fluidized bed provides the means for the reaction between the sulfur compounds and the limestone. Although other advantages of fluidized-bed combustion, such as efficient heat transfer, high heat release rate, low NO_x emission, and reduced equipment size, warrant its development, the desulfurization capability has been the major incentive for the development of the fluidized-bed combustion technology in the U.S.

Limestone and dolomite have been the most widely used SO_2 sorbents. Use of Ca/S mole ratios two or three times the stoichiometric requirements has been necessary to achieve low SO_2 level in the off-gas. Loss of stone reactivity is the primary reason for low stone utilization. This loss can be due to the formation of an impermeable sulfate shell, loss of porosity due to pore pluggage, or formation of limited pore size distribution due to improper calcination. Attrition and decrepitation of stone also contribute to high sorbent consumption.

Limestone is a relatively cheap raw material. Its present price is \$2–\$3/ton at the quarry, and transportation could add up to \$3/ton. A heavy limestone requirement, however, would introduce a significant cost. Ultimately, the use of fluidized-bed combustion will depend on how its economics compares with that of conventional boilers with stack gas desulfurization.

To enhance sulfur capture and therefore improve the economics of fluidized-bed combustion, two alternatives may be pursued: (1) techniques to improve the utilization of SO_2 sorbent for a once-through absorption system and (2) processes to regenerate spent sorbent for cyclical operation.

Proper disposal of large quantities of spent and unreacted sorbent is also a major concern. Improved sorbent utilization will ease the burden of disposal, and regeneration of the spent material will essentially eliminate the need for disposal.

EPRI's research program has been directed toward developing techniques to reduce the quantity of sorbent needed for desulfurization in a once-through system. EPRI is supporting research to investigate the effect of sorbent particle size, carry-over recycle, stone calcination, stone type, chemical additives, and the fluidization made on the stone utilization.

The effect of a reduction in the sorbent particle size will be studied by Babcock & Wilcox Co. in a 9-ft² fluidized-bed coal combustor. A reduction in particle size results in an increase in the surface area available for the reaction between SO_2 and limestone, as well as a reduction in the SO_2 penetration depth. Previous work on the use of fine particles has shown that the stone utilization and the desulfurization reaction have been improved. An interpretation of these earlier results is given in Figure 3. As the size of the particles is reduced, desulfurization efficiency is expected to increase.

The effect of fine carry-over recycle will be assessed as part of the experimental program planned for the EPRI development facility at B&W. Elutriated fine particles contain partially reacted sorbent. Earlier work on the recycle of the unreacted material is encouraging, although the results are not conclusive.

Since limestone must undergo calcination before sulfation takes place, the calcination reaction will affect desulfurization (Figure 4). However, it is important to determine whether the stone decomposition is the limiting factor. Preliminary results from Westinghouse Research Laboratories indicate that the calcination conditions also have a marked influence on the sulfation reaction (Figure 5). This is attributed to the difference in the structure and the size of the pores that are formed under different conditions. If calcination is found limiting, proper calcination conditions will be specified and techniques for achieving precalcination will be recommended.

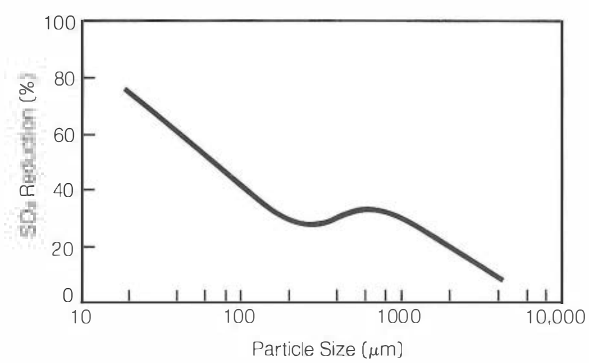


Figure 3 As the size of the particles is reduced, the rate of elutriation increases until a point is reached beyond which further reduction in size does not significantly affect the residence time of the particles in the bed. However, more reaction surface area is provided by the use of finer particles. This speculation is somewhat supported by the drop and then a further increase in desulfurization efficiency.

Figure 4 Effect of limestone calcination on sulfation.

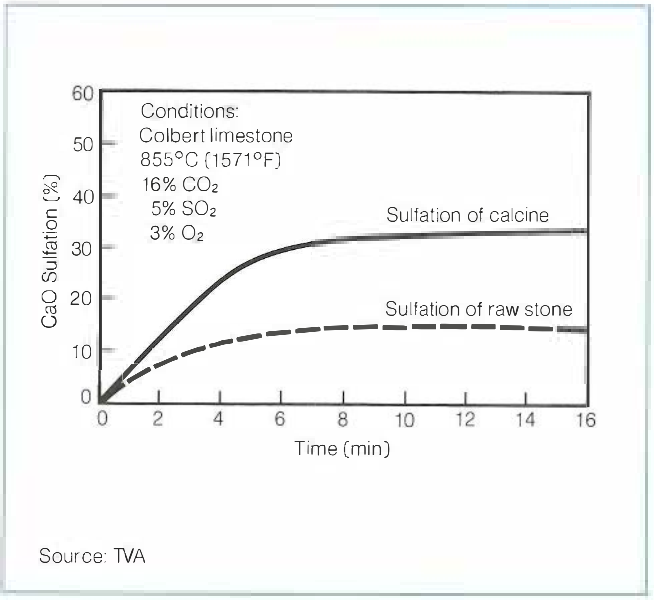
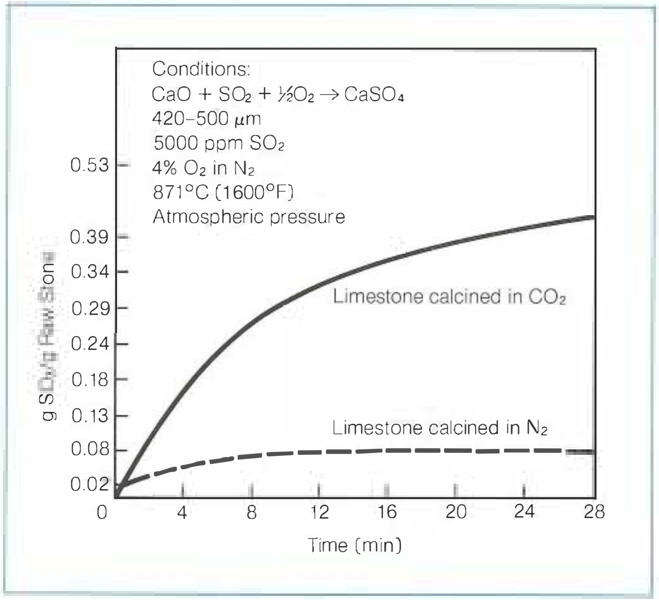


Figure 5 Effect of calcination conditions on sulfation.



The SO_2 absorption efficiency has also been shown to vary for different limestones. The properties and structure of these stones vary with the type and source of limestone. These observations suggest that the physical and chemical properties of the stone, such as pore size and sodium content, are critical in the sorbent reactivity. Criteria for the selection of SO_2 sorbents will be developed at Westinghouse so that their performance can be effectively predicted.

The presence of additives such as sodium chloride could increase the utilization of limestone, according to experiments conducted by Pope, Evans and Robbins. EPRI will investigate the mechanism of sodium chloride action on sulfur capture so that the same results can be achieved with other additives in place of the undesirable salt.

Since the gas-solid contact provides the means for sulfur capture, the fluidization mode influences this contacting medium. Higher gas velocities through the bed and the use of fine solids provide a more intimate gas-solid contact, which should improve desulfurization. An investigation of this mode of operation (i.e., higher fluidization velocities) is being considered by EPRI.

It has been suggested that synthetic sorbents could replace natural limestone and dolomite. An EPRI planning study confirmed the technical feasibility of using synthetic sorbents. In a regenerative process, the stone attrition could result in high makeup rates that would cause the system to become uneconomical. EPRI will continually evaluate the results of the exploratory work being performed by Argonne National Laboratory and Exxon Research and Engineering to assess the economic feasibility of these regenerable sorbents.

While there are no obvious attractive synthetic regenerable sorbents, the economic attractiveness of fluidized-bed combustion can be enhanced if a viable spent sorbent regeneration process can be developed. This is the second alternative for the enhancement of sulfur capture in fluidized beds. Regeneration of spent sorbent has also been suggested to reduce the environmental effects of large quantities of disposed spent sorbent. In a regenerative system, the sulfur can be recovered from calcium sulfate and the sorbent reused. This will minimize the quantity of fresh feed and that of spent material.

In an effort to fully establish the engineering and economic feasibility of regeneration, EPRI is planning a systematic R&D effort to develop a regenerative SO_2 absorption process and to demonstrate this scheme on a continuous pilot plant. *Project Manager: M. Maaghoul*

GAS TURBINE SYSTEMS

The gas turbine system effort has been broadened to encompass reliability and utility interface problems. At the outset, the research was slanted toward gas turbine design and construction materials to increase efficiency and ensure compatibility with future coal-derived fuels. Now that the longer-term projects have been initiated, more attention is being paid to increasing the reliability of gas turbines and to determining the consequences of near-term, foreseen changes in fuel supplies on gas turbine operation, design, environmental impact, and performance.

Gas turbines provide nearly 10% of current utility capacity.

Most of the nearly 50,000 MW capacity is for peaking service, although many gas turbines operate in intermediate service.

R&D under way and planned for gas turbines could lead to systems that are attractive from a cost-benefit and environmental impact viewpoint for intermediate and baseload service, particularly when integrated with coal gasifiers.

The gas turbine system research at EPRI is closely coordinated with ERDA through joint planning, projects, and information exchange.

The seven projects in progress and five projects in the planning stage can be classified as:

- Reliability assurance and operational improvement
- Fuel flexibility and performance improvement

The reliability assurance projects are focused on reducing maintenance cost and increasing availability. Initially, the major specific causes of unsatisfactory operation will be determined through workshops, Gas Turbine Working Group meetings, and cooperation with EEI committees. EEI data will be reviewed to determine the basic nature of the reliability problem and criteria for satisfactory operational characteristics will be developed. Projects will then be designed that will seek to develop technical or operational solutions to the most important problems.

A project has been established at Turbo Power and Marine Systems, a subsidiary of United Technologies Corp., to develop a system to control corrosion resulting from sodium ingestion. TPM will conduct tests to determine parameters causing corrosion, develop monitoring equipment, and add new control system capability to economically operate gas turbines in a regime of low corrosion potential.

A project at the Pratt and Whitney Division of United Technologies Corp. will study erosion and corrosion in gas turbines operating on coal-derived fuels. A ducted burner rig has been constructed that permits erosion tests of candidate turbine blade and vane materials. Particle velocities up to 1000 ft/s are possible. The initial work, done with 20 μ Al_2O_3 particles at a particle loading of 130 ppm and using Jet-A fuel, showed that erosion from the particulate matter was far greater than baseline oxidation. The effect of decreased particle loading (10 ppm), decreased particulate size (2 μ), and hot corrosion will be evaluated next. Other particulate material, such as char, will be evaluated later. However, since it is apparent that uncoated turbine materials will not survive long, the erosive environment and coatings will have to be developed.

The fuel flexibility and performance projects are concerned with increasing the range of fuels that can be used by gas turbines while also increasing performance and reducing fuel consumption.

Work on combustors with reduced NO_x emissions when burning residual oils and low-quality coal-derived fuels embodies such advanced concepts as premixed and two-stage combustion with ceramic liners. Ceramic heat exchangers designed to operate at 1800°F should allow use of minimally treated coal in both open- and closed-cycle machines.

A project at General Electric Co. on water-cooled turbines has shown a significant drop in hot corrosion with metal temperatures below 1050°F. These tests were 4000 hours in duration at temperatures of 800–1300°F. The motorized test rig experiments on water-cooled blades have shown that heat transfer under Coriolis forces is lower than expected. New cooling-tube designs that correct for this effect are under test. The shrouded scale test rig is being used to study concepts for water exit from blade tips. Ceramic combustors for high-temperature operation are being fabricated and should be tested before the end of this year.

The ceramic turbine blades and vane project at Westinghouse Electric Corp. has shown that preliminary designs for joining the ceramic blade to the metal hub are satisfactory at twice the nominal stresses expected in an actual machine. New yttria-base ceramic specimens have shown improved high-temperature creep properties.

The high-temperature heat exchanger project at Airesearch Manufacturing Co. of Arizona has shown that the proposed ceramic for the heat exchanger has a high resistance to coal ash corrosion. Tests show that carbon is impervious to helium leakage at pressures up to 500 psi and at temperatures up to 2000°F. Slagging of tubes is still a problem; methods of cleaning them are under investigation. In addition, methods of ceramic-ceramic and ceramic-metal joint construction are now under test. *Project Manager: Richard Duncan*

R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

RELEASES OF RADIOACTIVE IODINE EVALUATED

Experience with the licensing and operation of LWRs has shown that in the event of a release of radioactive iodine, the limiting dose generally is that which might reach the thyroid gland of a young child via the food chain. Consequently, even though the risk of such an event is remote, it is important to study and understand the paths and mechanisms of possible iodine release.

During power operation, the major source of radioactive iodine released is small leaks of steam and water. These may occur in the reactor and turbine buildings in BWR plants and in the containment and auxiliary buildings in PWRs.

The majority of the iodine released in BWRs comes from the turbine building, and the major source within the turbine building is the turbine condenser area.

Prominent sources during refueling and maintenance shutdowns are the fuel storage pool and the mechanical vacuum pump. The radioactive iodine from those sources becomes entrained in the ventilation air, with which it is subsequently released from the plant. These once relatively minor BWR sources have become the primary sources, since the radioiodine in the off-gas has been virtually eliminated by charocoal filtration.

The critical pathway to humans for radioactive iodine is the milk food chain. The dosage received via this pathway is determined by the following factors as the radionuclide is transported in sequential steps from emanation to accumulation in the thyroid:

1. Appearance within the plant effluent stream
   - pressure boundary and process system leakage during power operation
   - vaporization from fuel storage pool during refueling
   - operation of mechanical vacuum pump during plant shutdown
2. Emission from power plant to atmosphere
   - effective stack height
   - physicochemical form
   - release rate
3. Travel to start of food chain
   - distance traveled
   - change in physicochemical form
4. Rate of deposition from air to forage
   - physicochemical form
   - density of forage
   - wind speed
5. Retention by forage
   - removal by weathering or other material phenomena
6. Transfer from forage to milk
   - animal feeding practices
   - seasonal variations
7. Distribution of milk
   - pooling with uncontaminated milk
   - time before product is consumed

Each of these steps must be studied for an accurate determination of off-site dosage.

Radioactive iodine can exist in any one of the following physicochemical forms: particulate, elemental, other inorganic, and organic. Evidence indicates that the chemical form changes as the iodine progresses through the power plant system and the atmosphere. Only that portion of the release that is particulate or elemental tends to deposit on grass and enter the milk food chain. The environmental pathway by which the remaining fraction reaches human beings is direct inhalation, which produces a much lower dose for the same quantity of iodine released.

EPRI has undertaken two projects in this area: one to determine the specific sources of radioactive iodine releases in LWRs and the other to determine the persistence of the chemical forms and rates of deposition once the iodine is released to the environment.

In-Plant Study

The first study (RP274), conducted by Science Applications, Inc., will seek to identify sources and mechanisms by which the radioactive iodine becomes airborne in the power plants; evaluate important parameters and model its transport to the effluent pathways; and determine what the physicochemical forms of the radioactive iodine are at the source and how these forms change as they progress to the effluent release point.

This in-plant study is being carried out at three BWRs: Oyster Creek, Monticello, and Vermont Yankee, and three PWRs:

Calvert Cliffs unit 1, Ginna, and Three Mile Island. Measurements have also been made at Point Beach.

To sample ventilation air and isolate prominent sources, a sampler draws air from the ventilation ducts (Figure 1). The different iodine species are removed from the airflow and retained on the cartridges in the sampler train (Figure 2).

The study will also evaluate on site the effectiveness of charcoal for adsorbing low concentrations of iodine over long periods of time.

Environmental Study

The second study (RP600), by Nuclear Environmental Services, Division of Science Applications, Inc., will determine whether the chemical forms change in the environment once they are exposed to natural phenomena such as sunlight, humidity, and geographic variations in stable iodine concentrations, and to unnatural effects such as airborne pollutants. Plume depletion caused by rain and deposition rates from air to grass will also be investigated. Prevailing winds will determine the placement of eight environmental samplers around each nuclear power plant studied. One such sampler is currently being used to take measurements at the Oyster Creek plant (Figure 3). Plants at which measurements will be made in future are currently being selected, with a view to studying a wide variety of environmental conditions.

Direction of Work

The ultimate goal of the in-plant study (RP274) is to identify the sources of unplanned emissions so that escape to ventilation air can be prevented by minor design modifications. Where it is not practical to eliminate a source by design, the component can be isolated and the small quantity of air around it can be filtered locally. This will achieve a better ultimate cleanup at a cost much lower than treatment of the total ventilation system. Mathematical expressions are being developed to describe the behavior of the radioactive iodine as it moves from the source to the release point so that important parameters can be clearly identified and studied. BWR measurements have been completed, as have measurements of the long-term effectiveness of large charcoal filters.

The ultimate objective of the second, or environmental, portion of the iodine study is to deal with most of the important phenomena taking place up to the point where the iodine enters the agricultural system. This segment of the iodine pathway represents the preponderant part of the work remaining to be done in this area.

This information will be of direct benefit in the licensing of future LWRs and in the calculation of dose impact.

Future EPRI objectives include development of the capability to describe accurately the behavior of other important radionuclides in plant effluent and environmental pathways. *Project Manager: Henry Till*

Figure 1 Samplers such as this one monitor ventilation air inside nuclear power plants for radioactive iodine.

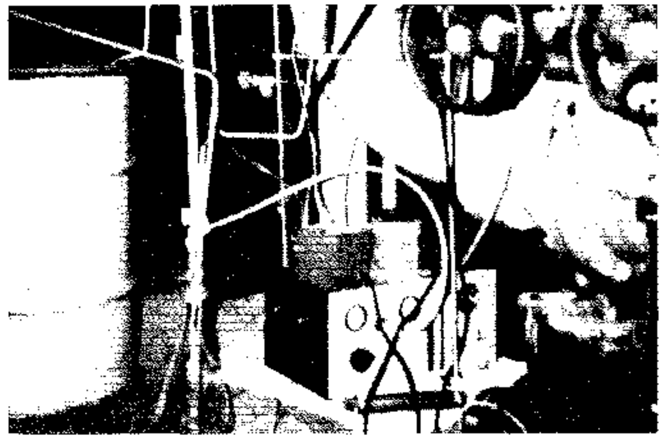
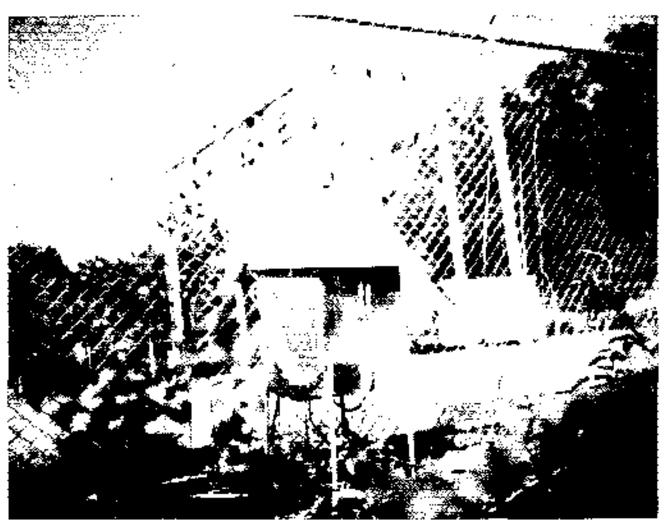


Figure 2 Iodine traces removed from ventilation air by a sampler are retained on the cartridges in the sampler train.

Figure 3 External samplers are also located on the plant perimeter fence to monitor any airborne iodine that may be released. This sampler is at the Oyster Creek nuclear generating station at Toms River, New Jersey.



PROBABILISTIC SAFETY ANALYSIS

Nuclear power plants are among the mechanical systems most thoroughly designed for safety. Because of good engineering, redundancy in design, and extensive layering of safeguard features, system failures exhibiting any out-of-plant consequences are extremely few. So few, in fact, that we have not yet seen an event in any commercial nuclear power plant that has affected the public adversely, except for shutting down the plant for repairs. Yet the requirement of safeguarding the public makes it necessary to understand and quantify the underlying risks associated with a nuclear power plant.

A complete risk analysis not only yields information on potential plant behavior that may have out-of-plant consequences but also on those aspects of plant operation where the risk is plant shutdown. Such an analysis can lead to a clearer understanding of how to minimize and avoid the major portions of such risks. The EPRI effort in this area deals with these primary questions, as well as a number of collateral aspects that shed light on them.

Risk Assessment

A major effort is currently under way in risk assessment. This project (RP767 at Science Applications, Inc.) is directed to the question of how to apply and extend the methods and results obtained in the ERDA reactor safety study (WASH-1400). A sensitivity study already completed shows that human error is not as significant a factor in plant risk as had been indicated in WASH-1400. Great effort is being put into developing an understanding of, and documentation for, the codes used in the reactor safety study, so as to be able to quantify and deal with the optimisms, conservatisms, and limitations of the various models used to yield consequences. For example, it is known that the plume rise model and the chemical partition factors are quite conservative, as are portions of the meteorological models.

The question of anticipated transients without scram (ATWS) is also being treated in this project. A first report shows that the study published by AEC (now NRC) as WASH-1270 is quite conservative in its estimation of scram failure probability—perhaps by as much as two orders of magnitude. Futhermore, although analysis of WASH-1400 indicates a risk of ATWS as high as 23% of the total potential risk, more recent EPRI studies show that at the worst it is less than 5% of the total potential risk (expressed as 30-day whole-body dose at site boundary, assuming no evacuation). Hence ATWS should not be a likely candidate for requiring significant plant modification based on cost-benefit considerations.

A risk assessment, no matter how carefully done, yields a set of numbers that describe the frequency of events having a given consequence. But what such numbers mean for public or even technical acceptability is a different issue. EPRI is currently considering this matter and has initiated a study (SOA 76-331, at General Electric) whose purpose it is to establish a tentative set of decision criteria for risk acceptability.

Data Base on Failures

Collateral but vital to such numerical risk assessments is the availability of a data base on safety-related failure. Such a data base was put together for the reactor safety study, but it is considered to be, in part, inadequately documented, overly conservative where data are sparse or unavailable, and in some cases out-of-date. EPRI is in the process of collecting event data from the utility industry. In particular, such data (scrams, turbine trips, losses of condenser vacuum, etc.) are of great importance to the ATWS studies, since failure to scram is only part of the ATWS probability evaluation, the other part being the frequency of the anticipated transient of significance.

Our current abilities permit us to perform a technical risk assessment. By redefining *risk* to mean "plant shutdown without out-of-plant consequences," we can examine plant design and operations with a view to minimizing the magnitude of such risks. This may permit an increase in plant availability. Such reliability studies are being carried out at EPRI as part of our contracts RP767 and RP818, the latter with Kaman Sciences Corp. as the contractor.

Although the WASH-1400 reactor safety study made use of event and fault-tree methods, and although such methods are the backbone of the studies being done under RP767, there are other theoretical approaches. RP818 makes use of a systems approach, in that the modeling procedure produces a structure that more clearly appears to be a model of the system diagrams than an abstraction of those diagrams in the form of a probability tree. This systems method is still in development but is expected to be available for general use in two or three years.

NRC has licensing criteria and rules that have been arrived at empirically, as carefully as possible, but they do not form a fully consistent and objective system. When, for example, the Final Acceptance Criteria for ECCS state that, based on a certain accepted type of calculation, the peak clad temperature shall not exceed 2200°F, what does it mean with respect to reality? How likely is it that, given a LOCA, the peak clad temperature would exceed 2200°F? Studies on some best-estimate models indicate that a more likely peak temperature would be 1200–1400°F. Given the inaccuracies inherent in the experimentally determined heat transfer and other thermophysical correlations and manufacturing tolerances on sizes, one should be able to show from best-estimate calculations that the probability that 2200°F will be exceeded is insignificant. EPRI has studies aimed at developing methods for inferring such probabilities (RP768, Westinghouse).

Similarly, NRC has limits on dose in Regulations 10CFR100.

EPRI has studies under way (RP767, Westinghouse) that will attempt to quantify the probability of exceeding the limits imposed by 10CFR100.

Related Studies

Collateral studies and contracts exist whose purposes are to explore a number of advanced applications of probabilistic methodology, such as automating the construction of probability trees (RP297, University of California at Los Angeles) and examining a given control-room alarm pattern to determine the pattern's most likely cause (RP891, Combustion Engineering and Systems Control Inc.).

Other studies are under way that have suggested the existence of unsuspected generalities underlying the frequency of earthquakes (RP767). These studies yield theoretical justification for an absolute upper limit of magnitude in the neighborhood of Richter 9.5–10; they also indicate that the shape of the frequency/magnitude curve for magnitudes greater than about 4 is universal.

Still other studies are under way on risk due to tornado-driven and turbine-induced missiles (RP616, Carolina Power & Light Co.). These studies have led to the development (in-house, at EPRI) of simple methods of calculating impact probabilities and can be used to establish locations and configurations of turbine generators at multiunit sites to minimize risk. *Program Manager: Gerald Lellouche*

References

1. *Planning Support Document for the EPRI Light Water Reactor Fuel Rod Performance Program.* Special Report prepared by J. T. A. Roberts and F. E. Gelhaus, December 1975. EPRI SR-25.

2. R. Christensen. "Entropy Minimax, a Non-Bayesian Approach to Probability Estimation From Empirical Data." In *Proceedings of the Systems, Man and Cybernetics Conference.* Institute of Electric and Electronic Engineers, Boston, November 5–7, 1973.

ANALYTIC MODELING OF FUEL PERFORMANCE

The development of a comprehensive fuel performance data base with verified predictive models and codes is a prime goal of the EPRI LWR fuel performance program (*1*).

The analytic code development projects represent points of technical synthesis, wherein fundamental UO_2 and Zircaloy behavioral data are utilized within thermal-mechanical models of fuel pellets and cladding, which are then synergistically coupled to provide a system description of the fuel rod.

This is analytic simulation at a high level of detail. During a modeling projects review meeting with utility engineers in Kansas City in May, some of the utility representatives stressed their need for this capability, to assist them in evaluating design bids and making strategic operational decisions.

The utilities have also expressed a need to be able to calculate and predict the behavior of an entire core over an exposure lasting three or four reactor cycles. But this function cannot be met with such a detailed type of code: the running costs are prohibitive, and the level of detail is beyond that actually needed for core-management purposes.

Response to these wide-ranging needs is structured into EPRI's program. As shown by the areas highlighted in Figure 4, model and code research activities occur at the rod, bundle, and core levels of detail, which the program treats. How the present efforts focus on the goal in a complementary manner is indicated below.

Fuel Rod Studies

Fuel pellet cracking and rehealing can play a role in the relocation of a pellet through the transfer of free void space within a fuel rod. This phenomenon is being studied in RP508 at Argonne National Laboratory, using an out-of-core thermal test device; the data will be evaluated by a new technique of statistical modeling termed entropy minimax (*2*). Through pattern-seeking, this technique allows a model to be developed from the data rather than by fitting the data to a preestablished model.

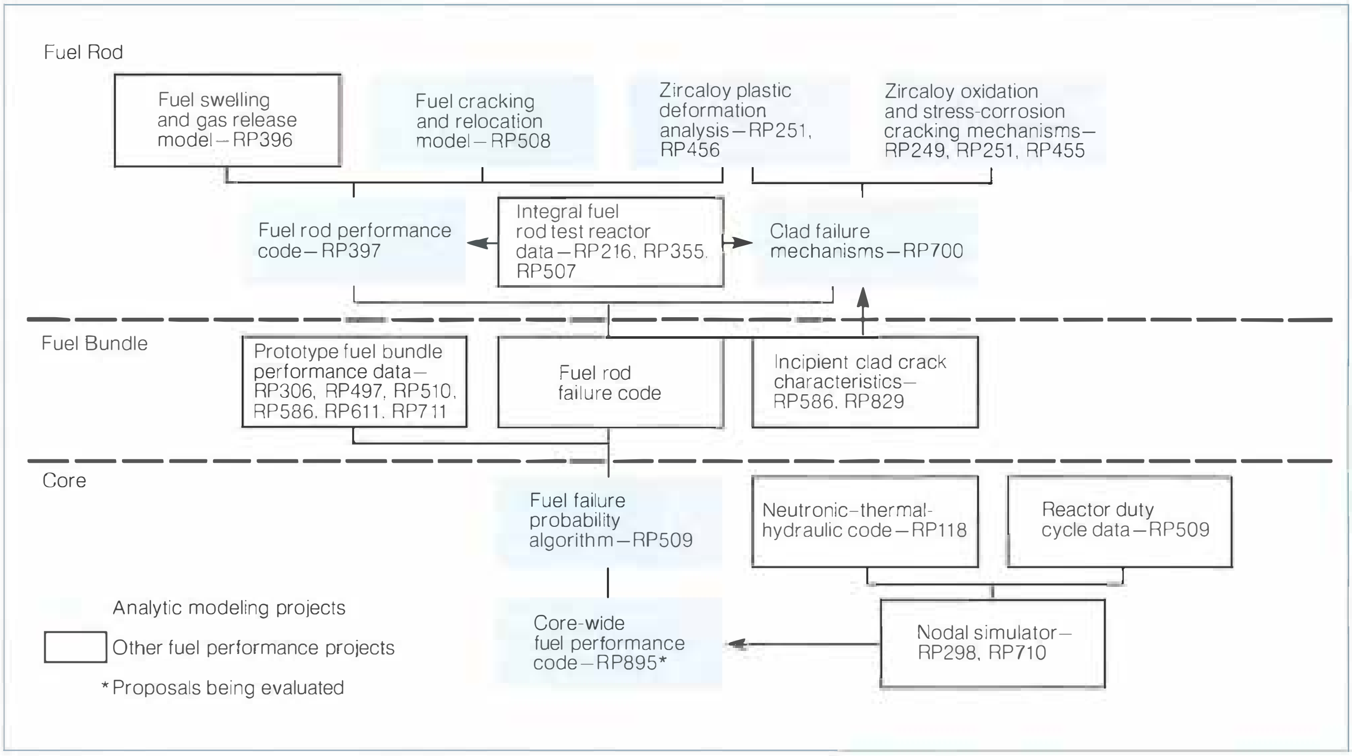
When the surface of a fuel pellet contacts the inside wall of the cladding, stresses and strains result in the Zircaloy tube. RP456 studies at General Electric, Stanford University and Massachusetts Institute of Technology are focused on obtaining fundamental material properties and developing a constitutive description of Zircaloy deformation as a function of temperature, stress, strain rate, and material microstructure. Other projects consider: (1) the initiation and growth of flaws in the cladding wall, (2) the influences of fabrication processing on strength and ductility of the cladding wall, (3) rates of flaw growth—with and without an accelerating chemical environment, (4) micromechanical aspects of stress and strain localization due to dislocation channeling, and (5) the applicability of fracture mechanics modeling for this cladding failure phenomenon. (This work is being carried out under RP700 at Failure Analysis Associates and RP455 at NASA–Ames and Stanford Research Institute.)

Integral fuel rod modeling codes presently do not model this failure process, which is felt as a shortcoming that must be rectified. To prepare for the addition of this computer logic, existing LWR fuel rod performance codes are being evaluated in RP397 to determine the best analytic vehicle for this advanced failure logic. (The contractors are Combustion Engineering, Science Applications, Inc.; O'Donnell & Associates; and S. M. Stoller Corp.) The resulting fuel rod failure code must then be further evaluated against prototypical commercial fuel performance data.

Corewide Predictive Techniques

To apply the fuel rod failure code described above in the performance analysis of a typical core loading of 50,000 fuel

Figure 4 EPRI LWR fuel performance program. Analytic modeling efforts are highlighted.



rods is neither financially nor technically reasonable. However, this code can be used to generate the parametric analytic results from which a less detailed correlation or algorithm can be developed.

Several such algorithms exist, one of which is being evaluated (in RP509 at Scandpower, Inc.) using the Quad Cities 2 and Maine Yankee reactor core performance data. The history of this project has underscored the need to employ computer technology in tracking the power history of a core. The laborious man-hours required just to gather the plant data needed—even with an efficient hard-copy filing system for the records—demand unattainable levels of effort by utility staffs. A proposal for the development of a computerized system that can gather and store plant and core data, and subsequently calculate the power-exposure history needed as input to the fuel-failure algorithm, is presently being evaluated. Such a system of neutronic–thermal-hydraulic and fuel rod behavior models and codes would provide the utility engineer a near-real-time description of corewide fuel performance and would allow simulation of an intended power maneuver to evaluate the variation in the risk of generating cladding fissures by alternative control strategies (RP895).

Steps to Understanding

The goal of providing the nuclear power plant operator with a computerized analytic system that can be used as an effective near-real-time core management tool is necessarily a step-by-step process. The LWR fuel performance program's projects span what are felt to be the needed steps, ranging from discrete to global, and yet they are formulated with sufficient flexibility to respond as required to new data and advances in understanding. *Program Managers: F. E. Gelhaus, J. T. A. Roberts*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

TRANSFORMER TECHNOLOGY

Transformers account for a major share of the capital cost of the transmission system. Accordingly, the major emphasis of the following projects has been to reduce the cost of the equipment, improve the efficiency, and maintain the integrity of the transformers. The projects can be separated into three groups: equipment, detectors, and insulating materials.

Transformer Development Projects

There is a serious need for explosion- and fire-resistant transformers to replace the current liquid-filled transformers used in distribution applications. For ecological reasons there is also incentive to develop a transformer that will be a satisfactory replacement for polychlorinated biphenyl (PCB) insulated units. Gas-filled and gas-insulated vaporization-cooled transformers have been developed in the past, but have not been economical. EPRI has initiated a project with Westinghouse that will develop a gas-vapor transformer at costs that will be acceptable to the industry and will eliminate the ecological concern for PCB environmental contamination.

The objectives of this project are:

- A 34.5-kV, 1000-kVa, 200-kV basic insulation level (BIL) gas-vapor distribution network transformer that will cost 5% less than a conventional oil-filled unit. This transformer will replace PCB-filled transformers and will cost 30% less.
- A 15-kV, 2500-kVA, 95-kV BIL gas-vapor secondary unit substation transformer. It is expected that this project will make this type of transformer available at least one year earlier than would be possible otherwise. This development will replace the largest share of the present PCB secondary substation need at a maximum cost objective of 120% of a comparable oil-filled unit, which is less than the cost for present PCB units.
- A 34.5-kV, 5000-kVA, 200-kV BIL gas-vapor substation transformer with a cost objective of 95% of the cost of a conventional oil-filled transformer. Since distribution systems have been requiring larger-size units, this development will cover the anticipated future range of utility distribution needs.

All the above transformers will have a size, overload capacity, load loss, no-load loss, and a weight-to-kVA ratio equal to or better than comparable conventional oil units.

Economically and dielectrically superior liquids and gases have been identified. Unique coil designs that take advantage of improved performance properties of this type of transformer have been developed so that cost objectives can be met.

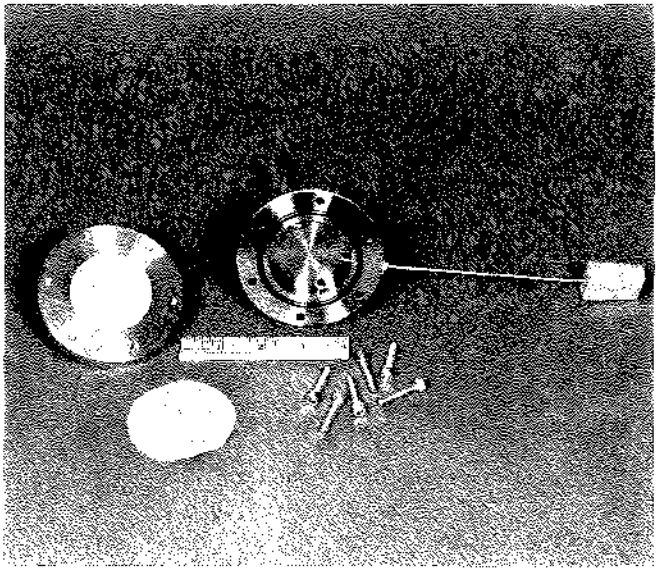
Another Westinghouse project will develop a 242-kV, 4000-A apparatus bushing that is small in diameter, low in cost, simple in construction and easy to maintain. Two strategies are involved. First, a "heat pipe" cooling system is incorporated within the central tubular conductor to permit operation at high current density. Second, cast-epoxy solid insulation replaces the oil-impregnated paper and porcelain that has been used.

A full-scale thermal model of the bushing with its heat pipe cooling system has been tested in a laboratory, simulating as many as 50 different combinations of heat pipe charge, load current magnitude, ambient temperature, test duration, and bushing mounting angle. Methanol was adopted as the working fluid for this heat pipe. It was introduced into the central, hermetically sealed conductor under vacuum. The fluid charge occupied one-quarter of the volume of the lead, a depth found advantageous in mitigating thermal transients when starting up cold.

Successful performance of the bushing requires transferring the internal losses to the ambient air through fins attached at the top. Each bushing will be provided with approximately 1¾ m^2 (19 ft^2) fins—an area that will permit a continuous current rating of approximately 5000—5500 A. The fins are a cylindrical extruded aluminum alloy 292 mm (11.5 in) diameter by 457 mm (18 in) long.

The features developed by testing the thermal model and components have been incorporated in manufacturing drawings. From these, manufacturing costs have been developed. With heat pipe cooling, the central conductor may be loaded to approximately twice normal current density. This results in heat-pipe-cooled bushing costs that are about 30% of the conventional paper-oil-porcelain construction for 5000 A.

Figure 1 Permeation cell for detecting combustible gases dissolved in oil for incipient fault detector.



The design will be used to construct 6–12 prototypes. Manufacturing experience will probably produce design modifications. Prototypes will be subjected to exhaustive electrical and mechanical tests.

A project by Allis Chalmers stems from research that was begun in England. This research has identified a theoretical approach to sound enclosure that eliminates many of the disadvantages of current practice. Application of this technology to power transformers offers the potential for lower noise and lower costs. The approach uses a unique noise shell consisting of close-fitting, tuned sound barrier panels mounted on the outside surface of the transformer tank. No sound absorption materials are needed and the panels can be easily installed at the factory without adversely affecting shipping, handling, or installation.

Three major benefits anticipated from this technology are an up-to-50% reduction in cost of noise abatement, large reductions in sound (by 15—20 dBa), and the potential for retrofit.

The purpose of the project is to verify the sound-enclosure theory and to develop design rules for its application to power transformers. This will include both laboratory experimentation and field tests in a Wisconsin Electric Power Co. substation and will culminate with the installation and test of an experimental shell on an existing transformer.

The project is on schedule and results have been extremely positive. Based on work to date, it has been established that (1) a noise reduction target of 15–18 dBa with an experimental shell is reasonable and will be met; (2) noise shell theory has been substantiated by lab tests; (3) design tools have been developed from the theory and verified with controlled sound-room tests; (4) field tests show that sound spectra of similar transformers are consistent, allowing simultaneous design of both the transformer and the noise shell; (5) all sides of a transformer tank must be covered for reductions greater than 10 dBa; (6) stiffening ribs (channels) are important noise sources and must also be covered; (7) radiators are a significant source, approximately equal to the noise produced by all four sides; vibration isolation from the tank is essential; (8) treatment of the top and bottom of the tank depends on the configuration used—e.g., gas cushion versus oil-filled, pier versus base mount, and the noise reduction goal; (9) 14 different materials are available as candidates for shell construction; economics and ease of manufacture have resulted in the selection of steel (11 gage) as centerline, with expanded acrylonitrile butadiene styrene (ABS) plastic as an alternative; (10) reductions in excess of 25 dBa were achieved with 30 × 30-in panels of these materials.

The experimental shell is in the construction stage and will be installed on a 45-MVA transformer of Wisconsin Electric Power Co. Testing will be completed in November 1976.

Detection Projects

One project in this program conducted by McGraw Edison Co. will develop the instrumentation and analytic techniques necessary for the early detection of partial discharges in on-line transformers, using acoustic emission methods. If successful, it will be possible to determine the condition of a transformer in real time. As partial discharges are often associated with incipient faults, their detection should lead to early recognition of potential failure conditions.

The project is approximately 40% completed. The instrumentation and data analysis systems have been assembled and checked out. Partial discharges have been successfully detected in laboratory setups and on-line distribution transformers. Due to the sensitivity of the system, signals other than partial discharges have also been detected. These other signals need to be identified as extraneous and not included in the analyses. The most serious of these proved to be Barkhausen-type noise emanating from the core material. The effects of these other noises have now been alleviated.

Good sensitivity has been achieved; discharge sources of approximately 45 picocoulombs have been detected in tests where it was possible to correlate with conventional partial discharge detector data. Where conventional partial discharge data could not be obtained (on-line testing in a distribution substation), correlation was obtained with absorbed gas-in-oil analysis.

The next stage of the project will check the system on a full-size power transformer. This will be carried out in a manufacturing facility in the near future.

Nucleonic Data Systems is constructing a sensor to monitor the temperature of transformer winding hot spots. Several compact sensors may be mounted within a transformer. Temperature information will be transmitted acoustically to a receiver mounted on the exterior of the transformer. The acoustic spectrum up to 52 kHz has been investigated and the region between 40 kHz and 47 kHz has been initially selected to transmit the information. The spectrum from 52 kHz to 250 kHz will also be investigated. Frequency modulation will be used to encode the temperature data.

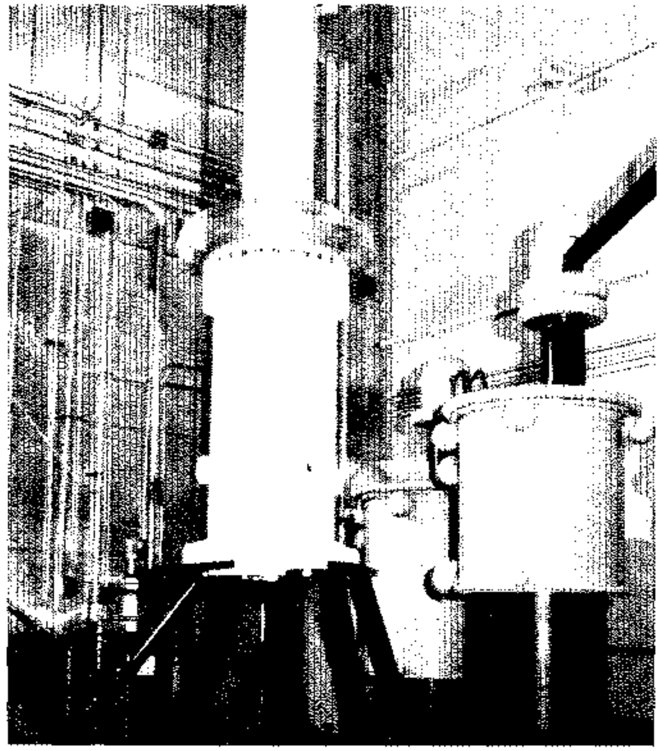
This method requires no wiring in the interior of the transformer and no connectable insulating link to ground. Two approaches are being investigated for the sensor: a crystal whose frequency output is temperature-dependent and a thermister that will control the frequency of a transmitter. Several alternatives for supplying power to the transmitter are also under investigation. At the present time the most promising approaches are piezoelectric coupling to the material flexure or acoustic noise and inductive coupling to the leakage flux. An operating hot spot detection system will allow the utility to accurately read the hot spot temperature. This knowledge will greatly help determine proper load management.

The application of advanced heat transfer techniques to improve transformer cooling, including the use of heat pipe and finned convectors, is currently being investigated by Sigma Research Inc. In addition, two-phase systems for transformer temperature measurement are also being developed.

The heat pipe transports thermal energy in the form of latent heat; the working fluid undergoes evaporation and condensation at opposite ends of a sealed envelope. Condensate is returned to the evaporator by capillary forces and/or by gravity. Hence, the heat pipe is without moving mechanical parts, consumes no auxiliary electric power, and has a very low thermal resistance. The use of heat pipes for cooling underground transformers, for example, may increase transformer life by a factor of two because of lower operating temperatures.

A second application of two-phase systems involves the measurement of hot spot temperatures in power-class transformers, using a passive sensor charged with vaporizable fluid. In a prototype unit, benzene working fluid is sealed in a small stainless sensor capsule that is 0.64 cm in diameter and 1.2 cm long. The working-fluid vapor pressure transmits a force to an external monitoring system by means of a miniature bellows inside the sensor. A hydraulic line connecting the sensor and monitoring system is oil-filled and produced from a polymer compatible with transformer oil and possesses a similar dielectric constant. Since vapor pressure rise with

Figure 2 High-pressure test cell for electrical testing of compressed gases at high voltages at Westinghouse.



temperatures is exponential, as opposed to a linear pressure rise in gas bulb sensors, it is possible to achieve high accuracy. In laboratory tests, accuracies of 3°C over a temperature range of 75–150°C have been demonstrated with the prototype. Preparations are now under way to install a sensor system in a commercial power transformer.

A project with Westinghouse is concerned with the development of an on-line device to detect the presence of combustible gases dissolved in the oil. Economic impacts of a power transformer failure or a power outage make this study extremely important. Gas detectors presently used have a built-in time delay since the oil must saturate before the gases are detectable in the gas space above the oil. The concept of this particular device involves using a membrane to separate dissolved gases from the insulating oil, passing this gas through a simple chromatographic column, and using a thermal conductivity detector to indicate changes in the gas composition.

The concept has been proved feasible in laboratory test equipment. Current studies of membrane material have shown fluorosilicone rubber to possess the best stability and permeability. Additional work is establishing the best design of the permeation cell and the optimal geometry for the membrane. Both flat and tubular membranes are being studied. Nitrogen appears to be the best suitable carrier gas for the detector system, providing adequate sensitivity and low cost. Various flow rates are being examined to determine the best rate for the desired sensitivity.

Also being studied are the life of the membrane material and other components of the system. Thermal aging tests are presently in progress. All test results have been very encouraging and the prospects of developing a relatively low-cost device appear to be very good.

Insulating Materials

While SF_6 is not used widely in power transformers, a superior dielectric gas would give incentive to the designer to develop a gas-insulated transformer. Westinghouse Electric Corp., in collaboration with E. I. DuPont de Nemours & Co., Inc., is undertaking a two-year project to develop alternative gases or gas mixtures superior to SF_6. Mixtures with only small additive contents will be included in the program. At present, SF_6 is used for both dielectric purposes and as an arc-interrupting medium in circuit breakers. While it is desirable to find a replacement gas or mixture superior to SF_6, in all respects it is more realistic to look for two alternatives, one for dielectric purposes and one for arc-interrupting purposes. In particular, the cost of the gas is important for compressed-gas insulated equipment. The gas cost for circuit breakers or as an additive is less critical. The candidate gases and gas mixtures will therefore be different for two concurrent investigations of dielectric and arc interruption properties. An intensive study of the available literature will be undertaken to select the candidates for both dielectric and arc interruption media.

Experimental screening will follow and further experimental work will be undertaken on the best candidates. Concurrent tests will be run on the compatibility of candidate gases and mixtures with commonly used materials, both in compressed-gas insulated equipment and circuit breakers. A design evaluation of the final candidates will be carried to the point that a realistic estimate of the cost of production of the gases is obtained. The benefits of utilization of the gas in existing designs of circuit breakers and gas-insulated equipment will be assessed, as well as the improvement in designs that the availability of the new gases and mixtures may make possible.

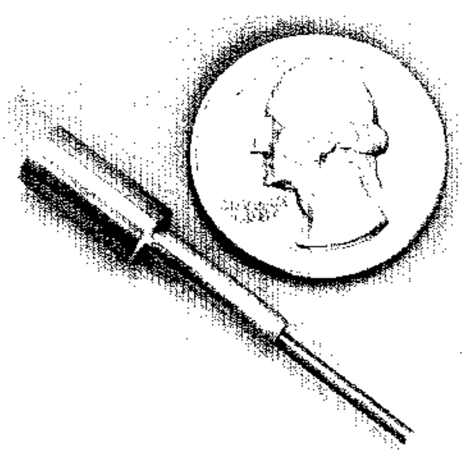


Figure 3 A "passive" hot spot detector sensor charged with benzene as the vaporizable fluid. An insulating oil-filled hydraulic line connects the sensor and the monitoring system.

Westinghouse will also consider using SF_6 instead of nitrogen in the gas space over the oil in power transformers. This study will be in sufficient detail to evaluate solubility, electrical properties, gas evolution and absorption, convection effects, compatibility, stability, corona performance, and metal reaction.

This project will evaluate the possibility that an SF_6-oil mixture will result in improved transformer characteristics. In addition, if no adverse effects are discovered it will be possible to eliminate oil condenser bushings on transformers that interface with gas-insulated substation (GIS) equipment. This will produce savings in cost, space, complexity, and maintenance. Finally, this project will resolve existing questions on the consequences of accidental introduction of SF_6 into transformer oil at gas-insulated substations.

Naphthenic crudes have been the basic source of insulating oil for cooling and insulating electrical apparatus. There is a serious concern that we are running out of low-pour crudes of this type. With the increased worldwide demand for energy, paraffinic or mixed-base crudes will be required. The paraffinic crudes are more readily available, and the successful completion of this project will ensure a long-range supply of insulating oil. General Electric Co., Westinghouse, and McGraw-Edison Co. have separate contracts for evaluating these new oils.

An initial task in the General Electric project was to survey the supply and demand of transformer oil in the next decade. All indications are that the supply of present transformer oils will decrease in a few years as supplies of naphthenic crude oils dwindle. Demand for transformer oil will rise and eventually will exceed supply. The crossover point will depend on the rate of electrical load growth and could come as soon as the end of this decade. A more pessimistic forecast of load growth predicts a crossover prior to the mid-1980s.

Ten oils refined by various means from nonnaphthenic stocks have been evaluated by standard test methods. Not all oils are satisfactory in all respects. However, it appears that transformer oils can be made that are satisfactory at ambient and at elevated temperatures.

Low-temperature behavior of nonnaphthenic oils is being evaluated. Preliminary results indicate that heat transfer properties are comparable with naphthenic oils down to the pour point of any given oil. This is apparently independent of whether the oil forms wax above the pour point and suggests that pour-point suppressors (viscosity modifiers) may be effective in obtaining satisfactory heat transfer. Work is progressing to determine whether wax is detrimental to electrical behavior at low temperatures.

The prospect of a new generation of oils requires that the most effective tools and test methods be available for evaluation of oils. The mechanisms involved are not electrical. Chemical tests are being evaluated and the relationship between the test results and actual service is being defined. To define the most effective and rapid test procedures, extensive work on accelerated aging of oils is being done both in actual transformers and in other configurations. A variety of analytic methods for hydrocarbon analysis (such as mass and nuclear magnetic resonance spectrometry and gas, liquid, and gel permeation chromatography) are being applied to both fresh and aged oil. Results of these analyses are being related to the behavior of oils in an attempt to provide guidelines for production of optimized oils.

The Westinghouse investigation will evaluate comparative performance between the presently used naphthenic insulating oils and the paraffinic insulating oils in (1) accelerated-life tests in distribution transformers, (2) tap changers, (3) power circuit breakers, (4) large gap breakdown studies, and (5) corona studies.

A worldwide study of electric insulating oil refiners was undertaken to determine the nature of the crudes being used and the refining processes being employed. It was found that more paraffinic crudes are being used and that solvent refining, catalytic dewaxing, and other methods are being investigated throughout the world.

Initial special tests have been started on experimental insulating oils produced in the United States from paraffinic crudes. These tests consist of lubricity, arc-formed gas analysis, and materials compatibility. Oils that successfully pass these tests will be considered for evaluation in the more extensive apparatus testing program described above.

The McGraw-Edison research project deals with system testing of dielectrics and their relation to distribution and power transformers. Using ordinary analytic techniques, the interaction of the various components in an electric system is complex and extremely difficult to evaluate. A systems approach is being evaluated, using miniature capacitors containing a mild steel case, 100% treated kraft paper, and copper foil. An acid-refined base oil will be evaluated with some of the new type oils to be put on the market. All oils will be evaluated with and without an oxidation inhibitor. All units will be stressed electrically while being aged at two different elevated temperatures. Both oil and kraft insulation will be evaluated during the course of the test.

The benefits of this project would be (1) the ability to quickly evaluate any modifications in solid and liquid insulating materials, operating temperature, and operating voltage, and (2) obtaining a much more accurate correlation between laboratory tests and actual units in service. *Project Manager: Ed Norton*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

SYSTEMS

Analysis for Application

Assessing the commercial value of alternative future energy technologies is fundamental to R&D decision making but it involves considerable uncertainty and subjectivity. There is uncertainty about when technology options will become commercially available, what their costs will be, and what technical alternatives they must compete with. Energy models cannot, therefore, provide definitive answers to questions on the relative values of competing technological alternatives, but they can provide a useful structure for incorporating subjectivity in a consistent way.

Two linear programming models being worked on under RP442 offer potential usefulness to R&D management: the Brookhaven Energy Systems Optimization Model (BESOM) and its dynamic version, DESOM.

BESOM is a linear programming formulation that represents the U.S. energy system from source to use at a key year in the future (e.g., 1985, 2000). Forecasted parameters assumed for the model include the end-use demand for energy, the sources and availability of supply, and the technologies through which the energy flows. An important feature of BESOM is that consumer energy demand is estimated in energy units (Btu) rather than in units of specific fuels, which allows for a full, feasible range of interfuel substitution. Since the range of feasible substitutability depends on the available supply and utilization technologies, the model is constructed around them. Technology-related parameters appear explicitly in the model as the costs (including capital, operating, and fuel), the efficiencies of energy conversion, and the emissions or environmental effects of each technology.

The output from BESOM includes a basic solution composed of the mix of energy technologies that, for example, minimizes total energy cost. Since the solution only reflects a particular set of cost and availability assumptions about the various competing technologies, it is probably the least useful and interesting part of the model's output. More useful are the results that can be obtained through the standard linear programming procedures of sensitivity analysis and shadow price analysis.

Through sensitivity analysis it is possible to establish the full range of relative costs that determine the inclusion or exclusion of a technology in the basic solution. Running the BESOM under a range of relative cost assumptions for several candidate technologies provides a maximum cost feasibility target for the development of a specific technology if it is to compete economically. Shadow price analysis with the BESOM establishes the marginal value of supply of technologies that are in the basic solution and the marginal value of the resources on which those technologies depend. Also available from shadow prices is the marginal cost of demand at the point of end use. This cost is particularly useful in evaluating end-use technologies and conservation initiatives.

BESOM was initially developed for the total U.S. energy system. The current project with Brookhaven National Laboratory provides regional data for an analysis more appropriate for EPRI objectives.

BESOM is limited because it is a static model of a dynamic system. While the dynamic characteristics of the energy system may be introduced by applying BESOM sequentially to a series of development periods, with growth of demand and change in technology specified exogenously, a great deal of analytic potential is lost in this process. Recognition of this led to the current development of the Dynamic Energy Systems Optimization Model (DESOM), an effort supported by EPRI. DESOM can be thought of as several BESOMs, one in each of 10 time periods, connected across all time periods. DESOM extends BESOM in the following ways:

- Where BESOM minimizes the cost of energy at a single point in time, DESOM minimizes the total discounted cost over time.

- DESOM makes it possible to optimize the timing of implementing available technologies as well as the technological mix, thus enabling the user to address questions concerning the rate of growth of new capacity.

- DESOM considers the total availability of fuel resources and calculates the cost-minimizing rate of consumption over time.

Such a dynamic optimizing approach as DESOM, recognizing both interfuel substitution and technological innovation with respect to time, provides a sensible way of gauging the impact of technical change on the energy system. Like BESOM, solutions of DESOM require forecasts of the costs and efficiencies of conversion processes, some of which do not now exist, and of supplies and demands that are equally uncertain. The appropriate use of either model for technology assessment is for gaining insight regarding possible implications of technology alternatives, rather than for predicting what choices will be made. *Project Manager: Ron Michelson*

DEMAND AND CONSERVATION

Transportation Sector

The Demand and Conservation Program has two demand forecasting projects under way in the transportation sector. These transportation energy forecasting models are important to EPRI for two major reasons. First, it is necessary to know the energy required for transportation in order to complete our forecasting effort for national energy needs. Second, it is necessary to analyze the structure of transportation supply and demand in order to evaluate the impact and likelihood of the widespread use of electric transportation technology, such as electric road vehicles, mass transit, and intercity rail electrification.

Our first project in the transportation energy forecasting area is on the analysis and forecasts of energy used for transportation services, RP757, with Wharton Economic Forecasting Associates of Philadelphia. Projects on electric cars, mass transit, commercial electric vehicles, and rail electrification will dovetail with the Wharton effort. The model is driven by information from the Wharton Long-Term Model, which is being tailored to fit EPRI's needs in a study on the effects of energy costs and availability on the national economy, RP440. The results of the transportation model will be fed into the Wharton Long-Term Model and will affect its projections.

The model is structured so that the demand for energy is derived from the demand for transportation services, itself derived from the demand for goods and services either intermediate or final. In turn, the demand for goods and services is a crucial function of economic activity. Thus, a model of energy demand relates the demand back to the economic activity through intermediate economic processes. To this end a model of transportation must be reduced to its components in several meaningful ways.

First, the demand for transportation services is broken down into freight and passenger demands. The working hypothesis of the model is that measures of industrial activity are the prime determinants of freight transportation demands.

On the passenger side, income, employment, and related measures play important explanatory roles. There is further detail within each subsector on choice of mode and type of commodity or the type of personal trip that might use each mode. Thus, the model can take advantage of the extensive information that exists in the Wharton Annual Long-Term Model. The Long-Term Model drives the transportation services model through links between the transportation model itself and the input-output structure of the Long-Term Model. A model consisting of only the demand side of the transportation services market is only half complete. To close the model and to make it fully responsive to economic forces, a supply submodel is needed.

The supply submodel explains the rate of installation of new transportation equipment and the scrappage and utilization of the entire stock of transportation equipment. It is linked to the demand side via the cost of operation of the vehicles in the fleet, specifically the cost per ton mile for freight and the cost per passenger mile on each given mode. These costs will play a crucial role in determining modal choice. In turn, modal choice gives load factors for each mode and hence determines the scrappage of deteriorated vehicles.

Finally, those vehicles must be replaced, bringing us back full circle to the investment equations. From modal choice, relative utilization (load factor) and conversion efficiencies, fuel consumption by mode can be derived. The consumption of fuel is then aggregated over the modes using the same type of fuel, yielding an aggregate demand for each type of fuel.

In its final form the model will yield predictions of the fuel consumption mix, modal use mix, and investment mix as a result of alternative assumptions about fuel prices and economic activity. In addition, the model's results will include analysis of the sensitivities of various fuel consumptions to changes in the structure of fuel prices.

Another current transportation energy demand project on the implications of electric automobiles for utility system loads (RP758) is linked to the Wharton Transportation Energy Demand Project through the equations that model automobile demand by size of vehicle and type of driving cycle (e.g., urban or rural). This project is being carried out by Mathtech, Inc., and deals primarily with the supply side of electric vehicles and an analysis of market penetration.

The supply analysis will reduce the various prototype electric vehicle designs to their basic engineering subsystems. Cost-estimating relations will be developed for each subsystem and then combined into cost models for the various electric vehicle designs. Inputs into the cost model will include the price of commodities necessary to build the electric vehicle and several likely scenarios to describe the future state of battery technology. Outputs of the cost (or supply) models will be technical performance and efficiency characteristics of the vehicles, their initial or capital cost, and a derived demand equation for electric power and energy necessary to recharge and operate the vehicles. The impact on electric utility system load shapes and kilowatthour sales will be computed on a variety of alternative battery recharging assumptions.

It is anticipated that a similar model will be developed to describe energy demands for commercial electric vehicles.

Furthermore, development of a transportation energy demand submodel is being contemplated that will focus on electric mass transit systems, including current bus and rail technologies and advanced technologies that are likely to be introduced beyond the year 2000. *Project Manager: Anthony Lawrence*

SUPPLY

Energy Production

The future supply of oil and natural gas is of concern to the electric utility industry for two reasons: oil and natural gas currently supply about 35% of the energy for thermal power generation nationally; and oil and gas are the main competitors of electricity in many markets.

Although the percentage of oil and gas as fuels for power generation will probably decline, the rate of decline can be significant for utility planning. Federal policy, as well as supply, will of course influence actual availability. Perhaps more important in the long run than the supply of gas and oil for power generation is the role of these fuels as competitors for electric power. In many areas two of the major determinants of electricity demand are the price and the availability of natural gas and oil. They may be more important than the price of electricity.

In order to effectively predict the probability of various levels of oil and gas supply, the Supply Program is analyzing the extent of natural gas and oil resources and the conditions under which they may be found and produced. The overriding objective of this research is to synthesize specific elements from selected existing research results and incorporate them into a computerized evaluation system capable of projecting regional oil and gas supply and transportation patterns under a variety of alternative scenarios. This implies correlative objectives that include extension and revision of existing models of offshore oil and gas supply and their application to onshore "frontier" areas; determination of the economic environment for evaluation of the role of supplemental and synthetic gas supply; examination of the possibility of extending economic engineering techniques to provide better characterization of the exploration and development of these fuels; and examination of the oil and gas pipeline network to ensure that regional transportation economics and capability are properly reflected.

Previous research efforts have ranged in scale from simplistic to highly complex models that reflect much engineering detail. The forecasting records of these models have varied—some have predicted enormous production, while others have predicted rapidly dwindling production.

Specific research projects supported by the program include a comparative state-of-the-art assessment of gas supply modeling, RP436-1, and a comparative state-of-the-art assessment of oil supply modeling, RP665-1. These studies report on the major gas and oil supply modeling efforts and have categorized the existing research efforts into three types: structural models of resource economics, pure econometric models, and resource-base geologic models.

Structural models are those that employ a variety of analytic techniques, algorithms, decision rules, various types of accounting identities, and similar quantitative methods to model the supply process. Modeling philosophy assumes that each of these techniques is selected for its suitability to handle specific subprocesses in the overall supply analysis.

Pure econometric models are those that rely strictly on statistical estimation procedures to develop mathematical relationships between dependent variables and their respective sets of explanatory variables. These relationships may be incorporated into a simulation model for making projections.

Resource-base geologic models are essentially mathematical equation-fitting methods used to calibrate coefficients corresponding to the total of the resource base, flow rates, and levels of production with respect to a depletable energy resource.

The research reports for these projects describe the existing models in a series of modular components so that the techniques and methodologies used to model each subprocess may be well understood and compared. The studies provide detailed discussions of the oil and natural gas supply sectors to give the reader some background and perspective into the importance of these fuels in the domestic energy economy and the pattern of evolution that has significantly influenced the industry's current composition and condition. A summary statement of model strengths and weaknesses, alternative projections and forecasts, and the implications of these methodologies were further researched, and policy analysis is presented. Recommendations for further study are also provided.

The research shows that, although there has been a diversity of results, part of these other supply analyses are quite useful. A new project will allow the Supply Program to use the relevant portions of existing work in the development of its own supply curves for the oil and gas industries (RP944). A more careful representation of supply curves of the natural gas industry, which is based on both the economics of production and the amount of resource in the ground, will afford a better evaluation of the complicated interactions of this fuel with both the electric utility industry and the other energy industries. *Project Manager: Rex Riley*

At the Institute

COAL CHEMISTRY WORKSHOP

The chemistry of coal, and liquids made from coal, was the subject of a two-day workshop sponsored recently by EPRI, Stanford Research Institute (SRI), ERDA, and the National Science Foundation.

Held at SRI's International Center on August 26 and 27, the workshop provided a forum for information exchange for more than 170 researchers working in the field of coal chemistry conversion. Participants represented the federal government, industry, the university community, and private research institutes.

"Workshops like this help to avoid costly and wasteful duplication of research efforts," commented William Rovesti, an EPRI project manager in the Clean Solid and Liquid Fuels Program. "With so many diverse organizations conducting research in this area, it's vital to keep abreast of the latest developments in the field."

This was the first coal chemistry workshop held on the West Coast, as well as the first one sponsored by the four participating organizations, according to Howard Peters, assistant to the director of SRI's Chemistry Laboratory.

Peters noted that the U.S. has been called the Persian Gulf of Coal because it contains so much of the world's coal. "Although we're still in the early stages of work on many coal conversion processes," he explained, "in a few years the U.S. may be called on to make a major commitment to expensive hardware equipment for this technology. Therefore, it's extremely important for us to learn about the processes today in order to be prepared for tomorrow's demands."

Reprints of the meeting's proceedings are available for $19 per copy from Howard Peters, SRI, 333 Ravenswood Avenue, Menlo Park, CA 94025 (415) 326-6200, ext. 3595.

Participants in a recent coal chemistry workshop sponsored by EPRI and three other organizations discuss the latest developments in the field. Left to right are Marion E. Hill, director, SRI Chemistry Laboratory; David S. Ross, physical organic chemist, Stanford Research Institute; William C. Rovesti, EPRI project manager for liquefaction research; Howard M. Peters, assistant to the director, SRI Chemistry Laboratory; and George Hill, director, EPRI Fossil Fuel Power Plants Department.

Assessing Intangible Impacts

How important are the "intangible" environmental impacts associated with electric power development, generation, and transmission? What methods are available or can be developed to assess such environmental effects as the visual impact of cooling towers and reductions in visibility caused by air pollution?

Attempting to answer these types of questions were 25 economists, psychologists, statisticians, and engineers meeting at a recent EPRI workshop held in Pacific Grove, California. Ronald Wyzga, project manager in the EPRI Environmental Assessment Department, explains that "increasing concern" has been raised about these intangible impacts and some measure of their relative importance is necessary so that the utility industry "can take proper account of them in future energy development projects."

According to Wyzga, the workshop group devoted much of their efforts to evaluating several potential techniques for measuring intangible impacts. They suggested the best methodological approaches for measuring specific impacts, such as the siting of a cooling tower or strip mining, reduced visibility from air pollution, and small changes in the risk of health effects.

Alan Kneese (left), professor of economics at the University of New Mexico and chairman of a recent EPRI workshop on intangible environmental impacts, reviews one of several current studies in this area with Tom Crocker, professor of economics at the University of Wyoming.

Economic techniques were among those discussed. "For example, economic methods exist for measuring intangible impacts based on observing differences in land values as functions of changes in visibility," says Wyzga. He added that other methods may involve the observation of changes in individual behavior due to environmental quality changes.

Wyzga points out that there are still other methods developed by psychologists, decision analysts, and economists. As an example, Wyzga cites a method that involves the determination of individual and group preference structures "by forcing them to make trade-offs among alternatives." The results of this approach, he says, allow the importance of various environmental impacts to be measured.

Corrosion Meeting

Louis Martel (standing), EPRI program manager for systems materials in the Nuclear Power Division, led a discussion last July on corrosion problems affecting nuclear power plant outages. About 40 scientists and engineers from utilities, universities, national laboratories, private industry, the U.S. Nuclear Regulatory Commission, and organizations abroad make up the EPRI Corrosion Advisory Committee. They meet twice yearly for discussions on corrosion and are instrumental in identifying needed R&D projects for EPRI.

Project Highlights

EPRI Negotiates 20 Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Mgr.
Fossil Fuel and Advanced Systems Division				
RP241-2	Fate of Fuel Nitrogen in Backmixed Combustion	6 months	25.1	University of Washington *D. Teixeira*
RP475-2	Central Receiver Open-Cycle Gas Turbine Solar Power Plant	2 months	64.2	Black & Veatch *J. Bigger*
RP779-3	Enhancement of Magnetic Separability in Coal Liquefaction	6 months	12.9	General Electric Co. *H. Lebowitz*
RP784-1	Detailed Design and Evaluation of Advanced Regenerable Flue Gas Desulfurization Processes	8 months	68.7	Stone & Webster Engineering Corp. *K. Yeager*
RP837-1	Effect of Chemical Additives on the Removal of SO_2 by Limestones	1 year	39.9	University of Maryland *M. Maaghoul*
RP840-1	Impact of the Voltage Safety Factor (VSF) on Advanced Power Converter	6 months	87.9	Power Semi-conductors, Inc. *J. Beck*
RP841-1	Advanced AC/DC Power Conversion Equipment for Batteries and Fuel Cells	32 months	497.1	United Technologies Corp. *J. Beck*
Nuclear Power Division				
RP519-5	Documentation of Operating Data from Light Water Power Reactors for Methods Verification	3 months	20.0	Science Applications, Inc. *B. Zolotar*
RP814-1	An Evaluation of the Portability of the DATATRAN Modular Data Base Manager	1 year	34.9	Rensselaer Polytechnic Institute *R. Whitesel*
RP821-1	Evaluation of the Effects of Hydrogen Peroxide Addition in PWRs Prior to Refueling	1 year	126.7	Nuclear Water & Waste Technology, Inc. *D. Uhl*
RP829-3	Determination and Microscopic Study of Incipient Defects in Irradiated Power Reactor Fuel Rods	20 months	114.1	General Electric Co. *J. Roberts*
RP829-4	Determination and Microscopic Study of Incipient Defects in Irradiated Power Reactor Fuel Rods	20 months	150.0	Argonne National Laboratory *J. Roberts*
RP830-1	Analysis of Critical Experiment Benchmarks for Testing Plutonium Cross Sections and Calculational Procedures	1 year	75.0	Stanford University *O. Ozer*
Electrical Systems Division				
RP577-2	Characteristics of Insulating Oils for Electrical Application	25 months	296.0	McGraw-Edison Co. *E. Norton*
RP848-1	HVDC Insulator Flashover Under Contaminated Conditions	2 years	248.1	University of Southern California *K. Griffing*
Energy Analysis and Environment Division				
RP857-1	Biological Effects of Electric Fields—General Support Study	1 year	129.8	IIT Research Institute *H. Kornberg*
RP866-1	Cost Models for Coal Transportation by Common Carrier	11 months	94.4	Manalytics, Inc. *R. Riley*
RP873-1	Applicability of Brookhaven National Laboratory's Energy Models to Electric Utility R&D Planning	7 months	84.9	Systems Control, Inc. *G. Karaganis*
RP882-1	Theory and Estimate of Residential Electrical Load by Time-of-Day	1 year	61.4	University of Illinois *A. Lawrence*
RP883-1	Foreign Uranium Supply	7 months	79.0	NUS Corp. *J. Platt/T. Browne*

Chemical Coal Cleaning

An alternative method for reducing sulfur emissions from coal may be found in the use of chemical processes now under development, according to EPRI's Terry Lund in a recent announcement concerning a new chemical coal-cleaning research project to be undertaken by the Atlantic Richfield Co. Lund says that this technology may be demonstrated by the early 1980s.

He explains that in chemical coal cleaning a reactant is added to coal that chemically attacks the bonds that hold the sulfur in the coal. "Several factors will significantly affect process performance and costs," comments Lund. "For example, how are the undesirable by-products separated out while maintaining the high energy content of coal? How are the chemicals regenerated so that costs can be kept down? Which chemicals will work and be cheap enough so that the process is economical? These are the types of questions that need to be answered."

With EPRI support, Arco will further develop its particular process, which is one of the most advanced chemical coal-cleaning techniques being developed.

Sulfur in coal is either in the form of pyrites or organic compounds, both of which produce SO_2 during combustion. To meet government standards on sulfur emission levels, power plants are designed with systems to remove sulfur, mainly through physical preparation techniques and/or flue gas desulfurization (FGD) systems, such as stack gas scrubbers. Before the coal is burned, physical preparation can remove most of the pyritic sulfur, but it cannot remove organic sulfur.

Researchers working on an EPRI coal study are shown in front of a pilot plant now under construction for studying an Arco process for chemically removing sulfur from coal. The researchers are (from left) Terry Lund, EPRI project manager; Emmet Burk, Arco senior research associate; Lavern Beckberger, Arco project manager; and Jin S. Yoo, Arco research associate.

If chemical processes are successfully developed, they could offer utilities an alternative to physical cleaning and scrubbers. "Chemical coal cleaning has the potential of removing both types of sulfur. And unlike scrubbers, chemical coal-cleaning plants can be totally detached from the power plant, thus simplifying plant operation," remarks Lund, a project manager in the Fluidized Combustion and Coal Cleaning Program. "Another advantage is that the primary coal product is dry, clean, and ready for direct burning by the utility."

Researchers working in chemical coal cleaning are unsure of the exact costs, although current indications are that costs will be similar to those for stack gas scrubbing. Lund believes that test results in the next few years will clarify the cost question and will also identify the most promising techniques.

"By the time demonstration plants are in operation in the early 1980s, the energy industry will have a clearer picture of the role of chemical coal cleaning," states Lund.

New Role at Wilsonville for ERDA

The Energy Research and Development Administration (ERDA) agreed last month to assume two-thirds of the costs of a pilot plant operation at Wilsonville, Alabama, where the solvent-refined coal (SRC) process is being developed. The electric utility industry, which until now has covered the entire cost of the $4.5 million-a-year project, will fund the remaining one-third through EPRI.

The Wilsonville project began in 1972 as a joint effort of the Edison Electric Institute and the Southern Company utility system for studying the process of coal solvent refining. ERDA also operates an SRC test facility at Fort Lewis, Washington.

The government's involvement in Wilsonville will allow the 6-tons/day plant to provide process support experiments for the larger, 50-tons/day Fort Lewis facility.

Coal solvent refining is a process that removes most of the major pollutants from coal before it is burned.

"The process produces a solvent to dissolve the coal, removes the pollutants, and yields a clean solid fuel," stated Norman Stewart, EPRI's project manager for Wilsonville. "The product can then be burned in utility boilers without the use of scrubbers, which are expensive to install and often not present on existing coal-fired plants."

Stewart explained that over half the country's electricity is generated in coal-fired plants. "These plants are designed and built to burn a solid fuel and sometimes cannot accommodate scrubber systems. Solvent-refined coal would offer utilities the prospect of continuing to use these plants without extensive modification, while meeting environmental emissions standards."

According to Stewart, the Wilsonville plant has been producing low-sulfur (less than 0.96 wt%), low-ash (less than 0.16 wt%) SRC since 1974, about six months after coal was first fed to the unit. He noted that efforts will continue to focus on improving the process, exploring the performance potential of different types of coal, and reducing process cost.

He further noted that the process is "well on the way to commercialization," but added that the costs and risks for the potential producer are high, so that financing a commercial venture is difficult.

"ERDA's involvement at this point adds longevity and promise to the project," he commented, "and hope that the government will take an even greater role in helping the utility industry commercialize a technology that is clearly in the public interest."

Environmental Effects of Power Plant Cooling

The beginning of a new research project to assess the effects of thermal-power-plant cooling systems on aquatic environments was recently announced by EPRI.

The study is directed toward developing a methodology for use by utilities in assessing the environmental effects of power stations on a body of water. Tetra Tech, Inc., Pasadena, California, will perform the research under a $478,000 EPRI award.

Robert Goldstein, project manager in the EPRI Environmental Assessment Department, says the study emphasizes a new approach to environmental assessment that is more efficient than traditional methods, which consider the isolated effects of a single project, such as the operation of a chemical, electricity generating, or sewage treatment plant.

"We'll now be working to develop a methodology that focuses on the resource [water body] first," explains Goldstein. "This will enable utility engineers to analyze a water resource and plan for power production with minimum impact on the environment."

According to the EPRI ecologist, this approach, called ecosystem management, is a "more sensible way of using our country's resources and could serve as a model for many industries." With ecosystem management, the focus is on the ecosystem and its capacity to support a combination of industrial, municipal, and recreational demands while preserving desirable environmental qualities.

Tetra Tech researchers will work to develop an analytic framework that incorporates the biological, chemical, and physical characteristics of water bodies as well as alternative designs for power plant cooling systems.

Storage Batteries

A $2.5 million contract for developing a superbattery that could be used by utilities for bulk energy storage was recently awarded to the General Electric Company's Corporate Research & Development Center by EPRI. The objective of the project (announced in the October issue of the JOURNAL) is to develop a rechargeable sodium-sulfur storage battery that potentially offers five times more storage capacity per pound than a standard lead-acid battery. GE scientists (left to right) Manfred W. Breiter, Stephan P. Mitoff, and Robert W. Powers compare a small experimental sodium-sulfur cell (right) with a larger developmental prototype.

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

Electrical Systems

TD-138 INVESTIGATION OF MECHANISM OF BREAKDOWN IN XLPE CABLES
Final Report

This research program explores the basic hypothesis that microporosity plays a significant role in the mechanism of breakdown of XLPE cable.

In Part I, the potential improvement achieved by impregnating the microporous regions of the cable core with a neutral liquid is evaluated, with relation to ac voltage life and impulse strength. The effect at higher frequency is also demonstrated.

In Part II, a similar test program is pursued on model cables, designed to explore the effects of gas pressure and gas type on breakdown and life, since it is reasonable to expect that only the microporous regions of the insulation should be sensitive to the gas-pressure environment.

Comparison of gas-pressurized model breakdown stress (and related microvoid size) with basic Paschen curves demonstrates reasonable good agreement, indicating that partial discharge is the basic mechanism of fatigue and breakdown.

The form of the voltage life curve above and below the discharge inception level is proposed, and evidence is presented indicating that breakdown originates in the bulk insulation as well as at the shield interface.

It is also shown that model cable discharge energies are below 0.1 pC, even at very high stress, and cannot be measured with modern detectors. Results with liquid or gas impregnation suggest a possible approach to dielectric improvement. *Phelps Dodge Cable and Wire Co.*

TD-153 EVALUATION OF UNDERGROUND FAULT LOCATION TECHNIQUES
Final Report

A number of techniques already exist to locate cable faults. This project is a study of all available techniques and their advantages and shortcomings. The objective is to recommend an optimum technique and to design a first-order system encompassing the best features of all techniques.

The project report summarizes the study findings and provides a recommended design for both a distribution fault location system and a transmission fault location system. Improvements incorporate modular design, automation, and reduction of the operator experience factor for efficient operation. *BDM Corp.*

TD-200 DEVELOPMENT OF Nb_3Ge CONDUCTORS FOR POWER TRANSMISSION APPLICATIONS
Final Report

This report describes successful attempts at the Los Alamos Scientific Laboratory to produce coatings of Nb_3Ge as thick as 70 μm, deposited on Nb tubes 0.64 cm in diameter and 23 cm long, exhibiting losses of 12.7 $\mu W/cm^2$ at 12 K, 50 Hz, and 500 rms A/cm, and carrying a current density of 4,200,000 A/cm^2. Details of producing the samples by the chemical vapor deposition method are described. The effects of variation of process parameters to optimize the superconducting properties of the material are given, along with descriptions of diagnostic techniques used to characterize and correlate these properties. Initial attempts to produce longer lengths of conductor are also described.

The primary conclusion of the first phase of this work is that Nb_3Ge possesses the best superconducting properties—high current density and low ac losses—yet available for application in ac power transmission cables operating at 12 K or above. Further, if long lengths of conductor could be produced with the properties found here in short samples, these would be completely acceptable for that cable application. The next phase of the program will concentrate on the latter problem. *Los Alamos Scientific Laboratory*

TD-204 SWITCHING TESTS OF SEPARABLE INSULATED CONNECTORS
Final Report

The need to evaluate changes to ANSI C119.2 prior to approval of revisions was expressed by a reliability working group drafting the proposed revision for the ANSI Subcommittee on Separable Insulated Connectors. A testing task force stated the objective: "To determine whether consistent switching and fault-closing results will be achieved when separable load break connectors are tested in various testing laboratories in accordance with the requirements contained in ANSI C119.2-1974 and proposed revisions developed by the Reliability Working Group. If consistent results among various testing laboratories are not obtained, the Testing Task Force is to revise the test circuits or procedures required to produce consistent results."

After testing connectors of three manufacturers in three separate laboratories, the data were evaluated.

The conclusion was primarily that no further revision was necessary of the test sections of ANSI C119.2, as revised. Consistent switching and fault closure results were achieved by the testers, using the prescribed circuits and procedures, yielding reproducible results that will identify connector designs capable of meeting the proposed ratings. *American National Standards Institute*

TD-229 DEVELOPMENT OF AN EVAPORATION–COOLED UNDERGROUND TRANSMISSION SYSTEM
Final Report

Growing economic and esthetic pressures encourage the development of advanced underground transmission (UT) systems for bulk electric power. An attractive general approach is the incorporation of forced cooling into otherwise conventional compressed-gas-insulated (CGI) cables. Forced evaporation cooling is one of several specific options with the potential of significantly increasing UT capacity and thereby reducing relative transmission costs.

The objective of this study was to investigate the development potential of a particular and novel configuration, described in this report as the separated-phase, evaporation cooling (SPEC) concept. Forced cooling would be provided by the evaporation of a halocarbon in the hollow conductors of a CGI cable system. Heat generated by electrical losses in the conductors is partially absorbed in the vaporization process. To avoid the large pressure drop associated with mixed two-phase flow, the coolant vapor is periodically and selectively vented through the conductor wall into the insulating gas space between conductor and sheath. If the coolant vapor has suitable dielectric properties it can function as the gas insulation in the system. The sheath provides a convenient return pipe for the vapor to periodic above-ground condenser stations. Pumps on the liquid side of the condensers supply the pressure required to circulate the coolant.

The development potential of the SPEC concept for underground CGI cables was studied by addressing crucial issues associated with coolant chemical stability, coolant distribution techniques, and system economics. *Battelle, Pacific Northwest Laboratories*

TD-232 MODELING TECHNOLOGY FOR BUNDLED POWER TRANSMISSION LINES
Final Report

The aerodynamic wake of the upwind conductors on a bundled conductor power transmission line can influence the aerodynamic conditions present at the downwind conductors in such a way that a form of conductor vibration known as subconductor oscillation occurs. This oscillation wears the conductors and hardware and has resulted in mechanical transmission line failure. The effects of the wake are dependent upon the relative position of the pairs of conductors involved. The downwind conductor must be in the wake influence area of the upwind conductor(s), before oscillation will occur.

This study sought to investigate twisting of the bundled phases, on a model basis, to determine support rotations that would minimize the aerodynamic interactions of conductors within the bundle. The mechanical properties of model conductor materials were measured, along with like properties of commonly used conductors. The test methods employed in these measurements are described. Models of the bundled power lines, based upon engineering similitude considerations, were built and tested for behavior during twisting.

Even though an actual twisted prototype system was not available for test, analysis of the 32 models built suggests that bundle behavior was adequately modeled for engineering purposes. Favorable end support rotations for two, three, and four conductor bundles are listed, along with detailed mechanical properties of nine commonly used conductors and 60 model materials. *Iowa State University*

TD-245 SUPERCONDUCTING RECTIFIER DEVELOPMENT
Final Report

This is the final report on the evaluation of superconductors for rectifiers of large-scale electric power. Although originally this project was to be substantially experimental in nature, the results of considerations of economics and technical feasibility of a full-scale prototype rectifier have clearly shown the impracticality of such a device operating at 60 Hz. Therefore the experimental program was not concluded, but the preliminary results obtained are included in this report.

Because of a large number of parameters, many of which could not be fixed unambiguously, our calculations are for reasonable but also very optimistic values of these parameters. Because the formulas are given throughout, it is a simple matter to scale any result to different and perhaps more realistic values of the parameters. However, since we have always used optimistic values and our conclusions are negative, it is clear that such changes will not alter the final qualitative conclusions.

It should be emphatically stated that the superconducting switch, although impractical for 60-Hz rectification, appears to be well suited to lower-frequency switching applications like fault current limiters, and these possibilities are described briefly. A more detailed analysis will be part of another report generated by this project (RP328) in the near future. *Argonne National Laboratory*

TD-255 SUPERCONDUCTORS IN LARGE SYNCHRONOUS MACHINES
Final Report

Research progress from the continuing program to apply superconductors in the field windings of large synchronous machines is presented in this report. The background of the project since 1969 is briefly reviewed. The general conclusion is that large superconducting turbogenerators are feasible and that the projected advantages given in the report should be realizable. Contractual details and a list of contributors are included.

Research results are given for work in three key problem areas in the development of superconducting machines. These include: a reliable rotor shielding scheme to better satisfy the conflicting requirements for magnetic shielding, machine damping, mechanical strength, thermal capacity, cryogenic performance and good machine terminal characteristics; an optimized superconducting rotor that has the proper balance between magnetic field intensity, magnetic stability, mechanical strength, mechanical rigidity, cryogenic cooling, cryogenic refrigeration requirement and transient electrical performance; and an armature winding and structure optimized to fully utilize the high magnetic field produced by the superconductor and to take full advantage of the opportunity to manage the electric field distribution and achieve high machine voltage.

The chronology of the design, construction, and testing of the MIT-EPRI 3 MVA experimental synchronous machine is given. The experimental results are summarized and modifications of the machine are discussed. *Massachusetts Institute of Technology*

Nuclear Power

NP-122 DETERMINING FRACTURE PROPERTIES OF REACTOR VESSEL FORGING MATERIALS, WELDMENTS, AND BOLTING MATERIALS
Final Report

In March 1974 the Electric Power Research Institute (EPRI) initiated a large testing program to evaluate heat-to-heat variability in fracture toughness of ferritic nuclear pressure vessel steels, which are currently described by the reference toughness curve (K_{IR}) relationship found in Appendix G. Section III of the ASME Boiler and Pressure Vessel Code. This program was established using a Task A program office to coordinate and administer testing procedures, data analysis, and data storage, and to perform a statistical analysis of the data. Three Task B testing laboratories were chosen to perform the fracture toughness testing. Effects Technology, Inc., was selected to be the program office, and Babcock & Wilcox Co., Combustion Engineering, Inc., and Effects Technology, Inc. were chosen as testing laboratories. The results of the testing program are given in EPRI reports NP-119 (Task B), RP 232-2, and this report. The initial statistical analysis of the data is reported in EPRI NP-121 (Task A).

A further analysis of the data and development of a statistically based reference toughness curve (K_{IR}) is being performed by Fracture Control Corp. under RP696-1. The results of this work will be available in January 1977. *Babcock & Wilcox Co.*

NP-152 STUDY OF RADIATION DOSAGE TO STRUCTURAL COMPONENTS IN NUCLEAR REACTORS
Final Report

This study was sponsored in order to provide the nuclear industry with an analysis of the radiation levels inside typical light water reactor pressure vessels, with emphasis on those components designed to function throughout the lifetime of the system.

The report describes the calculation of the neutron and gamma-ray fluxes and spectra, determined by applying two-dimensional radiation transport computer codes to physical models of a pressurized water reactor and a boiling water reactor. The calculated neutron and gamma-ray distributions may be used to estimate the total radiation exposure to which a reactor component is exposed over a period of time for the two generic reactor systems studied. The accurate knowledge of these radiation levels can be used to estimate the safety and licensability of the pressure vessel and in-vessel components.

The report also provides a complete description of the methodology used in the analysis. The neutron and gamma radiation levels are given on a fine mesh spacing for all points within the pressure vessel. The radiation spectra are also given in a manner that can be correlated to physical property changes known to occur under irradiation. *Science Applications, Inc.*

NP-161 CONVERSION OF ^{238}Pu AND ^{252}Cf PRODUCTION CHAIN CROSS SECTION DATA TO ENDF/B-IV FORMAT
Final Report

Heavy actinides such as Np, Pu, Am, Cm, and higher-mass nuclides are produced when nuclear fuel is irradiated in power reactors. Although the cross section information for the major fissile and fertile nuclides ^{235}U, ^{238}U, and ^{239}Pu are fairly well known because of their direct impact on the design of nuclear reactors, much less is known about the other heavy actinides.

The Savannah River Laboratory (SRL) has for some time been involved in a government program aimed at producing the two heavy actinide nuclides ^{238}Pu and ^{252}Cf. While one of these, ^{238}Pu, is used as an isotopic power source for space and medical applications (e.g., heart pacemakers), the other, ^{252}Cf, is used as an intense source of neutrons for various physics experiments.

Because of this involvement, SRL has been able to accumulate a considerable amount of information on the cross sections and decay properties of over twenty heavy actinide nuclides produced when uranium fuel is irradiated in thermal reactors.

Under RP-451, these data have been processed into a form compatible with the national cross section data library (ENDF/B) and made available for inclusion in the next version of the library to be released. At present the data are being reviewed by the committee responsible for the production of the fifth version of ENDF/B and are being merged with other ERDA-supported evaluations emphasizing higher neutron energies. *E. I. du Pont de Nemours & Co.*

NP-179 WELD REPAIR OF HEAVY SECTION STEEL TECHNOLOGY PROGRAM VESSEL V-7
Final Report

The in situ repair of a flaw in a large nuclear pressure vessel is likely to be a complex undertaking. Normally, a thermal stress relief is required to reduce peak welding stresses; however, accomplishing this task under field conditions can result in difficulties related to warpage of the vessel. Consequently, Section XI of the ASME Boiler and Pressure Vessel Code has provided guidelines for making major repairs without a subsequent thermal stress relief. The repair weld procedure employs a technique known as the half (or temper) bead technique. In theory this procedure is structured so that each weld pass is applied in a manner that results in tempering the preceding weld pass. Thus brittle transformation products created during welding will be rendered ductile. Although this technique is used in the repair of petrochemical pressure vessels, a demonstration of its practicality and effectiveness has yet to be accomplished for a nuclear pressure vessel.

The Heavy Section Steel Technology (HSST) Program conducted by the Oak Ridge National Laboratories (ORNL) and sponsored by the Nuclear Regulatory Commission (NRC) has been pressure-testing intermediate-sized vessels roughly scaled to nuclear reactor pressure vessels. One such vessel, ITV-7, which was intentionally flawed in the axial direction, was hydraulically pressurized to failure. Leakage occurred when the vessel was pressurized to 2½ times the design pressure. Arrangements were made with the

HSST program office to use this vessel for the purpose of repairing the through-wall flaw according to Section XI procedures in order to demonstrate the utility of such a weld repair.

The repaired test vessel was returned to ORNL along with accompanying test pieces for the purpose of retesting the vessel. Plans are to reflaw away from the weld and pneumatically pressurize to failure. Since the applied flaw will be similar to the original, the effect of pneumatic loading will be evaluated. After this test, plans are to repair the vessel, reflaw in the new weld repair heat-affected zone, and retest. Thus, the serviceability of the Section XI repair procedure will be demonstrated for both the unflawed and the flawed conditions. Details of the testing conditions and results will be made known through HSST reporting channels. *Combustion Engineering, Inc.*

NP-186 DEVELOPMENT OF SYSTEM FOR MONITORING IN–SERVICE STRAINS IN POWER PLANT PIPING
Final Report
As a first step in developing a system for monitoring in-service strains in power plant piping systems, Southwest Research Institute developed and laboratory-tested a biaxial, long-life, high-temperature strain transducer. The transducer used a variable shield capacitance principle, and in laboratory tests had a resolution of 20 $\mu\epsilon$ (0.1% full range) and a drift rate of 6 $\mu\epsilon$/hr (0.003% full range) at 1100°F. Its resolution and drift compared favorably with the best characteristics of commercially available uniaxial strain transducers. Also, the differential capacitance design provided for in-service calibration of the transducer.

Future development of the strain monitoring system will include field evaluations in operating fossil fuel and nuclear power plants. *Southwest Research Institute*

NP-189 FEASIBILITY STUDY OF ON–LINE SAFETY EVALUATION AND MONITORING OF MALFUNCTIONS OF THE NUCLEAR REACTOR SYSTEM BY DYNAMIC DATA SYSTEM
Final Report
This report describes an advanced time-series analysis methodology and illustrates its application to reactor core barrel dynamics problems. Auto-regressive moving average (ARMA) time-series modeling is used.

To demonstrate the viability of this data-dependent approach, neutron noise data from two nuclear units were analyzed. The report claims these analyses duplicated classical statistical results but without complications of variance or bias. The superiority of the time-series method in procuring parameter estimates in a data-efficient manner is also discussed. *University of Wisconsin*

NP-213 REACTOR–COMPONENT INSPECTION WITH COMPUTERIZED TOMOGRAPHY
Final Report
In the last few years a new X-ray diagnostic tool called computerized axial tomography has produced many impressive results in medical examinations. Because of this success, a project was undertaken to evaluate whether this process was suitable for generating three-dimensional details on reactor components. An existing medical scanner was used to generate experimental data on objects geometrically similar to pipe joints. The combination of the experimental results and computer simulations indicates that this process has such promise for pipe inspection that a laboratory system should be assembled in order to evaluate the process on actual pipe samples. The details of this project are contained in this report. *Stanford Research Institute*

NP-251 ATWS: A REAPPRAISAL. PART ONE, AN EXAMINATION AND ANALYSIS OF WASH-1270, TECHNICAL REPORT ON ATWS FOR WATER–COOLED POWER REACTORS
Key Phase Report
This document is the first of a series that will examine the basis for the problem of anticipated transients without scram (ATWS). The purpose of these documents is to evaluate risk due to ATWS in the light of developments subsequent to the publication of WASH-1270 and to reevaluate the probabilistic basis for ATWS. The project's goals include estimates of: the actual probability of failure to scram; the probabilities of initiating events, such as MSIV closure; and the risk due to ATWS. There is also the possibility, in the very long term, of a cost-benefit evaluation for specific plant modifications.

The purpose of this report is to upgrade the numerical information presented in WASH-1270 by correcting deficiencies in that document and updating the input data. The two additions in the present approach are the use of a demand failure model instead of a time-dependent model for the scram system and the incorporation of Bayesian Priors into the probabilistic treatment of the data. *Science Applications, Inc.*

Energy Analysis and Environment

SR-45 PROCEEDINGS OF THE WORKSHOP ON MODELING THE INTERRELATIONSHIPS BETWEEN THE ENERGY SECTOR AND THE GENERAL ECONOMY
The Workshop on Modeling the Interrelationships Between the Energy Sector and the General Economy was sponsored by the Electric Power Research Institute (EPRI). It was held in Washington, D.C., on January 29 and 30, 1976, and was attended by economists and energy specialists. This report contains the proceedings of the workshop.

The importance of modeling the interrelationships between the energy sector and the rest of the economy has become increasingly evident, particularly since the oil embargo of 1973. EPRI has an ongoing program of energy systems modeling, with emphasis on modeling the interrelationships between the energy sector and the general economy. EPRI's purpose in sponsoring the workshop was to examine the state of the art of such modeling and to identify future research needs. One chapter of the proceedings discusses this.

At present, a leading effort to link the energy sector to a macroeconomic model of the United States economy is the Hudson-Jorgenson model, which was first reported as part of the Ford Foundation Energy Policy Project (EPP). A short discussion paper of this model appears here.

The rest of the document reflects the workshop schedule. It contains the papers and prepared comments presented at the workshop and provides synopses of the general discussions by the workshop participants at the end of each session. Appendix A contains workshop materials; Appendix B shows extracts from the *Grant Administration Manual* of the National Science Foundation. *J. D. Khazzoom, Stanford University*

EC-139 EFFECTS OF POWER PLANT EMISSIONS ON MATERIALS
Summary Report
This study assesses the available knowledge on the effects of air pollutants on materials, with special emphasis on those pollutants emitted from or related to emissions from fossil fuel power plants. The study indicates the relative importance of these various effects, summarizes current research on the material effects of air pollution, and identifies areas of needed research.

The areas of suggested research include the effects of atmospheric sulfates on materials, the effects of air pollutants on concrete, evaluation of the effects of acid smut from oil-fired boilers, and the development of more accurate estimates of SO_2 damage costs to materials. *Research Corporation of New England*

EC-140 COOLING WATER DISCHARGE RESEARCH PROJECT
Final Report
The project, which was initiated in 1963, supported activities that elucidated environmental effects resulting from once-through cooling systems. This report summarizes the diverse activities conducted over the duration of the project that included: theoretical and experimental studies of heat dissipation from condenser discharges; thermal effects studies of plankton, benthic invertebrate, and fish populations; entrainment effects studies of phytoplankton and zooplankton populations; and the construction and testing of a flume to study the interaction of fish species with cooling system intakes.

Biological effects studies were conducted both in the laboratory and the field. The field studies, which were conducted at three power-generating stations in mid-Atlantic states, indicated no significant detrimental effects to plankton, benthic invertebrate, and fish populations as a result of thermal discharges, and no significant effects to phytoplankton and zooplankton populations as a result of entrainment. *Johns Hopkins University*

EC-141 COOLING WATER DISCHARGE RESEARCH PROJECT
Progress Report
This report covers the final 8-month period of the project, which was initiated in 1963. Among the topics reported are the design, construction, and calibration of a test flume to study the interaction of fish species with cooling system intakes; laboratory and field experiments to determine impact of entrainment on zooplankton populations; a workshop (held June 1975 at Johns Hopkins University) on biofouling control procedures and their ecological effects; a study of the natural mortality rate of striped bass eggs; development of containment structures for studying the response of phytoplankton populations to perturbations; and the application of a mathematical model to study the effect of algal destruction on dissolved oxygen concentrations.

The zooplankton entrainment study is unique in its attempt to measure possible delayed effects of entrainment. The field work indicated no significant impact on the zooplankton community in the area of the power plant where the study was performed. The laboratory work indicated that entrained zooplankton did not incur any significant latent effects as a result of entrainment. Results also contradicted the hypothesis that mechanical stress was a major cause of entrainment mortality. *Johns Hopkins University*

ES-187 ELECTRIC ENERGY USAGE AND REGIONAL ECONOMIC DEVELOPMENT
Final Report
This study was undertaken by James H. Savitt of the State University of New York at Buffalo to investigate the feasibility of conducting an analysis of the relationship between electricity consumption and regional economic growth. In developing the prototype regional model, Savitt modified an existing model of economic growth in the Buffalo SMSA by the addition of electricity consumption equations and the development of feedback relationships to the income determination aspects of the economic growth model. The project established that it is possible to develop such integrated regional energy and economic growth models, although a number of research questions remain to be explored more fully. *State University of New York at Albany*

EC-224 HEALTH EFFECTS OF MERCURY
Quarterly Report
This is the third in a series of topical reports detailing the health impact of selected fossil fuel pollutants based on available toxicological and clinical research data. The first report dealt with selenium and its compounds, and the second with oxides of nitrogen. The next two reports in the series will deal with oxides of sulfur and polycyclic organic materials, respectively.

The purpose of these reports is to present an up-to-date critical examination of the toxicological and clinical data base in order to provide information on air pollutants of importance in a timely manner to utility personnel and to assist EPRI and utility membership in establishing priorities for an effective research program in the area of health effects of fossil fuel pollutants. *Science Applications, Inc.*

Fossil Fuel and Advanced Systems

ER-198 PENETRATION ANALYSIS AND MARGIN REQUIREMENTS ASSOCIATED WITH LARGE-SCALE UTILIZATION OF SOLAR POWER PLANTS
Final Report
Studies of solar plants operating as part of a conventional electric utility network have shown that additional margin—referred to as backup capacity—is required for the solar plants to prevent network loss-of-load probability from exceeding established criteria. In this study, computer simulations of network operation were carried out taking into account the availability for service of both solar and conventional plants as a function of scheduled maintenance and forced outage events. Solar plant capacities up to approximately one-third of the network capacity were examined and were found

to require as much as 60% of added conventional plant capacity as backup.

The effect of geographic diversity in which the total solar plant capacity is divided between two or three widely separated plant sites was also examined. It was found that proper distribution of solar plant capacity can significantly reduce backup relative to the amount required for any single site. *Aerospace Corp.*

AF-199 COAL LIQUEFACTION DESIGN PRACTICES MANUAL
Final Report

This manual assembles existing liquefaction equipment and operating history from the German pre-WWII days to the present. Considerable experimental and design effort has been expended over this period throughout the world on a variety of coal liquefaction programs. An open exchange of information has not occurred that would permit all investigators to contribute to and benefit from the experience of others. In many cases the same mistakes have been made over and over again. It is hoped that this equipment manual will be the start of an ongoing equipment record so the new engineers in the field can readily benefit from previous experience. It is anticipated that periodic updating will be required to keep the record current and useful. *Fluor Engineers & Constructors, Inc.*

AF-202 LIQUID–PHASE METHANOL
Annual Report

Chem Systems Inc. is developing a new methanol synthesis process for EPRI. The key to the process is a three-phase fluidized system. An inert liquid is used as a sink for the exotherm of the synthesis reaction. This temperature control feature allows greater per pass conversion and improved thermal efficiency as compared to presently available technology.

The first annual report presents experimental findings from a bench-scale apparatus. Thermodynamic calculations and a preliminary economic analysis are presented. *Chem Systems Inc.*

ER-217 SOLAR WATER HEATING AND DATA MONITORING SYSTEMS AT SOUTH COUNTY HOSPITAL, WAKEFIELD, RHODE ISLAND
Topical Report

Representing the initial effort to gather and disseminate information on the cost as well as performance of installation packages for solar heating and cooling demonstration projects, this report describes the installation of a hot water heating system at South County Hospital, Wakefield, Rhode Island. Engineering design and instrumentation of the solar system was a cooperative effort involving representatives of the New England Electric System (NEES) and Daystar Corp. Engineering procurement and installation of the instrumentation system was supported by EPRI. A two-year monitoring and reporting program will be conducted.

Contained in this report is a complete description of the solar system and the instrumentation package. Included in the system description are its application and performance, discussion of system plumbing, control logic, and collector mounting. The instrumentation package is introduced via methodology, general description, and functional block diagrams. Each component is discussed in detail, together with anticipated component and system accuracies, cost, and delivery data.

As anticipated, certain instrumentation system design and installation problems arose both during in-house testing and following startup at South County Hospital. These are summarized in the report. *Daystar Corp.*

EM-230 SODIUM–CHLORIDE BATTERY DEVELOPMENT PROGRAM FOR LOAD LEVELING
Interim Report

This interim report details 1975 progress for the EPRI–ESB jointly sponsored sodium-chloride battery development project. The objective of the effort is to develop the sodium–antimony chloride battery into a commercially viable energy storage system for utility application. The battery uses a molten sodium negative electrode, a beta alumina solid electrolyte, and a molten-salt mixture of antimony trichloride and sodium chloroaluminate as the positive electrode. It has an operating temperature of 200°C—in principle, a temperature high enough to allow good performance characteristics but low enough to utilize silicone rubber seals. The cell hardware and testing activities over the past calendar year (1975) have involved transition from small disc cells (1–2 Wh) to tubular cells (10–20 Wh) having a design representative of the full-scale cell. Most performance-related problems of the tubular design have been solved; however, further improvement in electrolyte quality appears necessary. Life of disc cells has been extended to 15,000 hours and 640 cycles (120 Ahr/cm^2) and life of tubular cells has been as high as 3600 hours and 160 cycles (15 Ahr/cm^2) during the 1975 contract period. The long life of the disc cells shows the basic compatibility of system components. However, electrolyte failure has prevented tubular cells from consistently achieving long life. Work over the present year is directed toward improving electrolyte quality and therefore cell life. Fabrication and testing of a multi-tube 1-kWh cell is to begin early next year. *ESB, Inc.*

AF-244 ECONOMICS OF CURRENT AND ADVANCED GASIFICATION PROCESSES FOR FUEL GAS PRODUCTION
Final Report

The purpose of this work was to estimate the cost of low- and intermediate-Btu fuel gas produced by gasifying coal in a variety of different devices. Gasification technologies investigated were: 1) Lurgi moving bed, dry ash, 2) IGT U-Gas fluidized-bed process, and 3) Combustion Engineering two-stage entrained flow at atmospheric pressure. The cost of producing clean fuel gas at low pressure from each of the above devices operating in both the air-blown (for low-Btu gas) and oxygen-blown (for intermediate-Btu gas) modes was estimated.

The results of this study indicate that fuel gas produced from coal by either the fluidized-bed or entrained-flow devices would be substantially lower in cost than gas produced by a Lurgi gasifier. It was also shown that for both the fluidized-bed and entrained-flow technologies studied, the cost of fuel gas was independent of the oxidant used, i.e., air or oxygen. This latter conclusion did not hold for the Lurgi gasifier, as the cost of intermediate-Btu gas was considerably higher than the cost of low-Btu gas produced by utilizing the moving bed, dry ash technology.

The report presents detailed flowsheets with material and energy balances for each of the systems studied. Detailed economic breakdowns as well as all assumptions used are included. *Fluor Engineers & Constructors, Inc.*

ER-246 CONCEPTUAL ENGINEERING DESIGN OF A ONE–GJ DISCHARGING HOMOPOLAR MACHINE FOR THE REFERENCE THETA–PINCH FUSION REACTOR
Semiannual Report

A conceptual design for a large, fast-discharging homopolar energy transfer system for application to fusion reactors is presented in this first semiannual report. The design constraints are 1 GJ of stored energy discharged into an inductive load in 30 ms and then recovered with better than a 95% efficiency. The resulting machine design incorporates 8 drum-shaped rotors spinning in very high magnetic fields provided by superconducting coils and an array of metal-graphite brushes for current collection. Subsequent project activities include the scaling and design of a prototype machine. *Los Alamos Scientific Laboratory*

AF-252 THE NATURE AND ORIGIN OF ASPHALTENES IN PROCESSED COALS
Annual Report

This report presents the results of the first year of a two-year effort aimed at obtaining a fundamental understanding of the chemical nature and structure of solubilized coals and the kinetics and mechanisms by which these liquefied products are formed from various coals under solvent-refining conditions.

Coal liquefaction was studied under somewhat mild reaction conditions and at very low conversions, as well as under conditions typical of solvent-refining pilot plant operations, so that the solubilization process could be followed more closely. A much more detailed investigation of the skeletal structure and chemical function of products was pursued than previously.

A novel chromatographic fractionation procedure for the separation of soluble coal products into discrete chemical classes was employed, along with other advanced techniques to better assess the nature of the products formed under different reaction conditions. With this description of SRC products, a chemical basis for process optimization is being formulated. *Mobil Research & Development Corp.*

FP-253 HOMOGENEOUS GAS–PHASE DECOMPOSITION OF OXIDES OF NITROGEN
Final Report

Control of the emissions of oxides of nitrogen from conventional utility boilers continues as an environmental problem facing electric utilities. Present control techniques to limit oxides of nitrogen emissions entail combustion modifications that minimize oxygen availability or reduce peak flame temperatures. While these conventional techniques have been successful with clean fuels such as natural gas and low-sulfur oils, they may be limited in their application to coal-fired boilers due to the inherent problems of burning a solid fuel. Additionally, the success of these techniques on high nitrogen fuels such as shale oil (up to 3% nitrogen) remains largely unknown.

Alternatives to limiting the formation of NO_x through combustion modifications are processes that lead to destruction of combustion-generated NO_x. Results of tests in a 200,000 Btu/hr combustion tunnel show that selective gas-phase reduction of nitric oxide, in air-rich combustion products, can be achieved by the injection of small quantities of ammonia (NH_3) or other suitable compounds. With injection of these compounds into combustion products that are at a temperature between 1300°F and 2000°F, nitric oxide reductions exceeding 90% have been achieved in the combustion tunnel. Results showing the effect of temperature, excess oxygen level, initial NO_x level, and the amount of reducing agent injected are discussed. Measurements of the emissions of ammonia and cyanide are also presented. *KVB, Inc.*

EPRI 1235-3 INVESTIGATING STORAGE, HANDLING, AND COMBUSTION CHARACTERISTICS OF SOLVENT–REFINED COAL
Final Report
EPRI 1235-4 INVESTIGATING STORAGE, HANDLING, AND COMBUSTION CHARACTERISTICS OF SOLVENT–REFINED COAL
Final Report

The 1235 series of reports documents the results of the investigation of the storage, handling, and combustion characteristics of solvent-refined coal (SRC). Such information would permit boiler manufacturers to design new units for burning SRC and to determine retrofit requirements (if any) for existing units burning coal.

The SRC reports summarize activity for a wide range of tasks. Initial work included bench-scale analyses of SRC, such as fuel analysis, pulverizing, and transport. The culmination of the effort was a 2-t/hr ball-and-race pulverizing and direct-firing test to simulate as closely as possible operating conditions in a utility plant using conventional equipment. *Babcock & Wilcox Co.*

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