The Reemergence of DC

ELECTRIC POWER RESEARCH INSTITUTE

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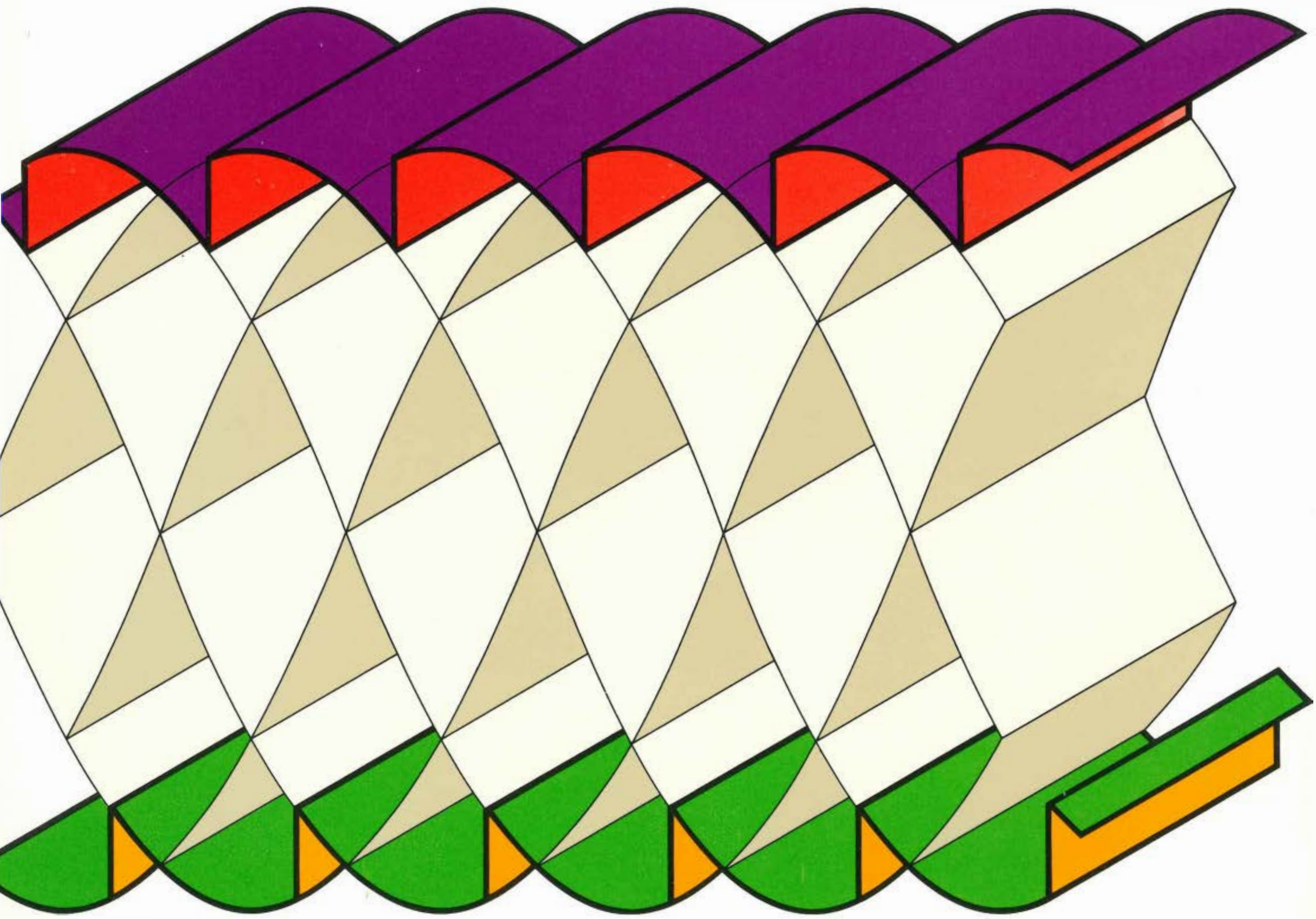

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Cover: Symbolic of three-phase, line-to-line voltage wave shapes, representing the conversion of ac power to HVDC in a modern converter terminal.

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The Future of DC Transmission

This month's lead article sweeps the long history of dc transmission and goes on to speculate on future applications in this country and abroad. Historically, the basic obstacles to dc development have been technical and economic in nature. But today, in my opinion, the greatest obstacle is a lack of experience with dc technology among our systems planners and perhaps a lack of appreciation for the essentially complementary role it can play in modern ac power systems.

I have been personally involved in the renaissance of dc technology in the United States since 1956, and in some ways I have been disappointed by its relatively slow rate of acceptance. Ironically, the misconceptions that have developed about HVDC transmission are often directly attributable to its staunchest supporters. For example, one of the first promotional features was the so-called breakeven distance at which dc became competitive. This resulted in an undue concentration on one aspect to the exclusion of other unique properties and characteristics of an HVDC transmission line.

Still others have tried to describe how an HVDC transmission link could be made to function like its ac counterpart. While this is of course possible, it is exactly what should *not* be done. Rather, we should become familiar with the specific differences that exist naturally between the two technologies and exploit these for our benefit. To steal from the French, "Vive la différence!"

Finally, it is extremely important that all the characteristics of a dc transmission link incorporated into an ac system be fully understood by the industry's power system planners. The proposed future use of HVDC transmission depends on dc's being considered an asset to an ac network, and this realization must start with our system planners.

John J. Dougherty, Director
Electrical Systems Division

Authors and Articles

Near the turn of the century, two giants in the history of electric power stood at opposite poles in a fierce controversy over whether ac or dc would be the form of electricity supplied to the nation. Thomas Edison and his supporters favored proven and safe dc. George Westinghouse and his allies pushed for ac, whose voltage could be stepped up for low-cost transmission and stepped down for low-voltage distribution. Transmission of ac was then far more efficient than dc, and ac power stations provided a greater service radius than dc stations. Patents that further improved ac performance were secured by Westinghouse, which led to ac as the power form chosen in the plan to harness the energy of Niagara Falls. This sealed dc's fate.

But as time cleared the controversial air, dc's potential was seen to complement rather than compete with ac's immediate advantage. What has been done to realize that potential, along with the technical developments and economic forces determining it, is detailed in "The Reemergence of DC in Modern Power Systems" (page 6), this month's cover feature by Narain Hingorani. "By the year 2000," Hingorani predicts, "a reasonable portion of power flowing through intersystem connections or into urban areas should pass through HVDC converters."

Hingorani, who came to EPRI in 1974 as program manager for dc transmission, is recognized as one of the country's leading designers of high-voltage, direct-current power transmission systems. As a consultant to the Bonneville Power Administration for six years prior to joining EPRI, Hingorani was responsible for system design and analysis of the 850-mile dc leg of the Pacific HVDC Intertie, which moves 1.4 million kW of power between the Pacific Northwest and the Southwest. In an earlier appearance in the *Journal* (December 1976), Hingorani coauthored "Compacting DC Terminals," which reviewed an EPRI project aimed at proving the technology for linking two prototype dc terminals at Consolidated Edison Co.'s Astoria Substation.

For nearly a dozen years before his work at BPA, Hingorani held research and teaching posts at three universities in England. He earned MS and PhD degrees in HVDC power transmission at the University of Manchester in England; earlier, he received an EE degree from Baroda University in India. Hingorani has written over 70 technical papers and articles and is a Fellow of IEEE, among other professional affiliations.

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Since EPRI's staff exchange program was set up four years ago, some 45 technical people from utilities and manufacturers have spent a year or more on loan to the Institute, lending their expertise, helping to evaluate and guide EPRI's R&D program, and in turn, gaining insights into how research is conducted. Last year the first EPRI technical staff member was on loan to a utility, making the program a two-way street.

Oliver Yu, an operations research specialist in EPRI's Planning Division, worked at a variety of tasks in Commonwealth Edison's System Planning Department. His major effort went into refining and improving that large urban utility's method for assessing system reliability. The two-way flow of benefits from the experience is related in "Making It Mutual" (page 14), by *Journal* staff writer Stan Terra.

Yu joined EPRI in 1974 as a project manager in the energy systems modeling program, and two years later moved to the Planning Division, where he is a senior member of the technical staff in the Program Plans and Technical Assessment Department. Yu has an MS in electrical engineering from Georgia Institute of Technology, an MS in statistics, and a PhD in operations research from Stanford University.

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Two converging R&D futures are those of coal-derived fuels and the power plants that can best use them. The new fuels promise to be costly and therefore require highly efficient thermal cycles if they are to be economical. Also, those efficient cycles must be routinely applied to intermediate—or even baseload—service if the new fuels are to replace imported oil in any significant volume. Combustion-turbine–combined-cycle generating units have the requisite performance efficiency. The open question is their reliability in the baseload mode.

"Baseload Reliability in a Combustion Turbine?" (page 17) poses this question and reviews some of the perceptions and problems being addressed in EPRI's Power Generation Program to define and develop a combustion-turbine–combined-cycle design with reliability as the first criterion.

Program Manager Vance Cooper and Project Manager Richard Duncan come to their task from long experience: Cooper from 9 years as manager of the General Electric Co. materials engineering laboratory at Schenectady, dealing with both nuclear and fossil fuels and especially with advanced gas turbines; Duncan from 15 years with United Technologies Corp., where advanced planning and gas turbines were his focus.

Cooper's General Electric career began in 1947 and included 14 years at the Hanford Atomic Products Operation, where he worked on solvent extraction processes for nuclear fuel reprocessing. He is a University of California graduate, with an MS degree in chemical engineering from the University of Michigan. Duncan was a Navy engineer and pilot for 24 years, during which he earned a PhD in aircraft jet propulsion from Purdue University.

Four members of EPRI's Nuclear Power Division have been tapped for the honor of presenting their research papers at the 1978 international meeting on zirconium technology. The conference this year is being held at Stratford-upon-Avon, England, June 26–29. The EPRI representatives are J. T. A. Roberts, program manager, Core Materials; Floyd Gelhaus, program manager, Fault Analysis and Modeling; Howard Ocken, project engineer, Nuclear Fuels; and S. T. Oldberg, Jr., project engineer, Fuel Analysis. Roberts and Ocken will journey to England for the occasion—Roberts to present the keynote address and Ocken to deliver his treatise on Zircaloy oxidation. John Kenton, the *Journal*'s nuclear editor, sets the stage and summarizes the content of the four papers in "Zirconium Behavior in a Nuclear Environment" (page 22). He points out that these papers go beyond the usual technical treatise by synthesizing the work done at a number of laboratories, universities, and other research organizations on each of the topics.

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This issue of the *Journal* contains current organization charts of EPRI's four technical divisions, each appearing with its respective R&D Status Report in the Technical Review section. Publication of the charts indicates the range of EPRI's research programs and identifies key technical personnel.

Hingorani

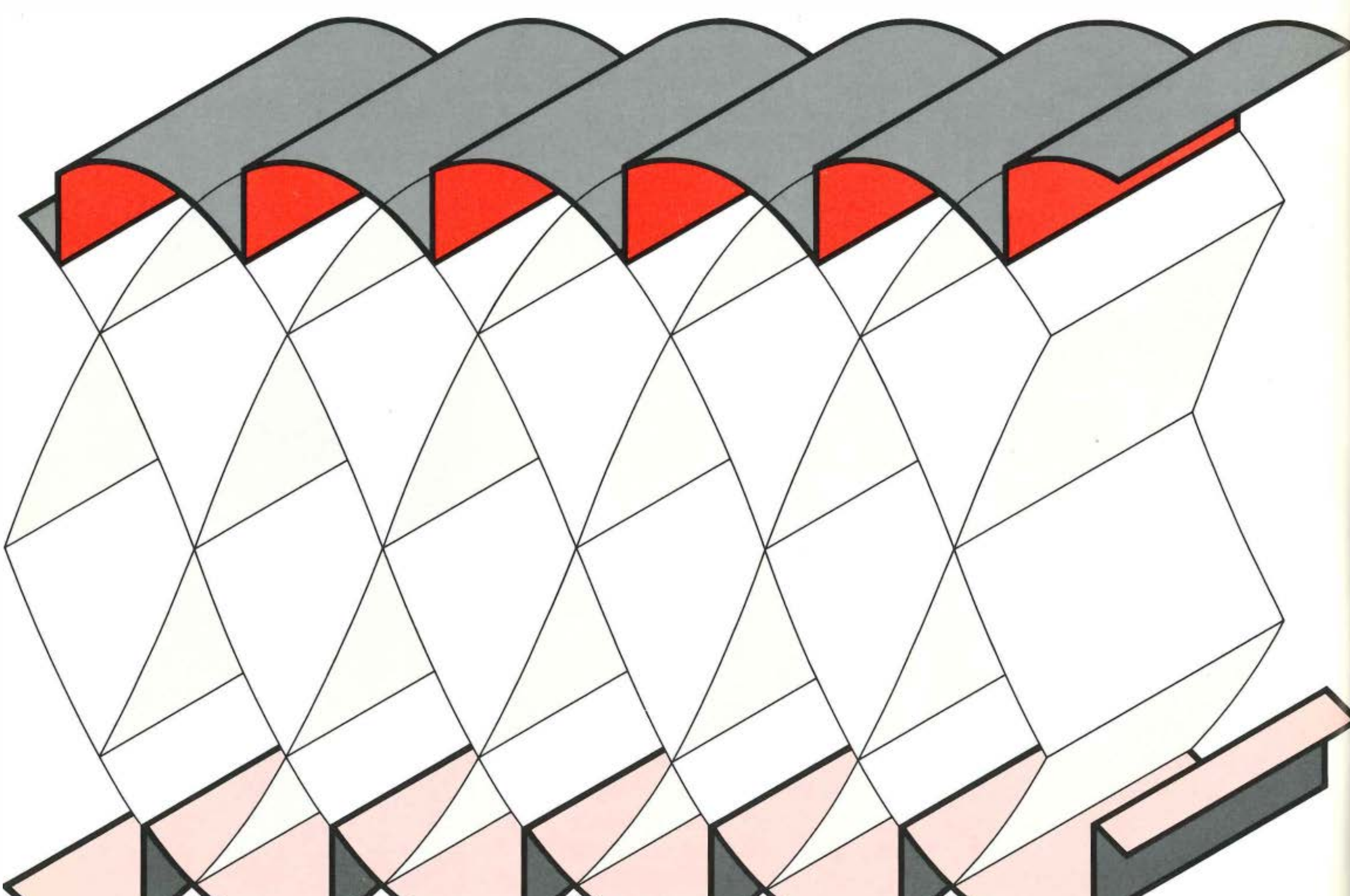
Cooper

Duncan

by Narain Hingorani

The Reemergence of DC in Modern Power Systems

Rapid advances in electronics and gas insulation have broken the barrier to practical dc conversion. Thus for the first time in the history of electric utilities, ac and dc have important complementary roles to play in electric power systems.



Stirring from its dormant state around the time of World War II, high-voltage direct current (HVDC) transmission is emerging today as an attractive complement to ac power systems. Many factors—technical and economic—have combined over the years to heighten interest in its development, long considered impractical for valid technical reasons. And in the foreseeable future, at least through the 1980s, applications of HVDC transmission are expected to increase steadily in industrialized nations and markedly in some nations just now entering the stage of electrification.

Despite inflation, the net cost of HVDC has come down considerably in recent years, and experts predict this trend will continue for at least another decade. Moreover, the reliability of dc systems has been steadily improved, and important progress has been made in designing all the elements that compose dc systems so they can meet utility needs at all power capacity levels. R&D programs now in progress hold the promise of still further cost reductions and system improvements in such components as valves, transformers, lines, circuit breakers, insulators, filters, arresters.

With such advances, the increasing integration of HVDC with existing electric power delivery systems seems assured, in part because of potent social forces. These include the projected continued growth of electric energy demand, the continued spread of urban congestion, and the national goal of energy self-sufficiency.

This national goal, for instance, could foster the exploitation of western coal reserves located at great distances from large population centers. Likewise, the possible location of nuclear power plants in remote areas would push the need for long-distance transmission, for which the use of dc shows a decided technical and economic advantage over ac.

Of relevance to our existing ac power networks is the special role of dc as an interconnect between regions and adjacent countries. In many places it is virtually impossible to link neighboring ac systems together because uncontrollable instabilities would result. In some places such connections are feasible but would not be stable under conditions that lead to cascading blackouts. But dc links, which can act as buffers, control the power flow by converting ac to dc and then to ac again. In other words, they can become valuable for achieving stable diversity interties. A prime example of this is the Stegall project in Nebraska, which was opened in 1976 to connect east-west systems at a point along what might be termed the electric continental divide.

HVDC, therefore, can become an important adjunct to ac in the United States. Some utilities have already begun to recognize the significant advantages in making selective use of dc in modern systems. And it is not too soon for all utilities to begin evaluations of the potential role of dc in their particular system developments.

By the year 2000, a reasonable portion of power flowing through intersystem connections or into urban areas should pass through HVDC converters. It is already evident that other nations, which do not have heavy capital investment in existing ac systems, will be able to exploit the new advantages of dc technology at an even greater rate than the "older" electrified countries.

Why did it take so long?

From the 1890s to the early 1970s there was no commercial use of dc for transmission in the United States, despite the fact that dc transmission offered significant advantages over ac. Dc is inherently stable and requires smaller line, less insulation, and less right-of-way at *any* power level. But for those 75 years, one fact prevented the widespread use of dc: the converting equipment needed to make dc transmission economically feasible was simply not available.

With the development of the mercury-arc valve converter after World War II, dc transmission became economical in special circumstances and became even more attractive in the 1960s with the advent of the more reliable thyristor valve converter. Given this latter development, the cost of conversion equipment and the scarcity and escalating cost of urban land for converter stations emerged as the outstanding obstacles to the increasing use of HVDC. As a result, engineers worked hard at compacting—that is, reducing the size of converter stations—and reducing equipment costs. They have been notably successful, with the result that HVDC is now a viable supplement to ac in many circumstances.

From this quick review we begin to see that dc's history is very unusual. It is the story of the transformation of a once-obsolete technology into an attractive potential one, and then into a commercially practical one. The present state of HVDC technology has been brought about by powerful social trends combined with breakthrough applications from solid-state physics, as well as supporting work in fiber optics and gas insulation.

But dc's reemergence contradicts some of our habitual views. We tend to think of technological progress in terms of the straight-ahead development of ongoing and emerging research fields and the development of commercial applications for the advances in those fields. Such a viewpoint could be an obstacle to the careful reassessment of dc and the recognition of dc's special advantages. Understanding dc's unique history will permit us to look with a fresh eye on possible uses of HVDC in modern power systems. Therefore, let us turn back to the days in which ac first surpassed dc.

Narain Hingorani is manager of the Substations (AC and DC) Program in EPRI's Electrical Systems Division.

The twilight of early dc

In the 1880s and 1890s there was widespread controversy over whether ac or dc systems should be selected to meet the nation's electric demands. In essence it was a struggle between Thomas Edison and George Westinghouse. Edison and his backers were on the side of tried, safe, and at that time, efficient dc. Westinghouse and his backers favored ac, whose voltage could be stepped up for low-cost transmission and stepped down for low-voltage consumption. By 1886 the transmission-to-consumption voltage ratio for ac was set at 20:1 (1000: 50 V), while the comparable ratio for dc was less than 3:1. In other words, ac transmission was far more efficient than dc transmission. The dc ratio was low because the voltage attainable with dc generators was limited by mechanical problems involving commutators. Furthermore, once dc was generated, there was no useful way to transform its voltage. Since dc transmission was at low voltages, long-distance transmission provided no advantages and line costs would have been prohibitive. As a result, Edison's dc system required the location of central stations near consumers.

Westinghouse recognized that ac systems would realize great economies in conductor costs and that an ac power station could have a far greater service radius than a dc station. He also foresaw the possibility of long-distance transmission of power from step-up transformers at hydroelectric sources to step-down transformers at load centers.

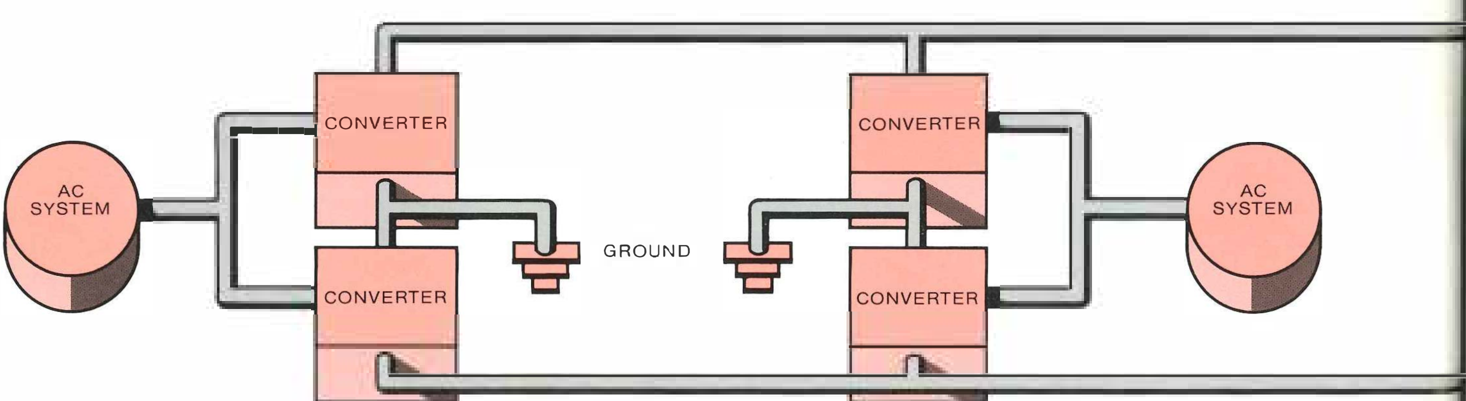
Westinghouse's foresights about ac transmission would not have had wide application, however, without earlier advances made by Edison. The gas companies, which provided the home illumination system of their day, scoffed at Edison's proposed advances, failing to recognize that Edison's system would prove useful and gain acceptance. Yet within 10 years after Edison first envisioned his ac system, he in turn was unable to recognize its far-ranging possibilities.

There was doubt about whether ac could be safely controlled for commercial purposes—there were difficulties in keeping voltage and current from going out of phase. The plan for rendering ac manageable and effective commercially was conceived and reduced to practice by the Serbo-Croatian genius Nikola Tesla, inventor of ac polyphase systems. By 1888 Tesla (once an employee of Edison's) held patents on ac motors, generators, transformers, and an ac transmission system. Westinghouse bought the patents to these fundamental inventions, inventions which have not undergone basic change since then. Their development secured ac's victory over dc, and helped set the stage for the era of electric revolution, which is still with us.

Ac's victory would not be evident for another five years, however. Edison's forces battled with Westinghouse's, at first in the marketplace, trying to withstand Westinghouse's incursions. As use of ac spread, Edison voiced concern about the safety of HV lines and ac distribution. He permitted the launching of a large campaign against what he alleged to be the dangers of ac. The stakes were high—the future of the electric power industry in the United States rode on the outcome of the ac-dc debate. Questionable practices were used at times, public ignorance was exploited crudely, and accusations of industrial espionage were made.

With pros and cons on both sides, the debate was not resolved until 1893, the year in which Tesla's system successfully provided the light and power for the Chicago World's Fair. Subsequently, the Cataract Construction Company, which had been reviewing a variety of plans for the harnessing of energy at Niagara Falls, opted for ac because dc could not be transmitted to Buffalo, just 22 miles away.

In effect, the Niagara decision, which represents the high-water mark of nineteenth century R&D, essentially sentenced dc transmission to the status of a



The ac system may be a power station or a utility network.

Converters are usually designed for power flow in either direction. The converter station includes valves, transformers, ac and dc filters, and control equipment.

For a multiterminal arrangement, a dc line may be tapped along the way. Similarly, ac systems may be connected to the dc link in a back-to-back arrangement.

dormant technology. Ironically, dc was not acceptable for what was then long-distance transmission. (Similar events could well be traced with regard to the struggle between ac and dc in other industrialized countries.)

But there still remained a large place for dc. Since late in the last century, dc has been used for electric traction and electroplating. Dc has come to have many applications in the chemical and mining industries, in rolling mills, and in variable-speed devices, and it is now used in all electronic equipment, either directly or indirectly by passing current through ac-dc-ac converters in order to enhance control of ac loads. The first such uses in an ac system relied on the rotary converter. This mechanical device, first displayed at the Chicago World's Fair, was used to change ac to dc in established lower-voltage dc systems. However, rotary converters were judged too costly and inefficient to justify general coordination of ac and dc.

Start of dc's modern era

The ac-dc conflict was an all-or-nothing affair, in part because the virtues of blending ac and dc were unforeseen, and in part because large financial interests and famous individuals were ranged on competing sides. But once the air cleared, engineers realized that dc transmission had important advantages over ac because dc required fewer conductors and less insulation. If HVAC could be converted to HVDC for transmission and later reconverted for step-down and distribution, then substantial cost benefits might be realized. If conversion could be done economically, the best of both worlds—ac and dc—could be enjoyed.

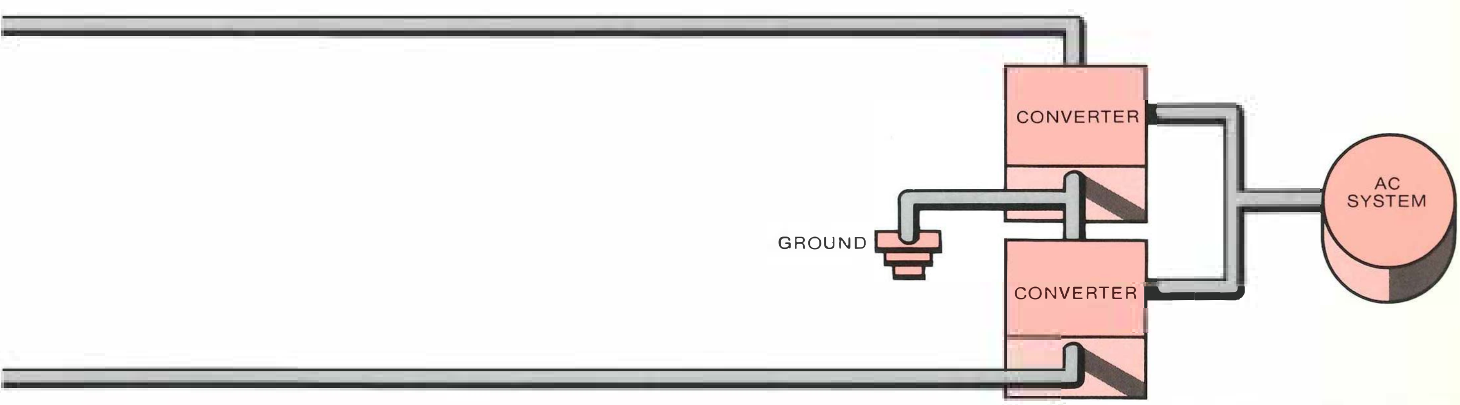
In the early 1930s the lure of this possibility led to the experimental application of state-of-the-art electronics to the problem of conversion. The basic theory of conversion was established by 1934, but commercial application was still 20 years away. Nevertheless, in 1936 a 17-mile dc transmission system was energized between Mechanicville and Schenectady, New York, transmitting 5.25 MW at 30 kV, connecting 40-Hz and 60-Hz ac systems.

Some research advances were made during World War II in Germany and Sweden. By 1950 the Soviets operated an experimental dc transmission line, based on valves developed in Germany and subsequently in USSR after the war. That system used a type of mercury-arc valve invented by U. Lamm in Sweden and described in a paper published in 1946. In 1954 Sweden made the first modern commercial use of dc transmission, running a 20-MW, 90-km dc connection underwater between the mainland of Sweden and the island of Gotland. The system is still operating with high reliability.

The underwater link was only possible by dc because the intermediate reactive compensation required for long ac transmission (to keep voltage and current from going out of phase) was not feasible for underwater transmission.

The reliable and economic operation of Sweden's underwater dc line justified later underwater connections between Sweden and Denmark, between England and France, between the main islands of New Zealand, and between mainland Italy and Sardinia; as well as overland connections in the United States, Canada, England, Japan, USSR, Zaire, and between Mozambique and South Africa. But as projects and mercury-arc valves got larger and larger, the valves suffered from increasingly frequent arcbacks. The lower reliability and the rising cost of mercury-arc valves prevented more widespread acceptance of HVDC transmission.

The design of higher voltage and higher current mercury-arc valves during the 1960s led to the first major use of HVDC transmission in the United States, the Pacific Intertie. Installed in parallel with two 500-kV ac interties to transmit a huge seasonal surplus of hydroelectric energy southward from the Columbia River, in 1977 the Pacific Intertie was put into operation—77 years after the



Dc may be used for long-distance transmission (underground or overhead), feeding bulk power to a remote load center. Usually the systems are bipolar, with the midpoint grounded.

A terminal at the load center may be in an urban area and therefore of compact design.
Ac systems may be independent or interconnected with other ac systems. Dc power flow can be modulated to stabilize the ac systems interconnected.

Niagara decision. The length of the line (1354 km) was a determining factor in the decision to use HVDC. The savings in conductor and insulation costs and the fact that dc suffers less energy loss in transmission than does ac were very attractive over that distance.

HVDC comes of age

Nevertheless, mercury-arc valve problems and lack of familiarity with HVDC transmission remained and would have curtailed using HVDC for a significant role in transmission systems. So once again, as in the early 1930s, state-of-the-art electronics were applied to converter design. The use of solid-state devices known as silicon-controlled rectifiers, or thyristors, pioneered in the United States, showed great potential for the production of valves with the required high-current, high-voltage ratings. To achieve the voltage ratings desired for a valve, thyristors are strung together in series; increases in the ratings of thyristors reduce the number needed and result in higher efficiency, lower cost. At present, thyristors 77 mm in diameter and rated as high as 3800 V are available for HVDC converters, and larger thyristors rated at 5000 V or higher should be available by 1980.

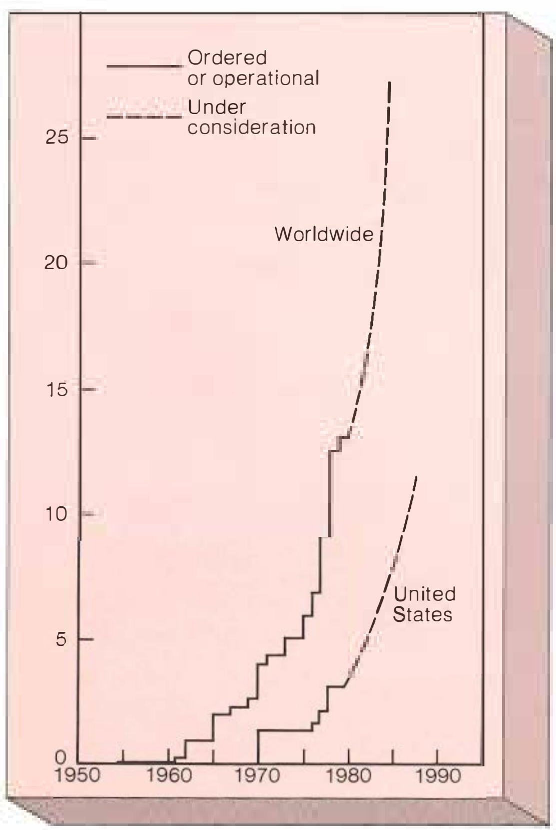
The refinement of thyristors and thyristor valve design increased the reliability of converter valves dramatically. Since the 1972 successful demonstration in the Eel River project in Canada, thyristor valves have become standard equipment for dc converter stations. The project has attained full availability of almost 99%, with an annual load factor exceeding 100%.

Historically, therefore, the capability of dc transmission has been extended by advances in electronics and related fields, and the incorporation of these advances in power systems has occurred at ever faster rates. About 25 years elapsed between the first experimental work on mercury-arc valves and their commercial use in dc conversion. Less than 10 years elapsed between the experimental application of semiconductor technology to dc conversion and the first commercial use of thyristor valves. And it now looks as if less than 5 years will elapse between the experimental application of fiber optics in HVDC valves and the first commercial use of light-fired thyristors. Thyristors now in use are fired by electric pulses, but those that are fired by laser diodes via optical fibers—now in development through EPRI funding—are expected to improve valve performance while reducing cost. Much of the electronics used in valves now will be eliminated.

The Eel River project is also noteworthy because, like the project at Stegall, Nebraska, it does not involve the use of HVDC line for transmission. Instead, two ac systems are tied together through back-to-back HVDC converters. Normally, ac power connection between two systems would tend to open frequently because of overload resulting from disturbances on either side. But HVDC links are not susceptible to small disturbances (with related phase shifts and voltage changes) and are able to recover very quickly after large disturbances, even though the latter may cause transient changes in the dc power flow. The dc links with properly designed controls do not amplify transients and resonances but can, in fact, damp them. Also, dc links do not add appreciable short-circuit duties to the ac systems.

HVDC interties permit selective delivery of peak power and reserves in either direction, which in turn allows generating capacity to be used more effectively and efficiently. This ability of dc links (whether back-to-back or extended) to control power flow flexibly is now widely recognized and is a regular feature of all new HVDC systems. The Pacific Intertie, where modulation of up to ± 50 MW has been used to damp steady-state oscillations in the ac lines, is a good example of the benefits to be derived from using HVDC in this manner. Stabilizing the parallel ac interties has been a major factor in increasing their transmission capacity by a total of 400 MW.

DC Transmission in the United States and Worldwide



HVDC SYSTEMS

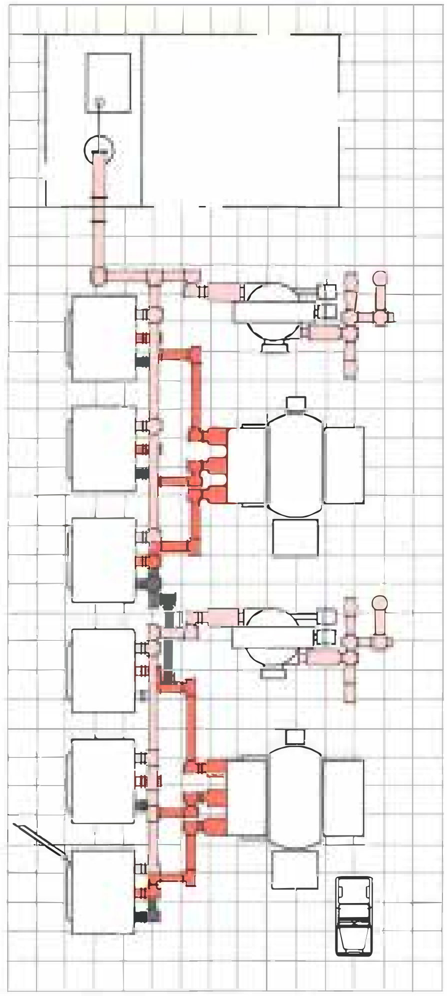
System	Year Operational	Capacity (MW)	DC Voltage (kV)	Length of Route (km)	Valve Type
Moscow–Kashira, USSR (experimental)	1950	30	200	113 (overhead)	Mercury arc
Gotland, Sweden	1954 1970	20 30	100 150	98 (cable)	Mercury arc and thyristor
Cross-Channel, England–France	1961	160	±100	65 (cable)	Mercury arc
Volgograd–Donbass, USSR	1962	750	±400	472 (overhead)	Mercury arc
Konti-skan, Denmark–Sweden	1965	250	±250	95 (overhead) 85 (cable)	Mercury arc
Sakuma I, Japan	1965	300	2 x 125	0	Mercury arc
New Zealand	1965	600	±250	567 (overhead) 38 (cable)	Mercury arc
Sardinia–Italy	1967	200	200	290 (overhead) 120 (cable)	Mercury arc
Vancouver Stage III, Canada	1968–1969	312	+260	41 (overhead) 32 (cable)	Mercury arc
Pacific Intertie Stage I, U.S.	1970	1440	±400	1354 (overhead)	Mercury arc
Eel River, Canada	1972	320	2 x 80	0	Thyristor, air-cooled and -insulated
Nelson River Bipole I, Canada	1973 1973–1975 1977	810 1080 1620	{+150, −300} ±300 ±450	890 (overhead)	Mercury arc
Kingsnorth, England	1975	640	±266	82 (cable, 3 substations)	Mercury arc
Cabora-Bassa, Mozambique–South Africa	1975 1977	960 1440	±266 {+266, −533}	1410 (overhead)	Thyristor, oil-cooled and -insulated
Vancouver Stages IV and V, Canada	1976 1978	552 792	{+260, −140} {+260, −280}	41 (overhead) 32 (cable)	Thyristor, air-cooled and -insulated
Tri-States, U.S	1976	100	50	0	Thyristor, air-cooled and -insulated
Square Butte, U.S.	1977	500	±250	745 (overhead)	Thyristor, air-cooled and -insulated
Skagerrak, Norway–Denmark	1977	500	±250	100 (overhead) 130 (cable)	Thyristor, air-cooled and -insulated
EPRI Compact Substation, U.S.	1978	100	100 (400 kV to ground)	0.6 (cable)	Thyristor, freon-cooled and SF_6-insulated
Cooperative Power Association and United Power Association, U S	1978	1000	±400	656 (overhead)	Thyristor, air-cooled and -insulated
Inga–Shaba Stage I, Zaire	Unknown	560	±500	1700 (overhead)	Thyristor, air-cooled and -insulated
Nelson River Bipole II, Canada	1978 1981	900 1800	±250 ±500	920 (overhead)	Thyristor water-cooled and air-insulated
Shin–Shinano, Japan	1978	150	125	0	Thyristor oil-cooled and -insulated
Hokkaido–Honshu, Japan	1979	150	±250	124 (overhead) 44 (cable)	Thyristor, air-cooled and -insulated

Cost reduction

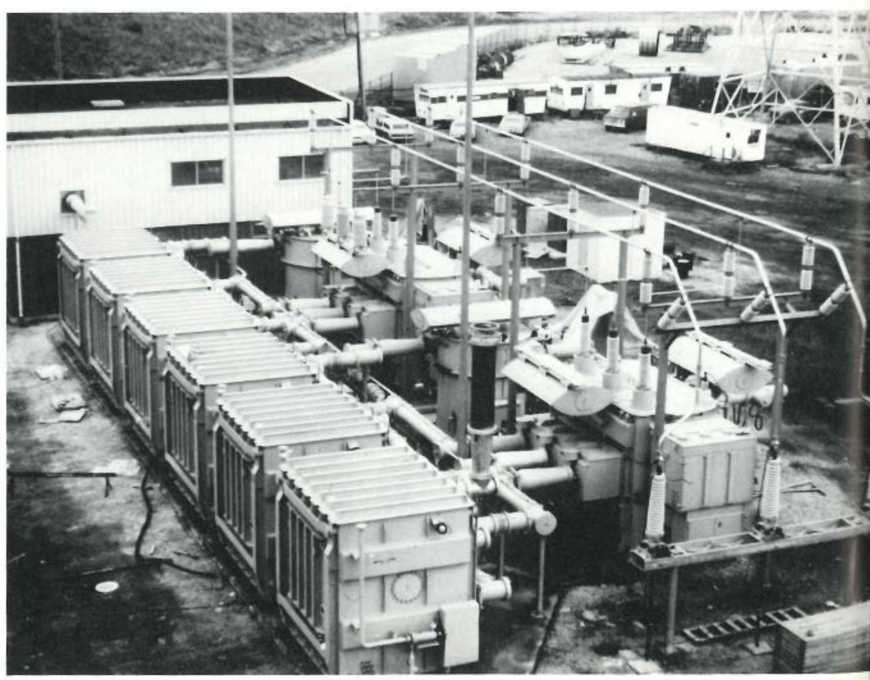
In view of the recognized benefits available in HVDC transmission, what has prevented its widespread adoption? There are two principal reasons: the lack of experience with HVDC and the cost of converter stations. Because of inexperience, it is difficult to assess the dollar value of modulation and stabilization, of reducing short-circuit currents, of operating at reduced voltage when insulation is partially damaged, and of having stable power under conditions that would otherwise lead to a cascading loss of an ac system.

With respect to converter station costs, one must remember that HVDC transmission lines usually run from converters at the generation site to converter stations in highly developed load centers. (A converter station may be visualized as an ac substation plus a conversion section.) In addition to special equipment costs, the real estate costs—including related structure and civil engineering costs—are the major factors to be neutralized before HVDC becomes cost-effective. Looking toward future urban applications, therefore, work on compacting the conversion sections becomes essential.

The prototype dc link at Consolidated Edison's Astoria Substation is an EPRI project designed for this purpose. As part of that project, a compact gas-insulated dc bus has been developed. It uses dead tank equipment (fully insulated, metal enclosed) first designed for compacting ac stations. Gas insulation and liquid cooling of thyristor valves have also been demonstrated there. EPRI has also sponsored a project whose aim is to develop compact ac capacitors and filters. It appears likely that capacitor banks consisting of capacitor units placed in SF_6-insulated tanks will take up less than 10% of the volume of comparably rated air-insulated banks and will be priced competitively at 345 kV and above. As a result, a large converter can be placed within a city block, or even in the basement of a large building if extreme compacting is essential.



Planning diagram and nearly completed installation of Astoria East terminal of Consolidated Edison Co. of New York, Inc., reveal the space saving and low profile made possible by gas-insulated bus connections and gas-insulated liquid-cooled valves. Each tank has twin valves so the 6 tanks correspond to 12 valves for the 12-pulse converter.



Finally, among other advances, dc arresters with high energy dissipation capability are now available. Resistors made of zinc oxide are also being tested for use in converter stations. By reducing insulation requirements, these should soon lead to further cost reductions.

Considerations for utility planners

HVDC's potential scope of application has grown as a result of reduction in converter station costs and gains in converter reliability, but HVDC use is still restricted to select applications. Given the present quality of converter technology, HVDC would no doubt become quite widespread if converter station costs were negligible. (In fact, if this was the case, the overall network would be quite different. There would be fewer lines, interchanges where none exist today due to instability and high short-circuit current, and little power going through all the voltage transformation stages it does in present networks.) But the cost for a terminal with a rating of 1000 MW, for example, runs approximately $30 per installed kW, with prices slightly lower at higher ratings. This figure has been steady, despite inflation, for the past 10 years and is expected to remain steady through the next decade.

Based on present converter station costs, overhead HVDC transmission generally becomes attractive at lengths in excess of 650–800 km (400–500 mi), whereas underground transmission becomes attractive at as little as 40–65 km (25–40 mi). For shorter distances, utility planners should consider the important but difficult-to-price benefits provided by the use of HVDC, with ultimate decisions being made on a case-by-case basis. The difficulty of assessing these particular benefits is due in part to the use of ac-based criteria for transmission needs, and this in turn is related to the lack of experience with dc transmission. Similarly, basic education in dc systems is lacking. There is as yet little attention given to dc transmission in electrical engineering education in U.S. universities, and few utilities have any in-house expertise in dc technology.

A benefit that is partly susceptible to meaningful cost analysis arises from dc's superior ability to respond to line faults, such as lightning surges. In dc systems, a faulted pole may be brought back to operation in 200 ms. If insulation is partially damaged, it can be brought back at reduced voltage while the other pole operates at full voltage and even at overload levels. On the other hand, it has not been possible to economically design ac systems so that they can run at reduced voltage. Therefore, the possibility of losing one out of two parallel ac circuits requires each ac circuit to have a 100% overload capability and calls for additional switching stations and compensating equipment. Incidentally, there is no known case of lightning taking out both poles of a dc transmission line, whereas lightning has often taken out both circuits of an ac double-circuit line.

Difficult to price are the benefits that can be provided by HVDC power modulation. And the protection against system shutdown afforded by dc stabilization is even harder to assess, although its importance grows as power grids grow. Methods of costing these HVDC benefits could play a crucial role in long-range power-system and energy-use planning, and they are beginning to receive greater attention. Without such methods, but in light of these benefits, it would make sense for utility planners to imagine how they would use HVDC if conversion becomes inexpensive and then to consider whether any of those uses could be justified even at present costs.

Some additional benefits arise when use of underground cable is contemplated. Increasing scarcity of land and increased concern with the esthetic impact of power lines tend to favor the use of cable for urban in-feed. But as ac transmission systems grow in length and load, problems related to short-circuit currents, voltage control, and absorption of reactive power from the cable network also grow. HVDC cable does not suffer these problems, and since the familiar advantages of overhead HVDC hold for underground uses too, it is probable that greater use will be made of HVDC for urban in-feed. Dc cable technology is already available for voltages up to ±600 kV, enough to carry 2000–3000 MW. Electric utilities in New York and Chicago have studied implications of future use of HVDC cable. Decisions made in those cities are likely to have a wide influence.

Furthermore, it appears that increases in voltage ratings may well tend to support increased use of underground transmission outside of urban areas. When such use is indicated, HVDC use is supported by all the reasons favoring its use in urban settings.

Whether underground or overhead, some use of HVDC transmission will be influenced by the need for tapping along the way. Single taps or interconnections of three or four terminals can be handled by converter control with dc load-break switches. If more interconnection is needed, then dc circuit breakers will have to be developed. These are difficult to design, and recognition of this has stimulated R&D efforts.

Complementary roles

After this review of the development of HVDC technology and the advantages of some HVDC applications, one fact should be underscored. Unlike the situation almost 100 years ago, ac and dc are no longer in competition. Instead, for the first time in the history of electric utilities, ac and dc have important and complementary roles to play in electric power systems. It is now possible to imagine ideal blendings of ac and dc, ideal adaptations to the geography and population distribution of vast service areas.

Given the huge investment in well-integrated ac in the United States, such an ideal will not soon be realized. But judicious blending may certainly be planned for, always with the recognition that future technological advances may shift the ac-dc balance yet again.

Making It Mutual

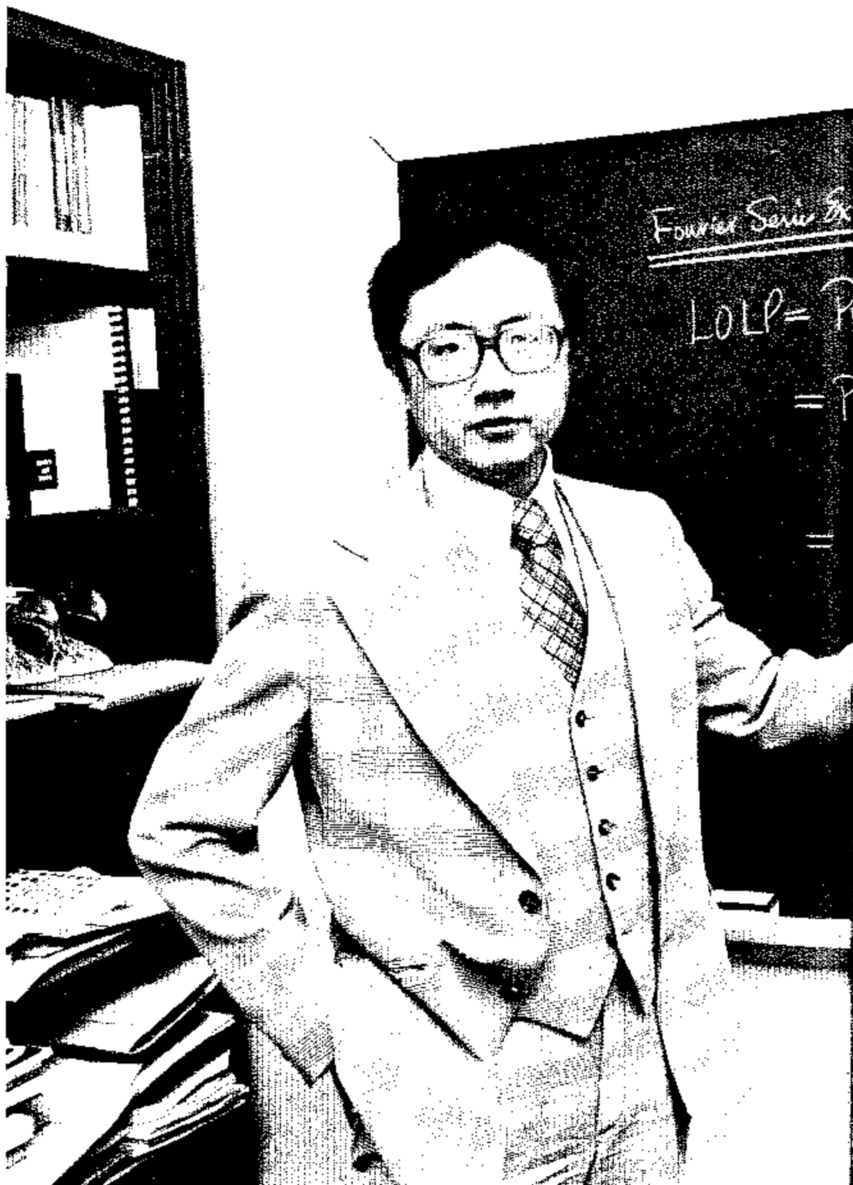
EPRI's staff exchange program moved into a new phase last year when the first Institute staffer worked on temporary assignment at a utility, resulting in a mutually beneficial experience.

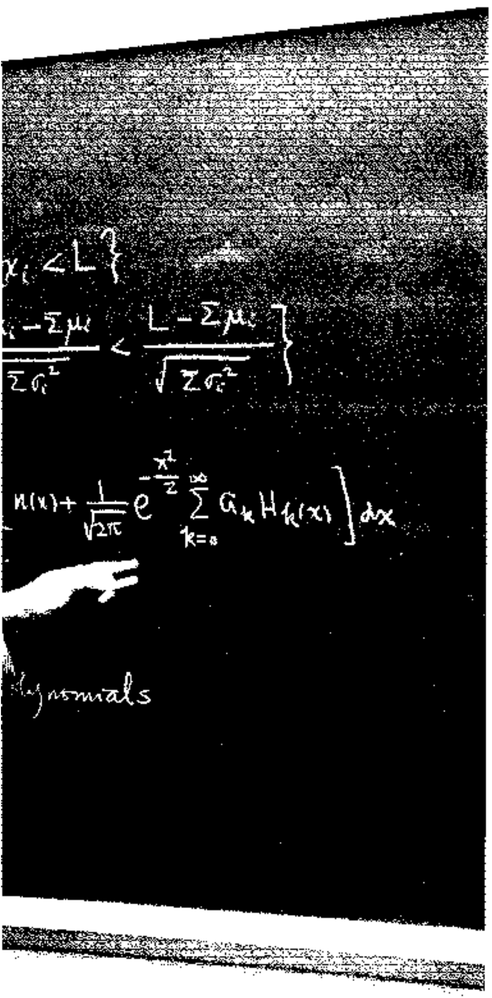
Last year EPRI's staff exchange program with utilities and suppliers became a two-way street when the first EPRI person put in a tour of service with a utility. And the results of that experience indicate that it was mutually beneficial.

Since it was set up by EPRI in 1974, the staff exchange program has brought some 45 engineers and other technical people from utilities and suppliers on temporary assignment to EPRI. Some of the benefits gained, such as fresh insights into utility problems and how research is conducted, were described in the May 1977 *Journal* by several loaned employees and EPRI staff members who worked with them.

Oliver Yu, an operations research specialist on EPRI's Planning Staff, spent 11 months last year working on a variety of problems in the System Planning Department at Commonwealth Edison Co. in Chicago. "We got quicker and better results for improving our methods of reliability planning and determining required reserve capacity as a result of Yu's being here," says Ludwig Lischer, vice president of engineering, research, and technical activities for Commonwealth Edison.

Yu's quick grasp of problems won the confidence of his colleagues, who treated him like a regular member of the staff instead of an outsider on short-term assignment. Yu believes the major benefit he derived from the experience was learning how decisions are made in a large urban utility and what forces influence them. He also gained insights into





the physical operation and technical problems of a large electric power system. All of which, Yu feels, now enables him to be more responsive to utility needs in his planning work at EPRI, where he is the technical assistant to the manager of R&D planning and assessment.

Improved analysis

Yu's main effort went toward refining and improving Commonwealth Edison's method for calculating the generation reserve capacity required to ensure the reliability of its system. After examining the methods the utility used for assessing reliability, Yu decided the best approach was to take the commonly used loss-of-load probability (LOLP) method and modify it to reflect the characteristics of the Commonwealth Edison system. Basically, the method computes the expected number of days during a year that load will exceed available capacity.

"The LOLP method," Yu explains, "has the advantage of providing more detailed information than any other method on the dynamic interactions between generating capabilities and system loads." The disadvantage of this method, however, is that the computations it calls for are excessively time-consuming. Yu notes that to figure the LOLP for a full year for a large interconnected system of about 200,000 MW would take about 30 minutes of computer time. Through mathematical series expansion—which takes into account such factors as generation system and load characteristics, interconnection capabilities, and reliability requirements—Yu developed an approximation procedure that cuts computer time to 10 seconds on an IBM-370 and reduces error to less than 5%.

John Bukovski, a senior staff engineer for generation planning who worked closely with Yu, says that Yu's refinements of the LOLP method enabled the utility to do more computer runs, quicker. Bukovski, who comments that "we got more than our money's worth from Oliver Yu," notes that Yu's calculations, using his modified LOLP method, confirmed the system planning staff's figures that a 14% capacity margin is needed by Commonwealth Edison to ensure its system reliability.

George Applegren, manager of system planning, credits Yu with "helping us over a serious hurdle by improving our method of calculating the reserve capacity requirement." Applegren says that a recommendation has been made to Commonwealth Edison's top management to adopt the modified LOLP method developed by Yu for use in the utility's reliability planning.

Testimony bolstered

Data derived from Yu's method were used to support supplemental testimony submitted last December to the House Subcommittee on Environment, Energy, and Natural Resources by Gordon Corey, vice chairman of Commonwealth Edison. The testimony was in response to the question of the effects on system reliability if 375-MW coal-fired plants were substituted for 1100-MW nuclear plants. Based on an LOLP of once in 10 years, and taking into account Commonwealth

Edison's interconnection capabilities, Yu calculated that substituting medium-size for larger generating units would cause an overall reduction of generating capacity in 1986 of between 2% and 4%, under various forced-outage rate assumptions.

The method was also used as the analytic tool in a special study by the reliability working group of the Mid-America Interpool Network (MAIN), a reliability council to which Commonwealth Edison belongs. Jene Robinson, supervisor of generation planning for Illinois Power Company and chairman of the MAIN reliability working group, credits Yu with "saving us 12 to 15 months in arriving at a rationale for assessing reliability." And Robinson adds that "such a rationale is important in answering regulatory questions on how a utility arrives at its forecasts and assessments."

Robinson also observes that Yu's "innovative work in developing mathematical computer programs that indicate the relative reliability of a generating system gives us insights into factors for which we previously had only an engineering gut feeling." Robinson notes the reliability working group has recommended that Yu's modified LOLP method be adopted for use by MAIN.

Yu foresees an increasing need by utilities for more comprehensive, refined analysis in their planning as they are faced with growing uncertainties in the areas of fuel supplies, finance, regulation, and environmental restraints. As utilities have grown in size and complexity, public awareness of power companies has sharpened, Yu points out. This has prompted regulatory commissions in some states, for instance, to question closely the forecasting and other planning methods used by utilities, "which in turn," says Yu, "places even more emphasis on their planning and analysis."

Varied tasks

While at Commonwealth Edison, Yu turned his attention to other tasks as well. He did a detailed assessment of the emergency generating capacity that could be expected from the company's interconnections. A preliminary computer program was also developed to schedule generation maintenance. Its aim is to minimize power production costs while holding generation system reliability at a level that is adequate for expected peak-season loads. A conceptual method for cost-benefit analysis of generation system reliability that was worked out by Yu considers not only the costs of energy losses and capacity interruptions caused by inadequate reliability but also the potential social and economic costs of a large-scale blackout.

Yu also applied operations research techniques to such matters as determining the practical range of potential economic benefits of a proposed interconnection project, assessing the load forecasting prediction error in terms of the time span prior to the actual peak, modeling the customer answering service system by a queueing theory approach, and developing an optimal selection of coal and oil suppliers and transportation routes. In addition, he conducted an in-company course on operations research for a group of managers and technical staff that covered modern concepts and techniques for scientific decision making.

Management style

Commonwealth Edison's management style gets high marks from Yu for its strong emphasis on the company's human resources. There are a number of programs aimed at staff development and growth. Aside from the series of short courses, such as the one on operations research given by Yu, the company holds an informal three-day conference each year at a resort in Wisconsin where staff members (engineering, economics, marketing, and others) engage in a free-flowing exchange of ideas about their work. In another effort, new career employees are briefed by top management about the company and the opportunities open to them. The management staff is given a state-of-the-company briefing in a day-long conference once a year. And people are rotated temporarily into other jobs in the company to gain a fuller understanding of the overall operation. "We try not to have organizational walls around here," says Vice Chairman Gordon Corey.

Field experience

Yu says he was given every opportunity to get firsthand experience. He visited a number of plants and observed equipment repairs and overhauls. Yu spent a couple of days getting an inside view of the company's power supply office, or control center, where he watched the load dispatchers at work and examined the computer system that assists dispatchers in controlling power distribution. He also attended the annual three-day conference in Wisconsin last year. And Yu had the rare experience of inspecting the inside of the reactor vessel of Commonwealth Edison's La Salle County 1100-MW nuclear power plant, Unit 1, scheduled to go on-line in late 1979. He notes that the working atmosphere at Commonwealth Edison is "informal and congenial" and that his fellow workers throughout the huge utility were "completely cooperative."

Benefits affirmed

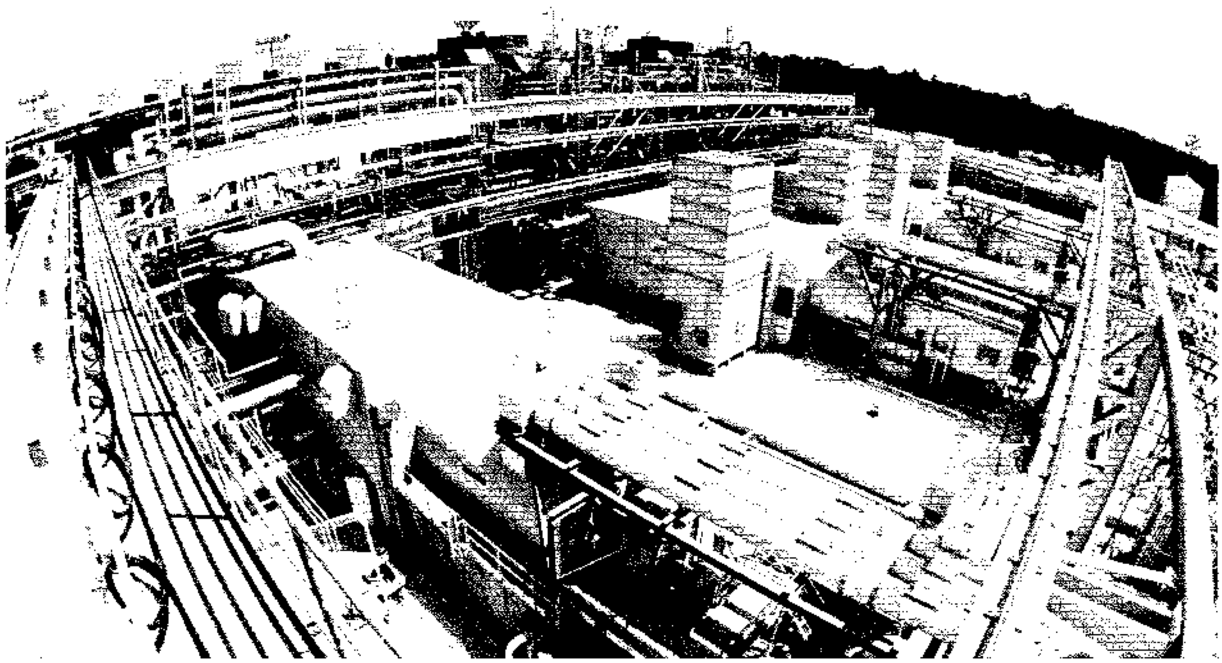
Yu says his experience at Commonwealth Edison reinforces his support of the exchange of EPRI and utility staff members. A second EPRI staffer, Paul Zygielbaum, an engineer in the Advanced Fossil Power Systems Department, is currently on two-year loan to Portland General Electric Co., where he is working on plant engineering for a new combined-cycle facility.

Among the benefits Gordon Corey sees coming from the exchange program is that "it helps avoid the tendency to become inbred." Richard Rudman, director of EPRI's Planning Staff, was involved in setting up the exchange program in 1974 and now says he "would like to see more opportunities for EPRI people to work on loan at utility companies." Rudman adds that "the insights gained from such experience help EPRI do a more effective job and, consequently, benefit the utility industry and its customers."

Baseload Reliability in a Combustion Turbine?

by Vance Cooper and Richard Duncan

If greater reliability can be designed into combined-cycle units, their higher efficiency can beat the high cost of fuel and result in economical intermediate and eventually baseload service.



The expanding horizon for utility combustion turbines is typified by the new Putnum Plant of Florida Power & Light Co., where four Westinghouse W501 gas turbines are linked with two steam turbines to establish 484 MW of net warm weather combined-cycle capacity for intermediate service. In an EPRI-sponsored test of fuel performance and operating cost, gas turbines in one unit (shown here) of the symmetrical plant are running on No. 2 distillate, and gas turbines of the other unit are running on No. 6 residual oil.

Combustion turbines represent about 10% of U.S. utility generating capacity but only about 2% of actual energy output. This relationship is consistent with their cost and need. The free-standing simple-cycle combustion turbine has the lowest capital cost and shortest construction lead time of all types of generating units. It also has the highest heat rate (low fuel economy in terms of Btu consumed per kWh output) and operating cost.

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For these reasons it has found increasing application on electric utility systems since the historic East Coast blackout of 1965. Its explicit purpose is to supply peak demand power. It is not counted on for long-run reliability or operating economy.

Still, this turbine is basically the same unit that powers the world's jet aircraft. If there is a note of uncertainty about its reliability in utility service (and there is) then the question is inescapable: What is it doing on the airplane I ride in?

The answer is a threefold difference in service conditions: environment, fuel, and duty. Aircraft fly above atmospheric contamination; they burn clean fuel exclusively; and they operate at maximum power for only a few minutes of each flight.

Utility turbines, on the other hand, are often sited in industrial and coastal areas, run on fuels that are becoming progressively lower in quality, and called on for high power whenever in operation.

Turbine service conditions

The contaminants inhaled by utility turbines are a function of their location. Units near the ocean pick up salt (sodium chloride). Those on the desert pick up sand (silica). Those near coal-fired power plants pick up coal ash. The harmful constituents are those that form saltlike deposits—sodium sulfate, calcium sulfate, sodium vanadate, for example—which attack metal components inside the turbine. Occurring in the temperature range 800–875°C (1500–1600°F), this attack is generally known as sulfidation. Metallic grain boundaries deteriorate, metal weakens, and components fail.

Typical utility fuels today are light petroleum distillate and (to a lesser degree) natural gas. The future is not likely to include natural gas but should see the advent of coal-derived fuels—liquids that will probably be low in hydrogen content and may contain significant amounts of fuel-bound nitrogen (potentially leading to high NO_x emissions).

Even today, as we head into a domestic petroleum production deficit, utility use of distillate is in question because it has higher uses in transportation. As a result, some utilities are beginning to use heavier, residual oils as combustion turbine fuel. These oils carry ash-forming constituents, such as vanadium, aluminum, iron, and silica, which are undesirable in the hot gas path of a turbine. At best, their deposits degrade aerodynamic performance; at worst, they cause premature mechanical failure.

The usual way to reduce sulfidation and other corrosive attack brought on by fuel impurities is to lower the maximum system temperature. However, this also reduces efficiency and raises the heat rate, which means greater fuel consumption. Another remedial action (which also adds to the cost) is fuel treatment: washing it to remove water-soluble contaminants and adding inhibitors, such as magnesium oxide, to tie up the vanadium and reduce its reactivity.

The third important service condition that distinguishes utility combustion turbines from aircraft engines is duty. After a plane reaches cruising altitude, its power may be cut back to as little as 30–40% of maximum. A utility turbine, on the other hand, usually runs near the manufacturer's warranted maximum output because this yields the best fuel economy.

Total service hours in a period and start-stop cycles within that period also have a bearing. Turbine components undergo thermally caused mechanical stress each time they are run up to operating equilibrium—or down again. Peak demand use, which implies many such cycles within only a few hundred hours annually, is more rigorous than baseload operation, but simple-cycle turbines are not economically competitive for the 4000–8000 hours characteristic of baseload operation.

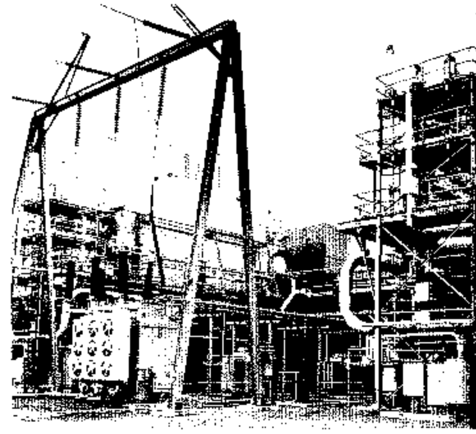
Open questions

Can these present and potential severities of utility combustion turbine service be remedied? What are the implications for reliability and/or operating economy? The two factors are exclusive of each other in the usual context of peak demand application. But the foreseeable future in fuel supply patterns suggests the need for improvement in both.

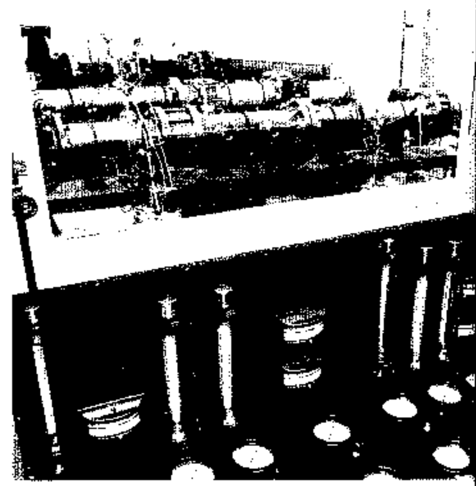
First, as the move toward heavier oils suggests, there is already an incentive to improve fuel economy. This can be done by coupling a combustion turbine to a steam turbine in a so-called combined-cycle system. The improvement in efficiency may be as much as 30%, but this is heavily influenced by system temperature and pressure. (Without changes in turbine design and hot-path materials, temperature and efficiency must be degraded in the presence of a wider spectrum of fuel impurities.)

Second, the combined cycle means a major increase in capital cost. A steam bottoming cycle may cost twice as much as a combustion topping cycle, and the resulting combined-cycle unit may therefore cost three times as much as a simple combustion turbine unit alone. In order to offset or defray this increased capital cost, it becomes desirable to operate the combined-cycle unit for more hours per day or per year. Here, then, is the incentive for improved reliability of the combustion turbine.

The future in utility fuels contains another incentive for long-run turbine reliability. This is the advent of coal-derived fuels in the late 1980s and early

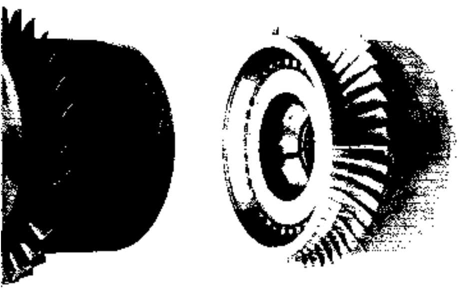


New findings in turbine engine aerodynamics by United Technologies Corp. have led to a compressor rotor (right) with fewer, more widely spaced blades per stage—and also fewer stages—for a given pressure ratio and performance level. Both rotors are about 56 cm (22 in) in diameter. The shorter, wider blade design (known as a low aspect ratio) means reduced cost and foreseeably greater durability.

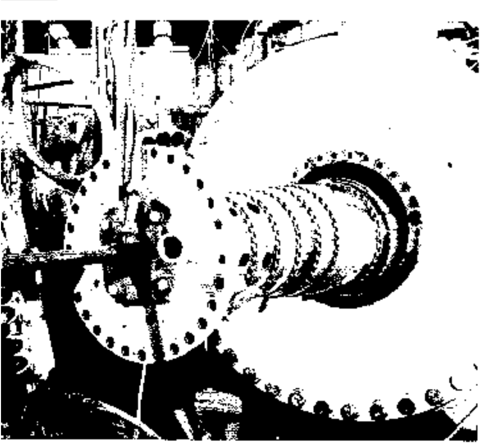


Full-scale gas turbine combustor is installed in Westinghouse test rig to establish correlation with subscale performance data on coal-derived liquid fuels. Because of the 20:1 ratio of fuel consumption rates, full-scale combustor runs are limited in duration.

Beaver Generating Plant, on the Portland General Electric Co. system, is among the largest utility combined-cycle stations: six General Electric MS7001 gas turbines and one steam turbine totaling 600 MW peak capacity, with fuel facilities for distillate, residual, or crude oil. The heat recovery steam generators for two gas turbines are a backdrop for a stepup transformer where overhead lines take output energy to the plant switchyard.



Instrumented subscale turbine combustor in this Westinghouse R&D Center test cell was run for 187 hours at 900°C (1650°F) on a middleweight wash solvent fuel from the solvent-refined coal process. Eight samples of different turbine blade alloys were placed in the gas stream to test their corrosion resistance, while emissions content (NO_x, CO, smoke, unburned hydrocarbons, etc.) was recorded.



1990s. If they are to replace any substantial volume of imported petroleum, electric utilities (and other stationary power producers) must provide the major market for long-running units. For utilities, this means units capable of and designed for intermediate and baseload service. The logic is seemingly circular, because such service in turn requires operating economy in order to realize low busbar energy cost.

Combined-cycle challenge

The combustion-turbine–combined-cycle plant can convert liquid or gaseous fuels to electricity more efficiently than any other proven technology. Further, unlike the steam cycle alone, which appears to have reached its economic limit in terms of temperature and pressure, the combustion turbine can be designed to operate at higher temperatures and pressures than have been justifiable for peak demand service. And such refinement will bring its own improvement in fuel economy.

The charter, therefore, is to develop a unit with high reliability (thus reducing the capital cost per kWh) and high efficiency (thus reducing the fuel cost per kWh). High reliability connotes reduced operating and maintenance costs. These are the goals of an advanced combustion turbine R&D effort in EPRI's Power Generation Program.

Reliability hinges on environment, fuel, and duty, and, in general, the tolerable range of all three must be broadened. The definition and assessment of reliability therefore becomes central to the EPRI program, and a major objective is to substitute a quantitative way of considering reliability for what is now a subjective approach.

Inconsistent documentation

The record for combustion turbines today is uneven. Among utilities there is widespread dissatisfaction, and this leads to uneasiness about future applications in baseload duty. Considerable statistical data have been compiled from peaking duty operation, with distillate fuel as the norm, but utilities point to numerous forced outages and to significant increases in operating cost above what was expected. The principal complaint is the high cost of parts that must be replaced because of deterioration.

An EPRI survey of 37 utilities last year revealed 27 were satisfied with turbine performance and 25 were satisfied with turbine operation. The rating of manufacturers' service was a standoff, but 22 of the utilities surveyed were dissatisfied with reliability, and 32 were dissatisfied with maintenance.

Manufacturers, it should be noted, feel that data are inexact in the assignment of outage hours (forced or scheduled), thus indicating an unrealistically high outage rate.

Combustion turbines in gas transmission and chemical process industrial service largely show satisfactory reliability while operating in baseload. Here, natural gas is the dominant fuel. However, other factors logically account for the difference in experience (actual or perceived). Foremost, perhaps, is the business environment. The industrial combustion turbine is a baseload unit upon which a plant or process depends: it must run or, for example, an entire petrochemical operation is down and its salable production lost. Consequently, maintenance teams are dedicated solely to combustion turbines.

A utility, on the other hand, by virtue of planned system interconnections, puts more reliance on purchased power. It employs trip-out circuits to protect and preserve its equipment, inevitably incurring some recorded turbine outage as a result. (An industrial user removes the protective circuits and relies on instrumentation and continuous maintenance to keep the unit on-line.)

The quantitative approach

The foregoing circumstances and perceptions characterize the subjective approach to combustion turbine reliability. They are traceable to the fact that combustion turbines have been developed to meet the peaking service market and its low-first-cost criterion. Turbines have not been designed for the optimal reliability of either the turbine itself or the ancillary equipment of a utility power plant. Since first cost has been so important in the evaluation of bids, suppliers have found a measure of business risk is necessary to remain competitive (e.g., limiting prototype testing before commercial introduction). Heat rate has also been an important evaluation factor, and it has been optimized to gain efficiency at some possible risk to durability.

An objective, quantitative approach to reliability will permit utilities to move beyond combustion turbine evaluation on the single basis of kilowatt capacity per capital dollar and to look more easily toward incorporating combustion-turbine–combined-cycle units in future baseload generating facilities. Implicit in this emphasis on reliability is a fundamental question: Can a combined-cycle plant be so designed that it will yield baseload service at satisfactory operating and maintenance cost?

What first becomes necessary is a thorough data base, component by component: performance statistics defining mechanical, thermal, and cyclical stress environments; information on failure modes and frequencies; facts on construction materials, fabrication techniques, and heat treatments. Analysis of failures as a function of material facts and operating environments can then be performed to develop probability data that categorize component lifetimes. Such information will provide a rational basis for establishing redesign priorities and for evaluating their worth in terms of their cost and contribution to better reliability.

A rough outline of the possible utility future for combustion-turbine–combined-cycle units exists in early results of EPRI studies. (The methodology was reviewed in "Market Potential for New Coal Technologies," *EPRI Journal*, May 1978, pp. 19–26.) These studies assumed what are felt to be conservative values for

Combined-Cycle Reliability

GOALS

Availability	Turbine ≥ 95% System ≥ 90%
Maintenance cost	Turbine 1 mill/kWh System 2 mills/kWh
Operating time between shutdowns	9000 h
Time between major maintenance	18,000 h
Hot-section parts life	50,000 h
Cold-section parts life	100,000 h
Starting reliability	99%
Fuel flexibility	Light and heavy oil
Turbine inlet temperature	≤ 1260°C (2300°F)
Combined-cycle heat rate	7500 Btu/kWh
Single-cycle heat rate	9500 Btu/kWh
Dry NO_x capability (to meet NSPS)	75 ppm
Overspeed requirement	120%
Load-following response	± 25%
Low-cycle fatigue	12×10^3 cycles
High-cycle fatigue	10^8 cycles
Power shaft speed	3600 rpm
Nominal gas turbine size	60–100 MW

TRADE-OFF STUDIES

Reliability—Cost	Assessment of capital and O&M costs
Reliability—Turbine Inlet Temperature	Up to a maximum of 1260°C (2300°F), with durability considered
Reliability—Hot-Section Metal Temperature	Evaluation of performance losses and determination of compromises
Reliability—Cooling Methods	Hot corrosion life included as a function of blade and vane temperatures and compositions
Reliability—Fuel Flexibility	Cost-differential evaluations for fuels ranging from clean distillate to contaminated heavy oil, including costs for cleaning turbines and/or fuels and for coatings and claddings to meet problems of corrosion, erosion, and deposition
Reliability—Emissions	Control techniques, as well as combustors designed for low NO_x formation without water or steam injection
Reliability—Starting Techniques	Determination of influential factors with goal of near-100% capability
Reliability—Maintenance Actions	Survey of methods and costs and their contributions
Reliability—Size	Evaluation of turbine size with respect to overall plant reliability

turbine performance criteria (e.g., heat rate and capital, O&M, and fuel costs) based on current technology. Optimized generation expansions of several regional utility models then produced measures of market potential for combined-cycle units. Given the rationally based cost of incremental improvements in any of several turbine parameters, these generation expansions can be run again to determine the revised market potential (and its worth) that would result from achievement of those improvements.

Program background

EPRI's investigation of combustion turbine reliability began with a 1976 workshop involving utility users, federal energy technologists, and four manufacturers (Brown Boveri Turbomachinery, Inc., General Electric Co., United Technologies Corp., and Westinghouse Electric Corp.). The need for better documentation of utility turbine availability and reliability was agreed upon, and from this flowed several recommendations:

- Organize representative utilities to initiate a comprehensive program of data collection and reporting
- Formulate research into utility plans and perceived needs for future combustion turbines
- Establish a background for research on NO_x reduction and protection from sulfidation attack by using coatings and claddings on blades and vanes
- Define a project for a controlled test of a baseload combined-cycle installation

Under EPRI auspices, the Operations Development Group has come into being; its members are 15 electric utilities that are major users of combustion turbines. Early efforts are directed toward the compilation of a manual for more effective operating, maintenance, and personnel training methods.

Ebasco Services Inc. has surveyed the perceptions and plans of 37 utilities. This EPRI-sponsored effort has also yielded operating data from utility experience.

Satisfactory emission levels are an important consideration in combined cycles. NO_x emission standards can be met if NO_x formation in the turbine combustor is held to 75 ppm. But this is a function of the flame peak temperature, while turbine efficiency is a function of average combustion gas temperature. Early work suggests the use of water or steam to cut the flame peak; since it occurs only in a limited zone, quenching it is feasible. Also, research by manufacturers indicates that it will soon be possible to meet NO_x standards without water or steam injection—even while attaining a higher average temperature—by sophisticated combustor design and materials.

The baseload combined-cycle test has been established, with Florida Power & Light Co. and Westinghouse Electric Corp. as cosponsors. It will compare the operating and cost experience of two identical Westinghouse units, one fueled with No. 2 distillate and the other with No. 6 residual oil.

Basis for new design

From these beginnings has emerged a multiphase program to develop a new combustion-turbine–combined-cycle configuration that has inherent baseload reliability and is capable of economical operation on a broad spectrum of fuels. EPRI's commitment is to the first two phases, a conceptual design from many innovative inputs and a preliminary design from the sequential analysis and synthesis of the best features. Contract negotiations are nearly complete for separate, competitive efforts by General Electric, United Technologies, and Westinghouse on the first phase.

Failure-mode effect analysis will be a key tool in determining reliability in each phase. Depending on results of the first two phases, five additional phases have been mapped: a detailed component design, the fabrication of a technology verification model, a test of that model by a manufacturer, the fabrication of a prototype, and a 10,000-hour field test of the prototype on a host utility system.

Given favorable benefit-cost projections at each phase, the outcome will be a highly reliable "core machine" that can be modified to burn coal liquids with a spectrum of compositions or to burn synthetic gas with a range of heating values. The impact of fuel on combined-cycle reliability begins with the combustion process, and we believe the most significant variations will be in the combustor, though the type of cooling used in hot-path components (and their protective coatings) is also an extremely important variable.

The cost of coal-derived fuels will depend on the extent of processing used in their production. For example, the more hydrogen introduced into the reactor, the more hydrogen in the product fuel and the higher its cost. On the other hand, if the fuel is heavy, of high viscosity, low in hydrogen, and high in bound nitrogen, it will be difficult to burn without producing radiant heat damage to the combustor lining or intolerable NO_x emissions.

These considerations again call attention to various alternatives in combustor design sophistication. In the interest of minimal heat rate (say, 7500 Btu/kWh for combined cycles), a known target is technology for burning heavy fuels at turbine temperatures of 1150–1260°C (2100–2300°F) as against today's norm of 1040–1100°C (1900–2000°F).

Technology leapfrog

The future projected above for reliable combustion-turbine–combined-cycle units, especially in conjunction with coal-derived fuels, constitutes a leapfrog over the incremental improvements being made in emission control technologies for power plants that today directly fire pulverized coal. A coordinated national program of technical management is in prospect. It includes elements for more reliable operation and maintenance of today's combustion turbines, several primary technical solutions and their backup, and a long-term combined-cycle development that promises major improvements in both technical and economic performance.

Zirconium Behavior in a Nuclear Environment

This once-rare metal is now of critical importance to utilities. EPRI is coordinating studies to obtain a fundamental understanding of zirconium behavior so that further improvements in the reliability of nuclear power plants can be made.

Zirconium, a curiosity among lesser-known metals only a few decades ago, is today in great demand and the object of extended research. Two properties have made it a key element in the nuclear industry: good corrosion resistance in hot water and a very low affinity for neutrons. The latter means that it does not interfere with the progress of a chain reaction, and its alloy —Zircaloy—is therefore the primary material used for jacketing, or cladding, uranium used in the core of nuclear power reactors.

In recent years, EPRI has launched a significant research effort to determine the specific properties of Zircaloy that control its performance and behavior during reactor operations. This work has now achieved international recognition by the acceptance of several papers—including the keynote address—to be presented at the Fourth International Conference on Zirconium in the Nuclear Industry, to be held at Stratford-upon-Avon, England, June 26–29. The meeting is sponsored by the American Society for Testing and Materials (ASTM), in cooperation with the American Nuclear Society (ANS), the British Nuclear Energy Society (BNES), and the Metals Society of the U.K.

These special symposia are held periodically to exchange current scientific and technical information from several viewpoints: those of producers of zirconium and its alloys; fabricators of reactor components and systems; electric utilities operating or building reactors; and government regulatory agencies. The prior meetings were held in Quebec, Canada (1976); Portland, Oregon (1973); and Philadelphia (1968). The proceedings of the meetings are published by ASTM.

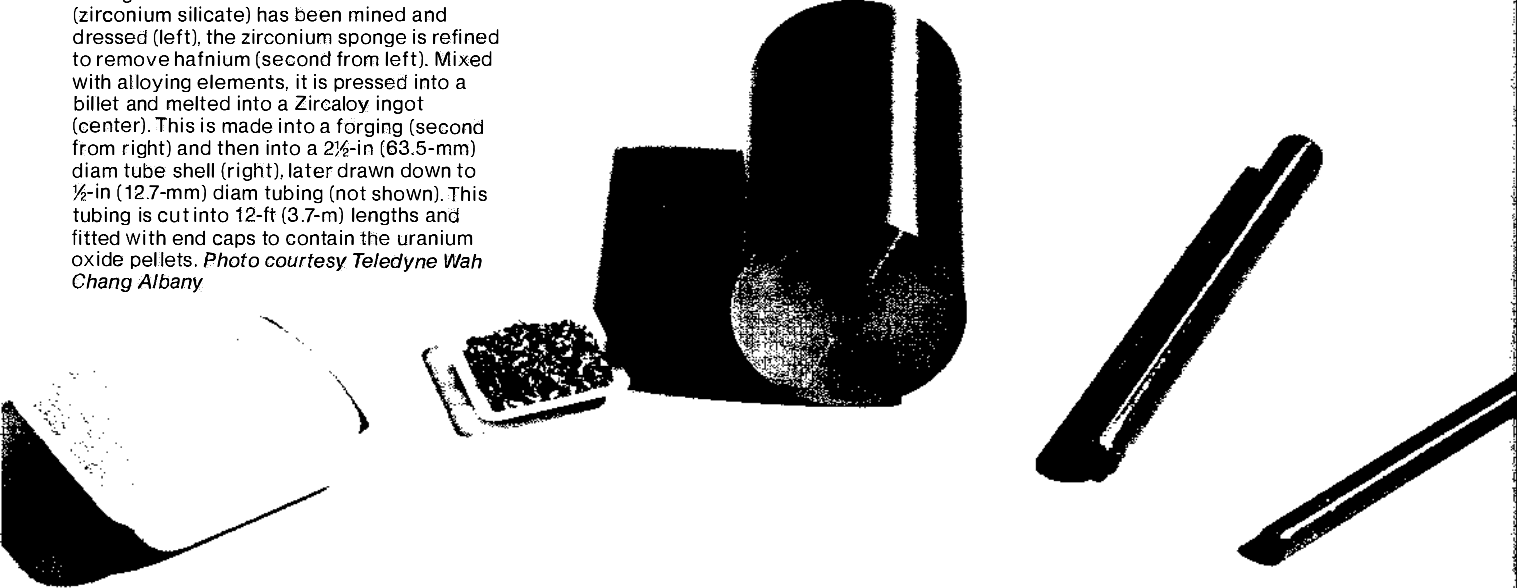
Keynote address

EPRI's contribution to the Stratford-upon-Avon meeting will begin with the keynote address that explores the progress being made in quantifying Zircaloy performance in LWRs. This progress will be set against a background of the broad surveillance programs of power reactor fuel performance that EPRI is carrying out with the five major U.S. nuclear fuel manufacturers. The address will be delivered by EPRI's program manager for reactor core materials, J. T. A. Roberts. Coauthor of the paper is Floyd Gelhaus, program manager for fault analysis and modeling.

In their summary of the performance record of Zircaloy-clad nuclear fuel, Roberts and Gelhaus point out that the integrity of both the individual fuel rod and the rod assemblies is dependent on the ability of this alloy to resist damage from the reactor environment.

Although Zircaloy performance in LWRs to date is satisfactory, uncertainties in particular properties and behavior result in a conservative mode of fuel operation. This in turn leads to losses in plant flexibility and capacity.

Pellet-cladding interaction (PCI) stands out as the primary example of Zircaloy-related loss of plant capacity. For BWRs, this capacity loss—resulting from adherence to vendor operating recommendations to minimize PCI failures —has reached 3–6%. For PWRs, the effect is on the order of 1–2%. This translates to an industrywide loss of $100 million a year, which may rise to $400 million by



Some steps in the production of Zircaloy tubing for fuel rods: After zircon sand (zirconium silicate) has been mined and dressed (left), the zirconium sponge is refined to remove hafnium (second from left). Mixed with alloying elements, it is pressed into a billet and melted into a Zircaloy ingot (center). This is made into a forging (second from right) and then into a 2½-in (63.5-mm) diam tube shell (right), later drawn down to ½-in (12.7-mm) diam tubing (not shown). This tubing is cut into 12-ft (3.7-m) lengths and fitted with end caps to contain the uranium oxide pellets. *Photo courtesy Teledyne Wah Chang Albany*

1985 if not corrected. The problem may be compounded by the potential requirement for high fuel burnup to conserve the uranium supply and to minimize spent fuel storage. This would mean longer fuel residence time in the reactor and, consequently, longer Zircaloy radiation exposure.

The primary goal of the EPRI fuel performance program is to eliminate such fuel-related losses in output. The key to success appears to be a detailed understanding of the behavior of Zircaloy in power reactor environments. The approach that has been adopted by the EPRI staff is to improve the characterization of fuel rods and fuel assemblies in operational reactors so as to bridge the gap between these data and the conventional laboratory and test reactor data. The major emphasis to date has been on characterizing the PCI defect mechanisms and the bowing of fuel rods and their growth under irradiation. Projects just getting started will emphasize various design modifications to eliminate PCI failures and rod bowing and to establish Zircaloy corrosion limits at high burnups of greater than 40,000 MWd/tU.

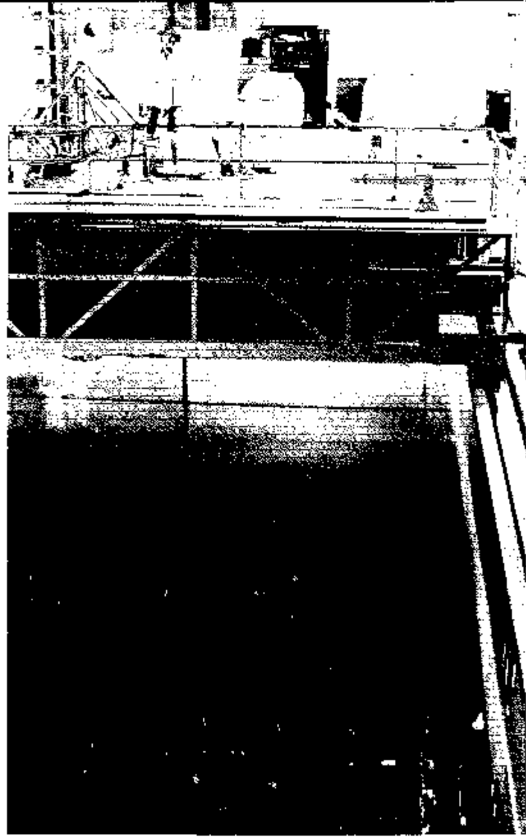
The EPRI projects are being conducted in cooperation with the five major U.S. fuel vendors and various utilities. Significant progress has been made to date and the EPRI data base, when combined with data from other programs, provides confidence that the goals set will be met in the 1980–1985 period.

Research progress on PCI has already yielded a number of results. Detailed examination of suspect rods from two PWRs and two BWRs supports the view that Zircaloy stress corrosion cracking (SCC) is the predominant failure mechanism in PCI. When combined with laboratory and test reactor data and fracture analyses, these data form the basis for selection of mid-term and long-term PCI remedies. In the mid-term (about 1980), EPRI will concentrate on minor modifications to the fuel pellet (to reduce fission-product release) and to the cladding (to raise the crack formation stress threshold). These modifications will be done in such a manner so as not to raise new safety and licensing questions. For the long term (about 1985), the program will propose radical barrier concepts that should entirely eliminate PCI defects and thus produce a nil capacity loss fuel.

Stress corrosion cracking

The second EPRI paper, also to be delivered by Roberts, was prepared in collaboration with the University of Manchester, England; SRI International; Argonne National Laboratory; Stanford University; and NASA, Ames Research Center. It presents a model for PCI failures. The model is based on the conclusion that SCC of Zircaloy cladding tubes by fission products (in particular, iodine) is the principal mode of PCI failure during normal fuel rod operations. The results of laboratory studies of the SCC behavior of Zircaloy in the presence of iodine are the primary inputs to the model. Observations from power reactor and test reactor rod examinations are incorporated through appropriate theoretical analyses, which include the effects of fuel chemistry.

Although iodine can penetrate very thin oxide films on unstressed Zircaloy, studies of iodine-induced crack initiation



Closeup detail of Zircaloy fuel rods just after discharge from a reactor (in this case, the Palisades reactor). The rods can be inspected through a periscope in the fuel storage pool (above) into which the fuel rod bundles are moved from the reactor. The second periscope view (below) shows rods and one of the Zircaloy grid spacers that hold them in position. *Periscope photos courtesy Consumers Power Company*

in unirradiated Zircaloy tubing indicate that thicker films must be mechanically ruptured before the iodine can reach the underlying metal. Tube burst experiments indicate that a threshold stress, which is believed to be associated with the formation of a crack in the metal, must be exceeded for iodine SCC to occur.

The threshold stress—and the time to reach failure at stresses above threshold—depends on such variables as metallurgical condition, irradiation, temperature, and iodine concentration. Of these, irradiation appears to have the strongest effect on the resistance of Zircaloy to iodine SCC. With irradiated Zircaloy the decrease in iodine SCC resistance is especially marked if the ratio of failure strength to yield strength‡ is considered, instead of the failure stress alone. Failure times generally decrease with increasing stress above threshold.

The model is shown to be consistent with known information on PCI failures of power reactor fuel rods, and the implications with respect to proposed remedies for PCI are discussed in the paper.

Zircaloy deformation

The third paper, presenting work by EPRI, Stanford University, General Electric Co., and Massachusetts Institute of Technology, puts forward a unified model of the anisotropic deformation of Zircaloy under irradiation in a reactor core. The presentation is being organized by S. T. Oldberg, Jr., EPRI project engineer for fuel analysis.

Utility attention has been focused on the inelastic deformation of Zircaloy in the past several years as the result of its significant role in several modes of failure involving reactor core components. These modes include rupture of fuel-rod cladding tubes, BWR channel distortion, and PWR channel closure due to bowing of rods.

A coordinated effort was undertaken to develop a material model useful in diagnosing the causes of failure, with emphasis on developing the ability to predict the mechanical behavior of typical Zircaloy tubing under normal in-core operating conditions. The overriding goal is to optimize utility operations and specify product improvement.

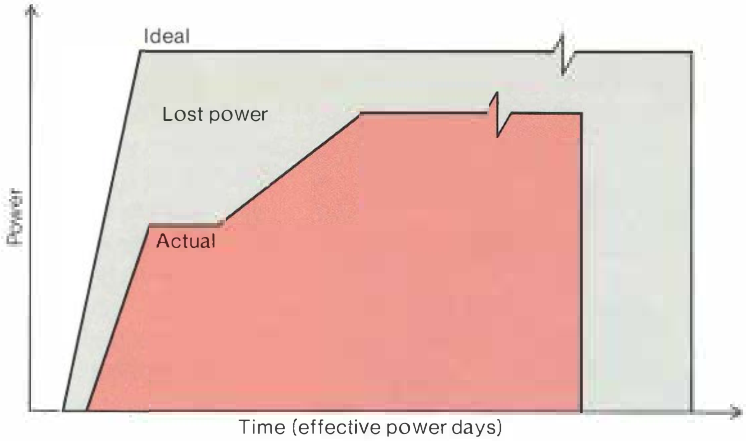
A large data base has been generated by the project, and a load-response model was developed from the test data.

Verification of the complete model's ability to track behavior under complex in-reactor loading histories has been limited to predictions of several strain-rate change tests performed outside of the reactor. A complex strain-time history was imposed on the test specimens with the strain rate chosen at random from a probability distribution approximating service conditions. To date, the resulting stress has been predicted to better than 17%. Several alternatives to the model developed in the project offer improved computability and possibly greater accuracy, but are applicable only to more limited operating regimes.

Zircaloy oxidation

The fourth EPRI paper, organized by Howard Ocken, EPRI project engineer for nuclear fuels, reports work done in collaboration with Worcester Polytechnic Institute (WPI) and Battelle, Pacific Northwest Laboratories, and it addresses the oxidation phenomena in Zircaloy.

The difference between the power from nuclear fuel under ideal conditions and the power obtainable in reality is significant. In the ideal case, power rises to design level within a short period of time as the reactor works gradually up to full output, remains level for the design lifetime of the fuel, and then drops to zero. In reality, a core takes longer to reach maximum output because of operating restrictions to avoid PCI failures; it never does reach ideal maximum output because of uncertainties in safety analyses; and it comes to an earlier end of useful life because of cladding corrosion and crud effects.



The goal of these projects was to quantify the conservatism built into the evaluation models specified for use by the U.S. Nuclear Regulatory Commission in licensing calculations to predict cladding-coolant reactions under postulated LOCA conditions. The rate of this oxidation reaction must be calculated, NRC specifies, using the so-called Baker-Just equation. Following the calculated time of hypothetical rupture of the cladding after onset of a LOCA, the oxidation rate calculation must be extended to include the inner surface of the cladding tube for an axial distance of 1.5 in (3.8 cm) on both sides of the rupture. It must be assumed that ID/OD ratio equals 1—that is, the oxide thicknesses on the inner and outer surfaces of the Zircaloy tube are equal.

Isothermal oxidation rate data obtained by WPI and Battelle at high temperatures are in agreement. These data indicate that the Baker-Just equation is conservative by a factor of about 1.8 at 2200°F (1205°C), which is the maximum calculated cladding temperature permitted by NRC for LOCA analyses.

Preoxidation effects provide an additional element of conservatism in calculations of oxidation over the course of a LOCA. Results with specimens having a prior film of oxide on the surface suggest that the total amount of oxidation measured over a simulated LOCA in a PWR with a sharp blowdown peak is less than that calculated from isothermal reaction kinetics data obtained from measurements on as-received tubing. The analyses suggested that the differences between values of the oxidation kinetics parameters reported in the literature can be reconciled if the procedure that is used to heat the specimens is taken into account.

ID/OD absorption ratios were measured by Battelle following rupture of simulated fuel rods. Although a great deal of scatter was found in the ID/OD oxygen ratios, the average value, even at the rupture position, was less than unity. The strongest trends in the data were a decreasing ID/OD ratio with decreasing test time and increasing distance from the rupture site. The ID/OD ratios were not strongly affected by temperature.

Looking ahead

The growing data base from this program indicates that the mechanical performance of Zircaloy components is well understood and that cladding and assembly distortions can be controlled to avoid problems with operation, handling, or licensing.

Future work will concentrate attention on the resistance of Zircaloy to chemical attack from both the fission-product environment and the coolant. The low resistance of Zircaloy to SCC by iodine has a definite impact on current reactor operations, in particular on BWRs. The potential for accelerated waterside corrosion could have an impact on PWR operations in the future.

Significant progress is being made in understanding the Zircaloy–fission-product SCC problem. A number of relatively simple remedies should be introduced into standard product line fuel in the next few years, which should improve plant capacity factor by 0.5–1%. Nil capacity loss fuel, using a metal barrier, should be a reality by 1985.

At the Institute

Floyd Culler Elected EPRI President

Floyd L. Culler, Jr., was elected EPRI president at the recent Board of Directors meeting.

Culler succeeds Chauncey Starr, 66, who has served as president since EPRI was formed in 1972. Starr has been elected vice chairman.

Culler, 55, joined EPRI in January 1978 as executive vice president. His affiliation with EPRI followed a 30-year career with Oak Ridge National Laboratory (ORNL), where he had served as deputy director since 1970.

In the annual report to the EPRI membership by the Board of Directors, EPRI Chairman Frank Warren said, "The pioneering efforts of Dr. Starr in organizing, inspiring, and directing this ambitious industry concept have given EPRI a strong and rewarding start. I am fully confident that Floyd Culler will lead EPRI with equal effectiveness through the coming years."

Culler is recognized nationally and internationally for his leadership in energy research and development. His emphasis has been on nuclear fuel reprocessing and waste management. While at ORNL he held several senior management positions, including director of the Chemical Technical Division, assistant laboratory director, and deputy director.

In 1974 Culler was elected to the National Academy of Engineering in recognition of his role in the development of nuclear power in the United States, particularly for his work on the nuclear fuel cycle.

He is a fellow of the American Nuclear Society and the American Institute of Chemists. He has received the E. O. Lawrence Memorial Award for his work in reactor fuel technology, the international Atoms for Peace Award, the Robert E. Wilson Award of the American Institute of Chemical Engineers, and most recently, the Nathan W. Dougherty Engineering Award of the University of Tennessee College of Engineering.

Board Appropriates Additional Civex Funds

The EPRI Board of Directors appropriated $6 million at its May 4 meeting to continue design efforts for a new type of nuclear power plant that would safely cycle nuclear fuel resources.

The plant would use a liquid metal fast breeder reactor (LMFBR), a device that is cooled by liquid metal and produces, or breeds, more nuclear fuel (plutonium) than it uses.

The plant could be operated on fuel produced by the new Civex process, which would cycle the nuclear fuel resources under conditions that are safe from terrorists, subversive groups, and national governments that suddenly decide to seek plutonium for nuclear weapons.

Since December 1975, EPRI has sponsored projects totalling $9.5 million to develop the LMFBR. The new Civex process was first announced during a March conference in Washington, D.C., by Chauncey Starr, then president of EPRI, and Walter Marshall of the United Kingdom Atomic Energy Authority.

The Civex process would ensure that no pure plutonium is ever isolated outside the reactor in the nuclear fuel cycle. Moreover, the Civex facility would be designed so that it would be impossible to modify it quickly to isolate pure plutonium. In the case of an attempted modification, sufficient time would be available to permit diplomatic actions, sanctions, or other necessary responses. Further, the spent fuel would remain so radioactively "hot" that it would quickly disable anyone attempting to steal it. It could be refabricated into fresh nuclear plant fuel by remote control, but only in facilities specially designed for this purpose.

The EPRI project was one of 95 new and ongoing research projects approved at the Board meeting, with a total funding of nearly $46 million.

In other Board action, Charlie F. Jack, chief engineer at Buckeye Power, Inc., and Keith L. Turley, president and chief executive officer of Arizona Public Service Co., were elected members of the EPRI Board.

The Board also appointed Arizona Public Service Co. Vice President D. L. Broussard to the EPRI Research Advisory Committee, which is composed of utility executives who advise EPRI's president, Board, and staff on research and development policy and on program planning.

In addition, the Board appointed the following people to the EPRI Advisory Council, a broadly based group that provides information and advice to the EPRI Board, officers, and staff. They are John A. Busterud, president, Center for Environmental Conflict Resolution; Charles J. Hitch, president, Resources for the Future, Inc.; Currin V. Shields, former chairman, National Conference of Consumer Organizations; and Margaret B. B. Wilson, chairman, National Association for the Advancement of Colored People.

Other appointees include Margaret N. Maxey, professor of Bioethics, Department of Religious Studies, University of Detroit; Gerald Tape, president, Associated Universities, Inc.; Robert L. Sproull, president, University of Rochester; Walter G. Barlow, president, Research Strategies Corp.; and Paul Hallingby, chairman, White Weld and Co., Inc.

René Malès Named Division Director

René Malès has been named permanent director of the EPRI Energy Analysis and Environment Division, a position he has held since February 1976 as a loaned employee from Commonwealth Edison Co. He will assume the directorship on August 1.

The research emphasis in the EAE division is on determining the environmental and health effects of energy production, the supply of fuels, and the future demand for energy.

With Commonwealth Edison since 1956, Malès has worked as director of economic research, as assistant to the vice president of division operations, and most recently as manager of general service.

Malès, 45, a graduate of Ripon College, studied mathematics at the University of Chicago and received an MBA from Northwestern University. Prior to joining EPRI, he was a member of the EPRI Energy Analysis Advisory Task Force.

New Department in Electrical Systems

Steiner

Shula

Kennon

A new department has been created within the Electrical Systems Division called the Power Systems Department. It incorporates the Distribution, Power System Planning and Operations, and Rotating Electrical Machinery programs.

Transmission, the other department in the division, includes the Overhead Lines, Substations, and Underground Transmission programs.

Division Director John Dougherty also announced the following promotions: Richard Steiner, former manager of the Distribution Program, has been promoted to direct the new department; William Shula has been promoted from project manager to program manager of the Distribution Program; and Richard Kennon, former project manager in the Substations Program, has been promoted to manager of the Overhead Lines Program.

Dougherty reports that the Power Systems Department was formed to complete and balance the division organization. It is part of a division structured to promote the timely introduction of new technology that is responsive to growing power capacity requirements, environmental constraints, and changes in the makeup of both loads and generation.

Transmission Seminar Scheduled

An EPRI-sponsored seminar dealing with longitudinal loadings on transmission line structures is to take place August 22–23 in Denver, Colorado.

The seminar program will present the results of two projects funded by EPRI on longitudinal loads. One of the projects, conducted by GAI Consultants, Inc., involved the development of a comprehensive design guide for preventing damage from static and dynamic loads that result from broken wire and ice-shedding disturbances on transmission line support structures. The seminar program will include discussions on the theoretical and experimental bases for the guide and a presentation of several illustrative examples.

The second project, conducted by the University of Wisconsin, involved full-scale broken-wire tests on an existing double-circuit line supported on steel lattice towers that were instrumented for static and dynamic load measurements. The seminar program will include a description of the tests and a comparison of the results with predictions based on the design guide.

A concluding panel discussion will allow attendees to comment on the program and provide input for future EPRI efforts in these areas.

No seminar fee is required for EPRI member utilities. The fee for nonmembers is $100 per person.

For more information, contact either Mike Silva at EPRI, P.O. Box 10412, Palo Alto, California 94303, (415) 855-2305, or Carmel M. Seibert at GAI Consultants, Inc., 570 Beatty Road, Monroeville, Pennsylvania 15146, (412) 242-6530.

German Scientists Visit EPRI

Representatives from the Institut für Werkstofftechnologie of West Germany recently visited EPRI headquarters to review the Pressure Vessel Technology Program of EPRI's Nuclear Power Division. Drs. Gustav Richter and Jürgen Ahlf were here to consult with Program Manager Karl Stahlkopf and Project Manager Ted Marston.

The German organization, known for its design of the nuclear-powered commercial cargo ship *Autohahn*, is formulating plans for a study of effects of neutron radiation on properties of metals. Their investigation will be part of a larger effort funded by the Federal Republic of Germany to study nuclear reactor safety.

"This visit marks the beginning of informal cooperation between EPRI and the Institut für Werkstofftechnologie," says Stahlkopf, "and EPRI and German investigators are interested in interrelating research procedures and concepts through a possible data exchange."

Dr. Jürgen Ahlf (left) and Dr. Gustav Richter (center) discuss research concepts with EPRI Pressure Vessel Technology Program Manager Karl Stahlkopf (right). The German scientists visited EPRI on April 24 to gather information for their proposed neutron radiation research efforts.

EPRI's Pressure Vessel Technology Program is sponsoring several major projects on irradiated metals, involving such concepts as neutron embrittlement, trace element effects, and thermal anneal.

Project Highlights

Report Forecasts Strong Electricity Growth

National energy consumption in general and electricity use in particular appear likely to maintain a strong growth rate between now and the year 2000, according to a report recently released by EPRI.

The report forecasts a total energy growth of between 3.2% and 3.5% annually for each of the 5-year periods between 1975 and 2000. This is slightly less than the 3.6% rate during the 20 years before the Arab oil embargo and leads to a total U.S. energy consumption rate equal to 27 billion barrels of oil per year.

Electricity growth is predicted to be from 6.8% to 7.0% per year until 1980, and then it will fall off to a rate of less than 5% per year. This compares with a historical growth rate of about 7%.

"The EPRI report approaches forecasting through an econometric model that emphasizes how people actually use energy rather than how they could or should use it," says Robert Crow, manager of the Demand and Conservation Program.

One critical assumption behind such an approach is that the key motivating variables, such as income, prices, and weather, can be measured. "This approach," Crow comments, "does not make allowance for intangible factors, such as an energy conservation ethic or other changes in values or tastes. That assumption appears consistent with postembargo consumption experience."

The report, *Demand 77: The EPRI Energy Consumption Model and Forecasts* (EPRI EA-621-SR), represents the second EPRI work of this type. The first was *A Preliminary Forecast of Energy Consumption Through 1985* (EPRI SR-37).

Evaluations Begin on Fluidized-Bed Combustion

A major research project with Babcock & Wilcox Co. is evaluating the potential of a new coal-burning technology for electric power generation.

In atmospheric fluidized-bed combustion (AFBC), a mixture of crushed coal and limestone is suspended during combustion by air that enters the bottom of the boiler combustion chamber. The mixture behaves like a fluid, with the limestone absorbing the sulfur dioxide gas produced by the burning coal. This technology would allow utilities to burn different types of coal (as well as low-grade fuels) in an environmentally acceptable way without the use of expensive pollution control equipment, such as scrubbers.

As part of the 1978 effort, existing data on R&D and on engineering are being collected, along with new data being developed at B&W's Alliance Research Center (Ohio), where a large pilot plant recently became operational.

Data from the first year's operation of the pilot plant are providing the key information needed to design commercial fluidized-bed boilers. The design work is being done by B&W's Fossil Power Generation Division.

R&D by Oregon State University and Westinghouse Electric Corp. in other projects will also be incorporated. Westinghouse is evaluating auxiliary systems for improving sulfur dioxide removal to meet federal air emission standards. Oregon State University is simulating a prototype of a "cold" (nothing is burned) fluidized boiler to better understand gas-solid mixing and its effect on the operation of the fluid bed.

Results from this year's $3 million effort and planned subsequent efforts may lead to the commercial use of the technology by 1990, notes Terry Lund, manager of the project for EPRI.

EPRI Negotiates 38 Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
Fossil Fuel and Advanced Systems Division				
RP536-2	Test and Evaluation of the Chiyoda 121 Jet Bubbler Scrubbing System	2 months	8.8	Ardaman and Associates, Inc. *T. Morasky*
RP547-5	A Study of Alternative Reactor Concepts	3 months	9.0	Science Applications, Inc. *N. Amherd*
RP718-2	Fluidized-Bed Combustion Development Facility and Commercial Design Assessment	10 months	2380.6	Babcock & Wilcox Co. *T. Lund*
RP982-6	Evaluation of Stack Gas Control Apparatus and Related Technology	1 year	28.6	Kaiser Engineers *O. Tassicker*
RP982-10	Demonstration Program for NO_x/SO_2 Removal	5 months	18.0	Air Pollution Systems, Inc. *K. Yeager*
RP1028-2	Preliminary Design and Assessment of a Circulating (Fast Bed) Boiler	6 months	59.9	Pullman Kellogg, a division of Pullman Inc. *T. Lund*
RP1091-1	Heliostat Cost Study	10 months	149.3	Arthur D. Little, Inc. *J. Bigger*
RP1184-1	Prediction of Fossil-Fired Steam Power Plant Performance	1 month	9.3	Utility Energetics, Inc. *J. Dimmer*
RP1190-1	Design of a Fusion Facility for "Neutronless" Fuels	17 months	564.6	TRW, Inc. *D. Paul*
RP1191-1	EPRI Solar-Heated Hot Water Instrumentation Project	17 months	25.6	Pacific Sun Inc. *G. Purcell*
RP1197-2	A Heat Exchanger Process for Removal of H_2S Gas	13 months	84.9	Coury and Associates, Inc. *P. La Mori*
RP1268-1	Modeling of Coal Gasification Reactors	3 years	233.1	University of Delaware *L. Atherton*
Nuclear Power Division				
RP507-2	Analytic Fuel Rod Modeling in Support of the Studsvik Inter-Ramp Test Project	10 months	19.9	Science Applications, Inc. *G. Thomas*
RP620-26	Liquid Metal Fast Breeder Reactor Plant Design	5 months	1020.0	Westinghouse Electric Corp. *G. Baston*
RP827-3	Radiation Dosimetry Support Work	10 months	11.5	University of Virginia *F. Rahn*
RP971-3	Application of Fast Fourier Transform and Related Techniques to Reactor Component Modeling	1 year	19.9	SRI International *T. Oldberg*
RP1124-3	Turbine Chemical Monitoring	27 months	151.2	Babcock & Wilcox Co. *T. Passell*
RP1127-1	Electroslag Remelt	21 months	183.5	Lukens Steel Co. *M. Lapides*
RP1159-1	Development of Instrumentation for Measuring Two-Phase Mass Flow	11 months	215.5	Columbia University *D. Cain*
RP1159-2	Development of Instrumentation for Measuring Two-Phase Mass Flow	18 months	211.4	Utah State University *D. Cain*

Breeder Steam Cycle Report Published

EPRI's LMFBR Project Office has issued a comprehensive report on various views and its own conclusions regarding the choice of steam cycle for the first large-scale prototype liquid metal fast breeder reactor.

Since December 1975, three industrial teams and a total of 11 companies have been studying design problems relating to that prototype and the steam cycle and type of steam generator it should use.

The resulting 370-page report, *Viewpoints on Superheat Versus Saturated LMFBR Steam Cycles,* gives equal time to all parties in what has become a controversial technical issue. Although the majority of steam generator designers and vendors in the United States favor the superheat cycle, EPRI comes out strongly in favor of the saturated steam cycle.

The LMFBR Project Office concludes that there are substantial advantages to the saturated cycle in terms of the sodium systems, steam generators, plant transients, plant control and operation, core performance, and turbine generator.

The superheat system approach is preferred by many because it holds the promise of higher potential thermal efficiency, but the report contends that the saturated steam cycle requires less development and extrapolation and therefore has a "substantial and demonstrable advantage in providing the highest level of assurance of reliable operation." Because the LMFBR is an urgently needed and essential energy option, reliability in early plants is seen to be of more importance than an attempt to approach a theoretical optimum.

It is vital, the report holds, that the limited national resources available for the next stage of breeder development be immediately concentrated on the saturated cycle; to do otherwise would cause undue competition for the limited resources available.

EPRI is hoping that the publication of this report will help utilities reach a consensus regarding the steam cycle for the prototype commercial breeder reactor.

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1165-1	Categorization of Cable Flammability	1 year	265.0	Factory Mutual Research Corp. *R. Swanson*
RP1166-1	Corrosion and Corrosion Cracking of Materials for Water-Cooled Reactors	2 years	2211.9	Ohio State University *T. Passell*
RP1167-1	High-Temperature Behavior of Chemical Species That Affect Boiler Performance	2 years	688.4	San Diego State University Foundation *T. Passell*
RP1242-1	Practical Methods for Inelastic Analysis of Nuclear Power Plant Components	1 year	50.0	Entropy Limited *T. Oldberg*
RP1242-2	Practical Methods for Inelastic Analysis of Nuclear Power Plant Components	1 year	50.0	Washington University *T. Oldberg*
RP1249-1	Hot Isostatic Processing of Nuclear Castings	1 year	97.0	Battelle, Columbus Laboratories *A. Roberts*

Electrical Systems Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP1207-1	Forced Vaporization Cooling of HVDC Thyristor Valves	27 months	400.0	General Electric Co. *I. Vancers*
RP1208-1	Extended Dynamic Stability Analysis Using Advanced Techniques	22 months	111.0	Arizona Public Service Co. *P. Anderson*
RP1278-1	Conductor Fatigue Life Research	18 months	50.0	Auburn University *M. Silva*
RP7871-1	Electrohydrodynamic Cable Pipes	33 months	238.7	University of Illinois *T. Rodenbaugh*

Energy Analysis and Environment Division

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP434-20	Rate Design Study: Load Research	9 months	29.7	Gilbert Associates, Inc. *R. Malko*
RP434-21	Rate Design Study: Research on Declining-Block Rate Structures	9 months	18.3	Chas. T. Main, Inc. *R. Malko*
RP805-2	Technical Services to Prepare Summary of *Air Quality Modeling Handbook*	3 months	10.8	Decision Focus, Inc. *J. Karaganis*
RP1015-2	Evaluation of System Expansion and Electricity Supply Model Used in Baughman-Joskow Regional Electricity Model	4 months	7.5	Tennessee Valley Authority *R. Richels*
RP1100-1	Impacts of Single-Family Residential Heat Pump Technologies on Utility System Loads	16 months	200.0	Gordian Associates Inc. *R. Crow*
RP1101-1	Electric Water Heating for Single-Family Residences: Group Load Research and Analysis	22 months	242.2	Gilbert Associates, Inc. *R. Crow*
RP1310-1	Chemical Speciation of Atmospheric Sulfur-Bearing Particles	13 months	99.5	University of Wisconsin *R. Perhac*
RP1313-1	Photosynthetic Response to Gaseous Pollutants: A Predictive Approach	2 years	120.5	Stanford University *R. Goldstein*

Washington Report

Bridging the Gap Between Petroleum and Coal-Derived Fuels

Combustion turbines figure prominently in the U.S. Department of Energy efforts to shift consumption patterns from gas and oil (especially imported oil) to more abundant fuels, primarily coal. Combustion turbines have traditionally run on natural gas and light distillate oil, but DOE is optimistic about technical improvements that will allow use of other fuels.

Thus, while improved reliability is the major thrust of EPRI's turbine program, DOE is primarily interested in the potential for fuel flexibility and energy conservation.

DOE also sees combustion turbines as having a central role in both cogeneration and combined-cycle power plants that will increase the efficiency of electric power production. Of course, DOE recognizes the importance of improved reliability, so EPRI and the federal agency have combined their interests and are working together on a number of projects that involve a common path of development.

Federal R&D efforts in combustion turbine technology fall under the jurisdiction of DOE's Power Systems Division, part of the Fossil Energy Program in the Office of Energy Technology. This division is a focus for utility industry interest. It has responsibility for R&D relating to a number of technologies used to convert fossil fuels to electric power and heat, such as heat engines, fuel cells, cogeneration, waste heat recovery, and fluidized-bed combustion. Controlling emissions with flue gas desulfurization and other coal cleanup techniques is also a responsibility. Division officials emphasize that no new system will enter the marketplace unless it can meet emissions requirements.

John Belding is director of the Power Systems Division. He describes his division as attempting to strike a balance between near- and long-term technologies for power generation, but he admits that the emphasis and dollars will go toward the former.

"We're going to put a lot more money into near-term technologies because we believe that we can make a significant impact by the mid-1980s," he says. About $160 million (in budget authority) is supporting division programs this year, and nearly $190 million was requested for FY79. Of that, approximately $55.3 million is for the Heat Engines and Heat Recovery Activity, which includes combustion turbines.

According to DOE's program definition, the term *heat engine* includes all types of prime movers used to produce power in stationary facilities: combustion turbines, steam turbines, diesels, and Stirling engines. (Engines for transportation are assigned to the Office of Conservation and Solar Applications.) The term *heat recovery* refers to the capture and productive use of waste heat. Since heat engines produce waste heat, they are grouped together with technology developments in cogeneration and heat recovery. "It fits together as a nice package," Belding comments.

The goal of the program is to save 1.5 quadrillion Btu of energy by 1985 and more than 10 quadrillion Btu by the year 2000 in the trimarket of utilities, industry, and the residential-commercial sector. By anyone's calculations, there is a lot of waste heat energy to save. DOE estimates that utilities consume 18.6 quadrillion Btu of fuel energy to produce only a little more than 6 quadrillion Btu of electric energy, rejecting two thirds as waste heat—some of which could be saved despite inherent conversion losses. The agency calculates that the industrial sector consumes 19 quadrillion Btu to produce process heat and rejects 9 and that the residential-commercial sector consumes 14.7 quadrillion Btu for space and water heating and rejects 7. The focus of activities in the Heat Engines and Heat Recovery Activity is to improve waste heat patterns in all three markets, while encouraging the use of fuels other than natural gas and oil.

The combustion turbine is seen by program officials as a tool for reaching these objectives in all three markets. Its role is evolving. As used in most cases by utilities today (in a simple cycle to provide peak demand electricity), the turbine is very low in efficiency, often wasting more than 70% of its fuel as exhaust heat. To make matters worse, it can run only on two fuels that are growing scarcer (natural gas and distillate), which are needed for other purposes, such as home heating. Even so, DOE officials believe that turbines may be used more extensively during the next few years.

"If we're off by just 1% on demand projections for the next four or five years," John Belding says, "we're going to see utilities turning to combustion turbines to take up the slack. They're the only machines that can be brought on line that quickly."

Combustion turbine efficiency—generally less than 30%—can be increased when the machines are used in combined cycles with steam turbines or when they are part of cogeneration systems that use the exhaust heat to make either process steam for industries or space heat for homes and businesses. Combined cycles may increase efficiency up to 40%, while cogeneration has the potential of increasing it even higher.

If turbines can be made to run more efficiently, even on scarce oil and gas, they can help stretch these fuel supplies until improvements can be made that will allow the burning of alternative fuels. This "bridging" will be helpful, DOE program officials explain, especially in areas of the country where power plants cannot be converted to coal for environmental or economic reasons. It may also be desirable for older power plants that can't be retrofitted.

Optimally, the Power Systems Division sees the combustion turbine used in both cogeneration and combined-cycle configurations with coal or coal-derived fuels. However, getting from present-day technology to such an advanced turbine is an evolutionary process, with step-by-step technology improvements along the way.

"EPRI and DOE agree that two generations of combustion turbines will probably be produced between now and the end of the century," says John Neal, Belding's assistant director for the Heat Engines and Heat Recovery Activity. DOE has labeled what it sees to be the next generation as the reliable advanced liquid fuel engine (RALFE). This is a flexible combustion turbine capable of burning low-grade residual petroleum fuels by the early 1980s and then coal liquids when they become available, probably in the late 1980s.

Why residual fuels? For one thing, they are available, Neal explains. "Our studies show that there is enough residual fuel capacity in the country to supply all existing combustion turbines up to 1985." But more important, they have properties very similar to those of coal liquids. "If we can solve the problems of burning resids, we can solve many of the problems encountered with using coal-derived liquids."

One problem is that both can be high in fuel-bound nitrogen, which is converted in the combustion process to nitrogen oxide, an emission restricted by government regulation. What EPRI and DOE are both trying to do is to improve combustion turbine technology to allow the burning of residuals and coal liquids, while controlling NO_x emissions. Improvements include new combustor concepts and new materials, such as coatings to shield turbine blades and vanes against corrosion and erosion.

Beyond RALFE, the long-term combustion turbine goal is to develop a very high temperature machine (1430°C [2600°F] or higher) that will use coal gas in combined-cycle modes. The high turbine temperatures are needed to offset the inefficiencies involved in gasifying the coal. In one option under study, coal would be gasified and used to run the combustion turbine, with waste heat captured and used for a steam turbine. In another option, coal would be burned directly in a pressurized fluidized-bed combustor and its gases expanded through the combustion turbine, then used to raise steam for the steam cycle.

Of the two systems, DOE feels that gasified coal will be easier to handle in a combustion turbine than direct combustion products from a fluidized bed. The agency agrees with EPRI that the low-Btu gasification, high-temperature turbine in combined cycles has the most promise for high efficiency. Neither technology, however, is expected to be on the scene before the mid-1980s.

DOE's main thrust for R&D in its long-term program is to develop advanced cooling techniques. Other problems involve materials compatibility, heat exchangers, and the durability of auxiliary equipment. As in much of the combustion turbine program, DOE and EPRI are working together on these problems.

R&D Status Report
FOSSIL FUEL AND ADVANCED SYSTEMS DIVISION

Richard E. Balzhiser, Director

FUEL CELLS

The objective of EPRI's fuel cell research is to develop and assist the commercial introduction of a fuel cell power plant technology that will provide the electric utility industry with a unique power generating option. The technology must be highly efficient, environmentally acceptable, and compatible with available utility fuels, as well as incorporate the economic and operating advantages of a modular configuration.

To accomplish this objective, EPRI's fuel cell projects are addressing both first-generation (FCG-1) and advanced technologies. The first-generation efforts are concentrating on the early demonstration and commercialization of dispersed 5–25-MW FCG-1 power plants. Targets for FCG-1 plants include a capital cost of $350/kW (1980 dollars) and a heat rate of 9000–9300 Btu/kWh that is essentially constant from 25 to 100% of load.

The advanced-technology efforts are concentrating, in the near term, on developing power plants for dispersed applications that will have an improved heat rate (7500 Btu/kWh) and use a wide range of available utility fuels, including clean-coal liquids and gases. In the longer term, the efforts will focus on integrating the fuel cell with coal gasifiers for central station, baseload electric power generators.

Previous *Journal* articles (April 1976, p. 14; June-July 1977, p. 46) discussed the issues that are critical to the successful commercialization of utility fuel cells. This report will specifically discuss the status of the major fuel cell development projects.

First-generation technology

A major demonstration project was initiated in 1976 (RP842). The scope of this project includes the design and fabrication of a prototype 4.5-MW fuel cell power plant and its test and evaluation as a dispersed generator on a utility system. The design and fabrication activity (RP842-1) was initiated in June 1976 as a joint effort by United Technologies Corp. (UTC), DOE, and EPRI. Of the $42 million project cost, UTC (the manufacturer) is contributing $12 million, DOE is contributing $25 million, and EPRI is funding $5 million.

In 1977, Consolidated Edison Co. of New York, Inc., was selected as the host utility for this project (RP842-2). The planned installation is shown in Figure 1. The site is located at East Fifteenth Street and Franklin D. Roosevelt Drive in Manhattan. This selection of a representative urban site will provide an early opportunity to fully characterize the potential of commercial fuel cell power plants as dispersed generators in urban, environmentally constrained locations. Data on the fuel cell's low emission and noise characteristics will be developed. This is expected to confirm the feasibility of siting fuel cells in such locations. Equally important, economic advantages in the forms of transmission savings, voltage control, load following, and system reliability will be determined.

The test and demonstration schedule specifies a 2200-h validation test to document the power plant's performance in the important areas of emissions, heat rate, power factor and power quality, transient response, and startup-shutdown characteristics. Following this test, several supple-

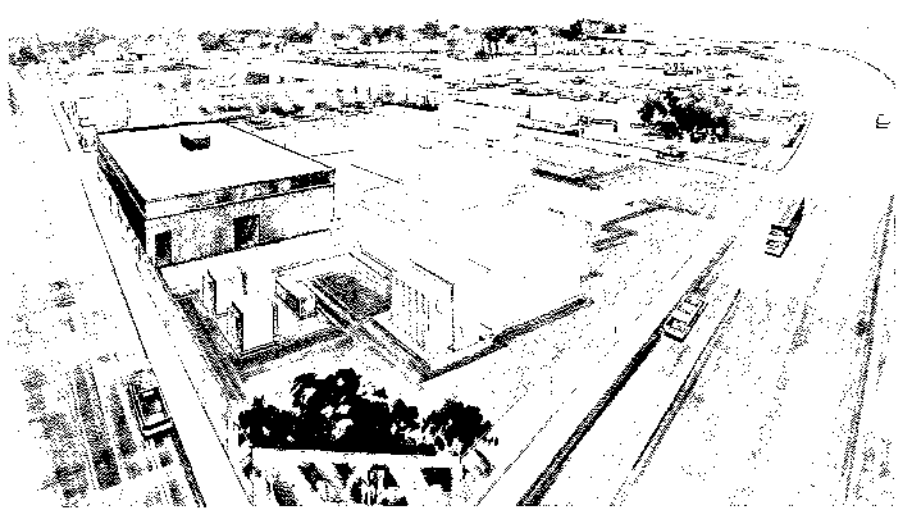
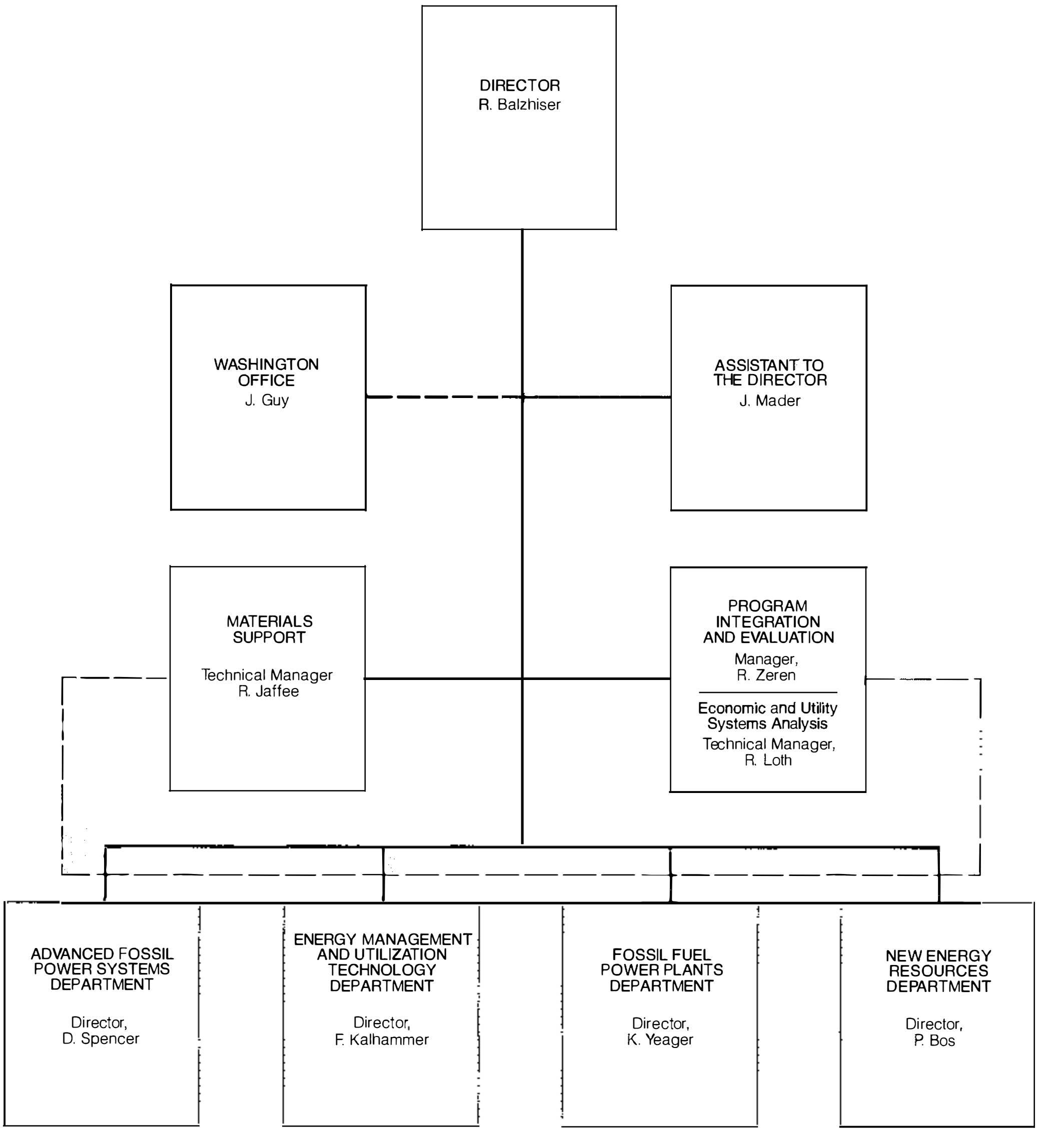


Figure 1 The 4.5-MW FCG-1 demonstration module will be installed on the Consolidated Edison system and located in downtown New York City at East Fifteenth Street and Franklin D. Roosevelt Drive. The power-conditioning modules and transformer are shown in the foreground. The dc module, located immediately behind the power conditioner, includes the fuel processing subsystem (to convert naphtha to a hydrogen-rich gas for use in the fuel cell), the fuel cell stacks, and the equipment necessary for system control and heat removal. The building on the left houses the control room, data acquisition and recording equipment, and classroom/conference facilities. The power plant's dry-cooling towers and other ancillary equipment needed to support the test are located on the periphery of the site. *Courtesy United Technologies Corporation*

ELECTRIC POWER RESEARCH INSTITUTE

Fossil Fuel and Advanced Systems Division



Clean Gaseous Fuels
N. Holt
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Clean Liquid and Solid Fuels
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Engineering and Economic Evaluation
M. Gluckman
Program Manager

Power Generation
V. Cooper
Program Manager

Energy Storage
T. Schneider
Program Manager

Energy Utilization and Conservation Technology
Q. Looney
Program Manager

Fuel Cells and Chemical Energy Conversion Technology
A. Fickett
Program Manager

Air Quality Control
D. Teixeira
Program Manager

Desulfurization Processes
G. Preston
Program Manager

Fluidized Combustion and Coal Cleaning
S. Ehrlich
Program Manager

Fossil Plant Performance and Reliability
D. Poole
Program Manager

Water Quality Control and Heat Rejection
J. Maulbetsch
Program Manager

Fusion
R. Scott
Program Manager (acting)

Geothermal
V. Roberts
Program Manager

Solar
J. Cummings
Program Manager

mental tests are planned to produce information on:

□ Use of the power conditioner for power factor correction at times when the fuel cell is not operating

□ Operating economics for peaking, spinning reserve, and baseload applications

□ Extended endurance, by accumulating a total of 6700 hours of operating time

The installation, test, and demonstration effort under RP842-2 is a $9 million project, with 50% of the cost funded by the Consolidated Edison team and with EPRI and DOE sharing the remainder equally. Other members of the Consolidated Edison team include Northeast Utilities Service Co., Niagara Mohawk Power Corp., Empire State Electric Energy Research Corp., and New York State Energy Research & Development Authority.

EPRI and DOE, under separate but coordinated contracts, have technology projects under way that address certain limitations in this first prototype power plant. The EPRI effort will determine the feasibility of an alternative fuel cell fabrication concept that could reduce construction cost by as much as 20% and simultaneously increase the maintenance interval by a factor of 4.

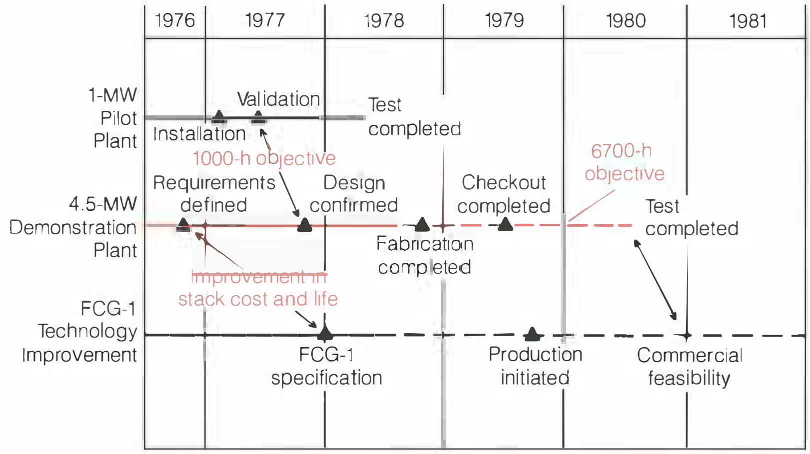
The overall program represents a $65 million commitment by EPRI, DOE, the manfacturer, and the utility team, with $11 million representing EPRI's share. The project concept and schedule are depicted in Figure 2.

Advanced fuel cell technology

To achieve the 7500-Btu/kWh heat rate targeted for the advanced fuel cell technology, individual cells in the fuel cell stack must operate at a voltage of 0.8 Vdc (versus the 0.64 Vdc required for the 9300-Btu/kWh heat rate of the first-generation cell technology). Since this voltage level is more easily obtained with high-temperature (650°C; 1200°F) molten carbonate fuel cells than with the low-temperature (190°C; 375°F) phosphoric acid fuel cells, a decision was made in 1977 to focus the advanced-cell efforts on the molten carbonate technology.

The molten carbonate fuel cell is approximately five years behind the phosphoric acid type in technological development. This is in part due to the lower funding levels allocated to molten carbonate efforts. However, the problems associated with attaining tens of thousands of hours of endurance at 650°C (1200°F) are also major factors in the slower progress made in molten carbonate programs. Molten carbonate R&D per-

Figure 2 The FCG-1 program is designed for completion of the 4.5-MW test in 1980. This is considered an important step en route to commercialization. Prior to EPRI–DOE involvement in mid-1976, FCG-1 development was utility supported.



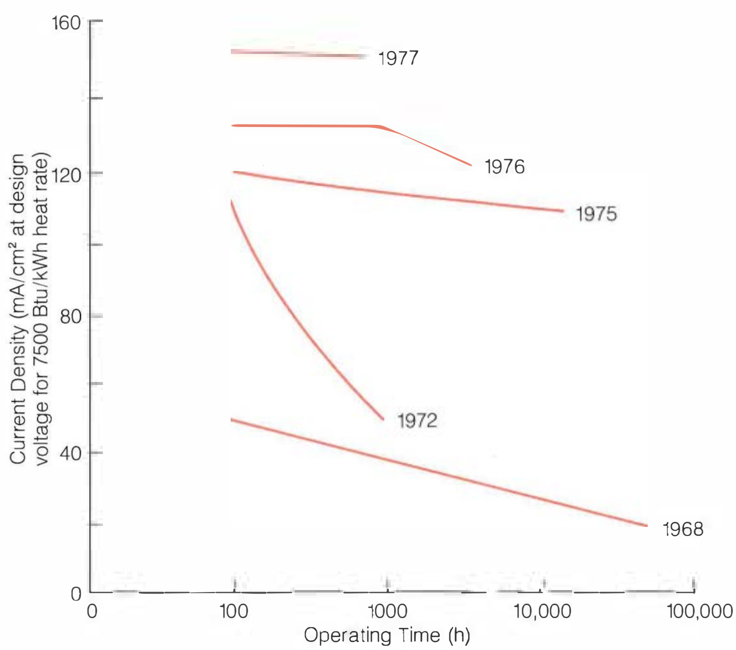


Figure 3 Molten carbonate fuel cell performance is now within reach of the 160 mA/cm² target at the 0.8 Vdc required to achieve a 7500-Btu/kWh heat rate (45% efficiency). Cell endurance remains a problem. Efforts are being concentrated on achieving a 40,000-h capability.

formed under RP114 with UTC has been concerned with achieving electrochemical performance levels of 160 mA/cm² at 0.8 Vdc with cell material and component configurations that will yield a 40,000-h cell life. As depicted in Figure 3, electrochemical performance has improved markedly, and the performance levels required to achieve targeted capital cost and heat rates are within reach. Cell endurance problems do remain, and these will likely set the pace of technological progress for some time. A small, single cell did operate for 15,000 h (1975 through 1977), and in 1976 a 19-cell stack operated for 1400 h. However, these and other tests have pointed out electrolyte structural inadequacies that must be resolved. RP114 activities are presently concentrating on this area.

A second major project on molten carbonate fuel cells is being managed by Argonne National Laboratory (ANL) for DOE. That activity is attempting to expedite development of a molten carbonate fuel cell integrated with a coal gasifier. A team of contractors, which includes General Electric Co., Energy Research Corp., Institute of Gas Technology (IGT), Oak Ridge National Laboratory, and ANL, is working on various aspects of that program. EPRI views this DOE project as an important parallel molten carbonate development, since it involves potential for an alternative manufacturer, as well as an opportunity to explore alternative cell configurations. Under RP1085, EPRI is supporting elements of that effort. RP1085-1 with General Electric comprises a system analysis of the technoeconomics of oil-fueled dispersed fuel cells and coal-fueled central station fuel cells. RP1085-2 with IGT is determining the effects of sulfur and high-pressure operation on molten carbonate fuel cells.

One advanced technology project group is addressing the phosphoric acid fuel cell technology (RP1200). If a cell voltage of 0.8 Vdc is to be achieved with phosphoric acid, a series of technical improvements must be achieved. Recently initiated projects of this group focus on the air electrode and include studies for mitigating platinum sintering, improving the kinetics, and reducing both carbon and platinum corrosion at high cathode voltages. A team of contractors that includes Energy Research Corp., UOP, Inc., and Stonehart Associates, Inc., will address the improvements necessary to significantly reduce the heat rate of the phosphoric acid fuel cell.

The effort to expand the range of fuels usable in dispersed generators has been increased over the last two years. An assessment of fuel-processing techniques capable of utilizing high-sulfur No. 2 fuel oil was undertaken. Because of this assessment, the autothermal reforming (ATR) effort under way at UTC (RP114) was augmented by a contract with Jet Propulsion Laboratory (RP1041-2) to better define the thermodynamics of the ATR process. Two foreign high-temperature steam-reforming developments were also identified as promising candidates in RP919. Under RP1041-1, Kinetics Technology International, Inc. (KTI) is conducting a detailed engineering analysis to determine the capability of these developments for modular assembly, load-following ability, efficiency, fuel range, construction cost, and so on. The process developed by Toyo Engineering Corp., which has demonstrated the capability to reform crude oil, continues to look promising.

Outlook

Significant to the prospects of fuel cell development is the dramatic growth of national fuel cell funding within the United States—from about $5 million in 1974 to $48 million in 1978, with a projected figure of $68 million for 1979. In 1978, approximately $38 million will be expended on first-generation systems and other phosphoric-acid-related activities, and $7 million will be spent on molten carbonate fuel cell technology (Table 1). Past concerns about the low level of government involvement in fuel cell RD&D have been dispelled by the recent escalation of government activities. And as we have discussed above, DOE is now taking a lead role in both first-generation and advanced-technology programs.

The most important question remaining is that of commercialization and the government's role in providing the required incentives or mechanisms to stimulate a commercial fuel cell market. Discussions are under way among DOE, the manufacturer, EPRI, and interested utilities to identify possible commercialization mechanisms.

If the first-generation fuel cell is expeditiously commercialized, the ultimate fuel cell market will be governed by the improvements obtained under the advanced-technology projects and the degree to which these advances meet or exceed goals. *Program Manager: Arnold Fickett; Project Manager: Edward Gillis*

Table 1

U.S. FUEL CELL FUNDING FOR 1978

($ million)

First-generation systems	
Electric utility demonstration	26
Other systems	9
Advanced technology	
Molten carbonate	7
Phosphoric acid	3
Other concepts	2
Fuel processing	[illegible]
	48

SOLVENT-REFINED COAL TECHNOLOGY

The overall objective of the solvent-refined coal (SRC) subprogram at EPRI is to develop the required technology to convert a wide variety of coals to clean, solid boiler fuels. A brief description and history of the process was presented in the *EPRI Journal*, May 1976, p. 12.

A significant effort has been devoted to solid-fuel development for these principal reasons:

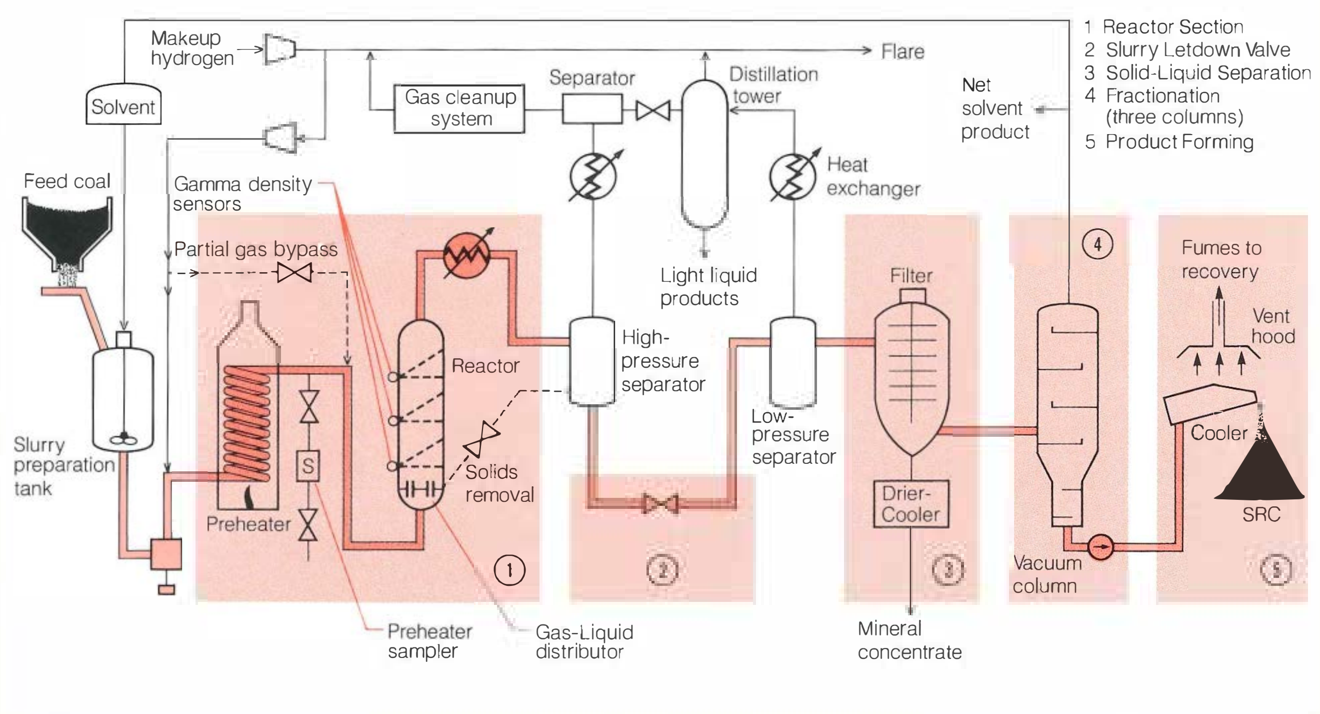
- A large component of the utility industry is equipped to burn solid fuel and prefers to continue that practice.
- Unlike other coal liquefaction products, SRC (which is a solid product) closely resembles its parent coal. The SRC approach to upgrading minimizes the hydrogen requirement and therefore the cost of hydrogen.
- SRC is expected to facilitate compliance with combustion emissions regulations.

Overall viability of the process has been demonstrated at both the Wilsonville, Alabama, and Fort Lewis, Washington, pilot plants during the past four years. The Wilsonville 6-t/d plant includes most of the operations required for the SRC technique (Figure 4).

The necessary unit operations represent major functional subdivisions within the total process. Each operation has a specific purpose, many possibilities for improvement, and unique problems. A systematic approach has been applied to improve the overall process by working on the individual parts.

The reactor, or coal dissolution system, comprises a preheater and a reactor vessel. Exploratory work has suggested that significant reactions take place in the preheater (RP410). Coal dissolution in the Wilsonville preheater has been found to be 50–90% complete at the preheater outlet. Since the

Figure 4 Simplified process diagram showing all major sections of an SRC plant.



preheater is actually a reactor, it must be included in the overall reactor design. Equipment changes have been made in the pilot plant so that the preheater outlet temperature and residence time can be varied independently. This new capability, coupled with a preheater outlet sampler, has significantly improved the ability to accomplish reaction kinetics studies.

Another reactor design problem has been the accumulation of granular solids in the reactor. Limited information was acquired by the direct measurement of these solids between reactor runs (RP1234). Recently, the reactor has been modified to continually remove these solids by withdrawing a modest stream of reactor slurry. Gamma ray instrumentation was installed to measure the approximate amount of accumulated solids present in the reactor during operation. As a result of these changes, the data that can now be obtained will significantly increase confidence in the process design of the reactor.

One of the major technical issues in the development of this technology is removal of unconverted coal and mineral matter from the product. Several approaches to solving this problem have been pursued. Filtration, recognized as the most efficient solids-removal system in terms of product recovery, was studied extensively. Detailed design and performance data were obtained for a horizontal-leaf filter. Determination of an optimal cycle was accomplished. Improved economics were demonstrated by successful use of alternative filter precoat materials. Both perlite and classified fly ash can be used instead of diatomaceous earth containing asbestos. A vertical-leaf filter, which should be more suitable for commercial application, will be installed and tested this year.

Centrifuges and hydrocyclones were investigated as alternatives to filters. In early tests, the desired level of solids removal was not achieved with individual or combined centrifugal equipment. Studies to improve the performance of these devices by means of feed pretreatment were undertaken by Conoco Coal Development Co. and the University of West Virginia (RP774). With antisolvent-pretreated feed, a single solid-bowl continuous centrifuge was found to achieve design-product clarity at satisfactory rates. Complete development of the centrifuge in this application will allow the use of centrifuges instead of very large settlers.

Another promising solid-liquid separation process, which is viewed as a potential replacement for filters and centrifuges, is Kerr-McGee critical solvent de-ashing. A skid-mounted unit built by Kerr-McGee Corp. will be installed and operated at the 6-t/d level at Wilsonville in mid-1978. The critical solvent system removes solids by rapid settling.

In addition, the Kerr-McGee critical solvent system will eventually be developed to separate de-ashed SRC into two or more fractions. Bench-scale work was started at Kerr-McGee in February 1978 to explore the fractionating aspects of critical solvent technology (RP1134-2). One application of the fractionating function of the critical solvent system fits with the now-recognized phenomenon of rapid coal conversion. Short-residence-time coal dissolution may present a more economical route to crude SRC if the crude is further processed in a critical solvent unit. Exploration of the above conceptual process was started late in 1977 at Conoco (RP1134-1).

A more satisfactory method for SRC solidification has been sought. The current method of indirect cooling is highly inefficient, and the product is very friable. Hard spherical product (nondusting prills) has been produced in a bench-scale

Table 2
SULFUR IN PILOT PLANT FEED COAL AND SRC PRODUCT

Coal Type/Mine	Organic Sulfur in Feed Coal (wt%)	(% of total sulfur[a])	Flue Gas SO_2 Feed Coal[b] (lb $SO_2/10^6$ Btu)	SRC Product (lb $SO_2/10^6$ Btu)	Sulfur Removal[c] (%)
Smith & Roland, Powder River/ Belle Ayr	0.71	88	1.36	0.18	87
Emery Field/ Emery	0.72	77	1.41	0.41	71
Illinois No. 6/ Monterey	2.53	65	7.04	1.12	84
Illinois No. 6/ Burning Star	2.0	65	5.85	0.78	87
Pittsburgh/ Loveridge	1.76	63	4.78	1.07	78
Kentucky No. 9 and No. 14 (A[d])/ Colonial	1.01	25	7.27	0.52	93
Kentucky No. 9 and No. 14 (B[d])/ Colonial	1.50	41	7.24	0.70	90
Indiana V/ Old Ben No. 1	1.25	39	5.88	0.75	87

Source: Southern Company Services, Inc.
[a]Coal contains organic sulfur (bound in organic compounds) and mineral sulfur (as pyrites and other iron compounds). The total sulfur is the sum of organic and mineral sulfur.
[b]Run-of-mine coal.
[c]Takes no credit for low sulfur liquids and gases produced.
[d]Wide range of coal composition from the same mine.

pressurized-water prilling tower, which was built and successfully operated by E. I. du Pont de Nemours & Co., Inc., using direct cooling (RP779-9). Further development of the du Pont design, using direct-contact cooling, promises a more efficient closed system. Fumes from the molten SRC will be eliminated from the plant environment as well.

Another hardware problem that has not been solved is the primary slurry pressure letdown valve (Figure 4). Valve life in pilot plants has been far shorter than is acceptable in commercial practice. Application of the best metallurgy available has produced valves that will operate for only about one month. A new design approach by Consolidated Controls Corp. (RP777) has resulted in a valve that promises significantly improved life. It will be tested at Wilsonville this year.

Product evaluation has progressed significantly. A large-scale combustion test was performed in a 22-MW commercial power generation boiler by Southern Company Services, Inc. (SCS) at Plant Mitchell, near Albany, Georgia, under a DOE contract in 1977. The test consumed about 3000 t of SRC produced in the 50-t/d DOE plant at Fort Lewis, Washington. SCS considers the test to have been an unqualified success. The final detailed evaluation of this test will be published by DOE this year. An EPRI evaluation focusing on the question of industry use of SRC product is being carried out by Bechtel Corp. (RP987).

A summary of data on low-sulfur, low-ash product produced from various coals in the Wilsonville pilot plant is presented in Table 2. The sulfur dioxide produced was less than 1.2 lb/10^6 Btu in all the cases presented. The sulfur removal on a Btu basis covered a range of 71–93% and depended on the sulfur forms and total sulfur in the feed coal. *Project Manager: Norman Stewart*

FLUIDIZED-BED COMBUSTION

EPRI's objective in developing a coal-fired combined-cycle power plant is to provide a more efficient alternative to the conventional coal-fired power plant equipped with flue gas desulfurization. Three systems are being evaluated by EPRI programs:

- A direct coal-fired ceramic heat exchanger with a closed-cycle turbine (Power Generation Program)
- Coal gasification, combined with a high-temperature, clean-gas turbine (Clean Gaseous Fuels Program)
- A pressurized fluidized-bed combustion (PFBC) boiler combined with a pressure recovery turbine, operating on a moderately dirty gas (Fluidized Combustion and Coal Cleaning Program)

It is too early to compare these three technologies, but each offers potential advantages. The gasification route should offer higher efficiency, PFBC may offer lower capital costs, and the direct-fired heat exchanger may offer simplicity.

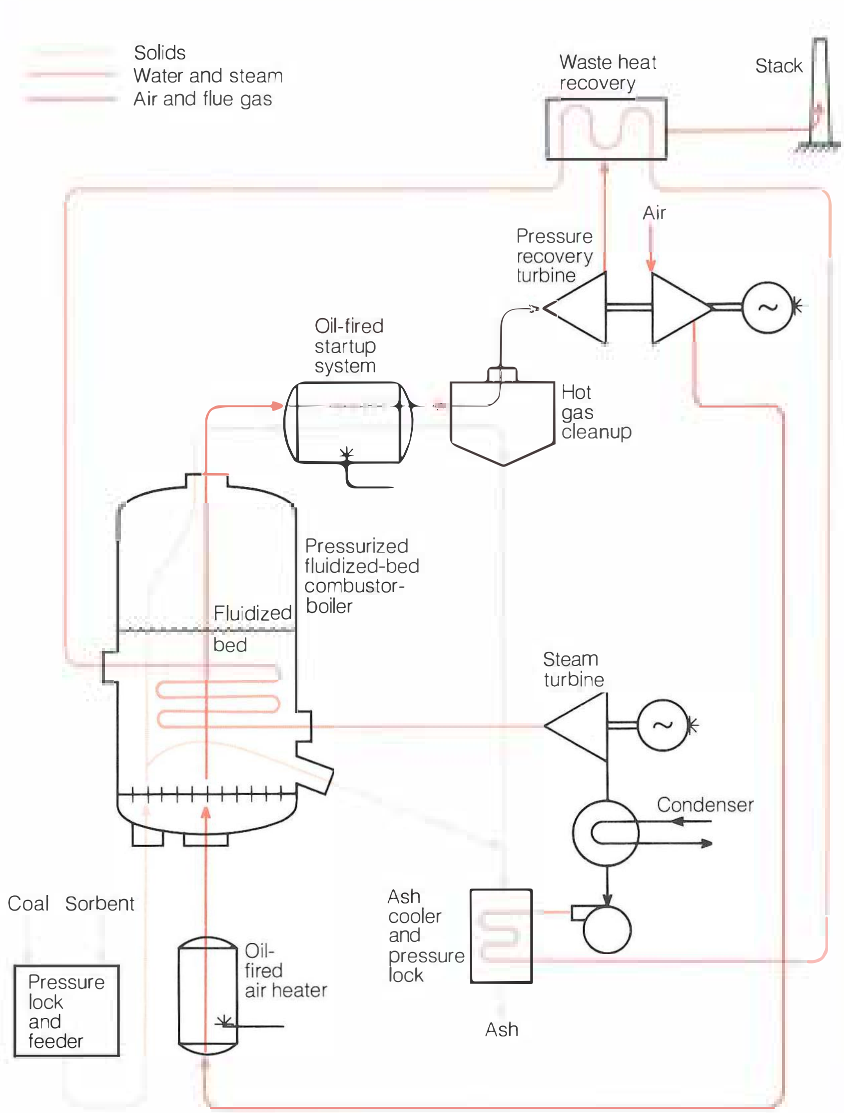
The recently initiated PFBC subprogram is partly a response to the potential impact of new air quality regulations on conventional pulverized-coal (PC) boilers. For example, EPA has proposed that the particulate emission standard be reduced to 0.03 lb/10^6 Btu, which is 70% lower than the existing New Source Performance Standard. But the gas cleanup requirements for a technically feasible PFBC plant may be even more stringent than the proposed emission standards—that is, the pressure recovery turbine might not survive a dust loading of 0.03 lb/10^6 Btu. Data also show that the SO_2 and NO_x emissions can be low without the addition of a postcombustion cleanup device. It follows that if the projected PFBC plant costs stay relatively constant, the PFBC option will become more attractive as the cost of conventional plants increases with the addition of more postcombustion cleanup requirements. In addition, under the elevated pressure conditions present in some PFBC concepts, regeneration of the spent SO_2 sorbent may be technically and economically feasible. Certainly, regeneration appears considerably less difficult than in either conventional PC power plants with scrubbers or atmospheric fluidized-bed combustion (AFBC). This is becoming an increasingly important requirement because of emerging regulations affecting by-product disposal and land use.

Figure 5 shows the essential features of a PFBC combined-cycle plant. Coal and sorbent (usually a dolomitic limestone or high-calcium lime) are crushed to size (~2 mm) and are fed to a pressure lock for transport into the PFBC boiler. At the bottom of this boiler furnace is an air distributor. The fluidized bed, made up of particles of coal ash and sorbent, has some liquidlike properties (even though the particles remain solid). For example, the fluidized bed flows around the heat exchange (steam-generating) tubes almost as if the bed were a liquid.

Coal will burn in a fluidized bed when the temperature of the bed particles is above 600°C. Startup is accomplished by spinning the gas turbine and starting the oil-fired startup burner just as if it were a conventional combustion turbine. The compressed air is heated with a second oil burner before it reaches the fluidized bed, and the bed temperature rises. Once coal flow starts, the bed temperature rapidly reaches design temperature, usually about 800°C.

The fluidized bed is ordinarily about 99.8% sorbent and ash, and it is this high concentration of inert solids that results in high heat transfer rates to the tubes located in the bed. The hot, dusty products of combustion leave the fluidized bed. If the particles were not removed, the gas, having a dust loading at the furnace exit of 55 g/m³ (25 gr/acf) at 800°C and 1500 kPa (15 atm), would destroy any turbine in a few hours. Figure 5 shows a hot gas cleanup system, which is required to reduce the dust loading to 0.1 g/m³ (0.05 gr/acf) —a removal efficiency requirement of 99.8%. This efficiency applies to particles over ~2 μm. Smaller particles may not cause erosion. The pressure recovery turbine comes after the hot gas cleaner. Steam is generated both in the combustor and in a

Figure 5 PFBC power plant system, showing the hot gas cleanup system for protecting the pressure recovery turbine.



waste heat boiler between the turbine exhaust and the stack. Generally, two-thirds of the electrical output is from steam and one-third is from the pressure recovery turbine.

It will not be possible to develop reliable and accurate cost and performance estimates for power plants based on PFBC technology until hot gas cleanup and gas turbine system hardware has been defined. However, preliminary EPRI cost and performance estimates indicate that the PFBC technology offers lower capital and busbar power costs and higher plant efficiency than do conventional coal-fired power plants with wet SO_2 scrubbers (Table 3). The EPRI R&D program for PFBC over the next year is directed toward establishing whether or not these potential advantages can be practically achieved.

The most formidable task facing PFBC development is the removal of 99.8% of the dust leaving the combustor with little or no loss of energy. Actually, although the

Table 3

COST AND PERFORMANCE ESTIMATES FOR PC, PFBC, AND AFBC TECHNOLOGIES

	Full-Load Heat Rate (Btu/kWh)	Total Capital Investment ($/kW)	30-yr Levelized Busbar Power Cost (mills/kWh)	Water Consumption per MW ($\mu m^3/s$)	Sorbent Requirement (Ca/S *M* ratio)	Sorbent Requirement (kg/kWh)
Conventional PC plant with FGD	9900	755	52	568–883	1.3[a]	0.07[a]
PFBC plant	8500	645	47	568	1.8[b]	0.17[b]
AFBC plant	9600	600	48	631	2.8[a]	0.16[a]

Note: Each plant is located in the East-Central region of the United States, each has two 500-MW units, and each uses Illinois coal (4% sulfur). The table is based on 1978 plant startup, mid-1976 dollar values, and proposed 1978 EPA New Source Performance Standards.
[a]Limestone
[b]Dolomite.

development problems are formidable, they are not nearly as severe as the removal efficiency value of 99.8% implies. The particles are coarse (~ 100 μm mean), and more than 98% can be knocked out of the gas stream by two standard cyclone collectors operating in series. This is common practice in the petroleum industry at temperatures as high as 700°C with even finer particles. After the cyclone treatment, the gas cleanup problem is reduced to removal of about 90% of the particles greater than 2–10 μm.

For the Clean Gaseous Fuels Program, Stone & Webster Engineering Corp. evaluated the state of the art of hot gas cleanup (EPRI 243-1 and AF-416). They concluded that no effective hot gas cleanup system can be considered to be available—that is, a straightforward engineering and design change would not produce a device that is reliable by utility standards. Substantial DOE- and EPA-funded research has been carried out, almost entirely on granular-bed filters (analogous to fabric filters, except that grains of stone form the matrix that filters the dust). The results have not been encouraging—structural failure, plugging, and low efficiency were encountered. Therefore, more advanced technologies for filtration impaction and electrostatic particulate removal are now undergoing screening tests at EPRI's Arapahoe Emissions Control and Test Facility. The most encouraging of these technologies will be incorporated into the PFBC development program.

In addition to a hot gas cleanup system, an effective materials-handling system must be developed for injecting and removing solids from a pressurized system, and a maintainable combustor-boiler must also be designed.

EPRI's recently initiated PFBC subprogram began with development of an EPRI program plan. General Electric is helping to detail the plan (TPS78-762).

Under RP543, UTC has developed a turbine simulator. Rods of turbine metal are bombarded with monosize particles of pure materials such as Al_2O_3 and MgO. Results from this work indicate that particles as small as 2 μm can cause damage to most turbine alloys. Under RP979-3, a 1000-h test is planned, using the 1-t/h PFBC pilot plant in Leatherhead, England. This experiment, which will be funded primarily by DOE (80%), will cost about $1.5 million and should clearly identify the materials problems that must be resolved in order to lower maintenance costs in commercial plants.

Westinghouse Electric Corp. is beginning a test and development program (RP1336) on hot gas cleanup with an existing, large simulator rated at 5.5 kg gas/s (12 lb gas/s). A contractor is being selected to carry out EPRI's major effort on improving erosion performance of turbine materials (RP1337). These two projects can be viewed as having equal importance. It may not be possible to develop a hot gas cleanup system that will remove enough particulate to allow state-of-the-art turbine materials to last more than a few thousand hours, and it is not practical to develop a turbine blade that can survive 2.3 g/m³ (1 gr/scf). But by working concurrently on gas cleanup and turbine hardening, it may be possible to develop a PFBC system capable of realizing its inherent advantages.

While the key issue is turbine life, there are other important problems. Over the next two years we will be developing a regenerable sorbent system for SO_2 control; a low-cost, maintainable combustor-boiler design; and an optimum cycle to exploit these developments. A U.S. utility and a Canadian utility are now considering 60–180-MW PFBC demonstrations. *Program Manager: Shelton Ehrlich*

R&D Status Report
NUCLEAR POWER DIVISION

Milton Levenson, Director

ENHANCEMENT OF STEAM GENERATOR INSPECTION RESULTS

For many years, single-frequency eddy-current testing (ECT) has been used in periodic in-service inspection of steam generator tubes to verify tube integrity. In ECT, two wire coils are placed on a probe and energized to generate eddy currents in the tube wall (Figure 1). Because the coils are connected in opposition, a null signal is observed when the probe detects good tube conditions. A defect changes the electrical impedance of the tube; this changes the eddy-current flow pattern and results in an output signal different from the null signal. In an in-service inspection, the probe is moved mechanically through the tube at a rate of 300 mm/s (1 ft/s), and the output signal is recorded. An off-line analysis of the data is then performed. The current method of interpreting these signals (manually) depends heavily on the skill and experience of the operator.

Until the recent onset of denting in steam generators, the information derived from ECT was adequate. Now the information

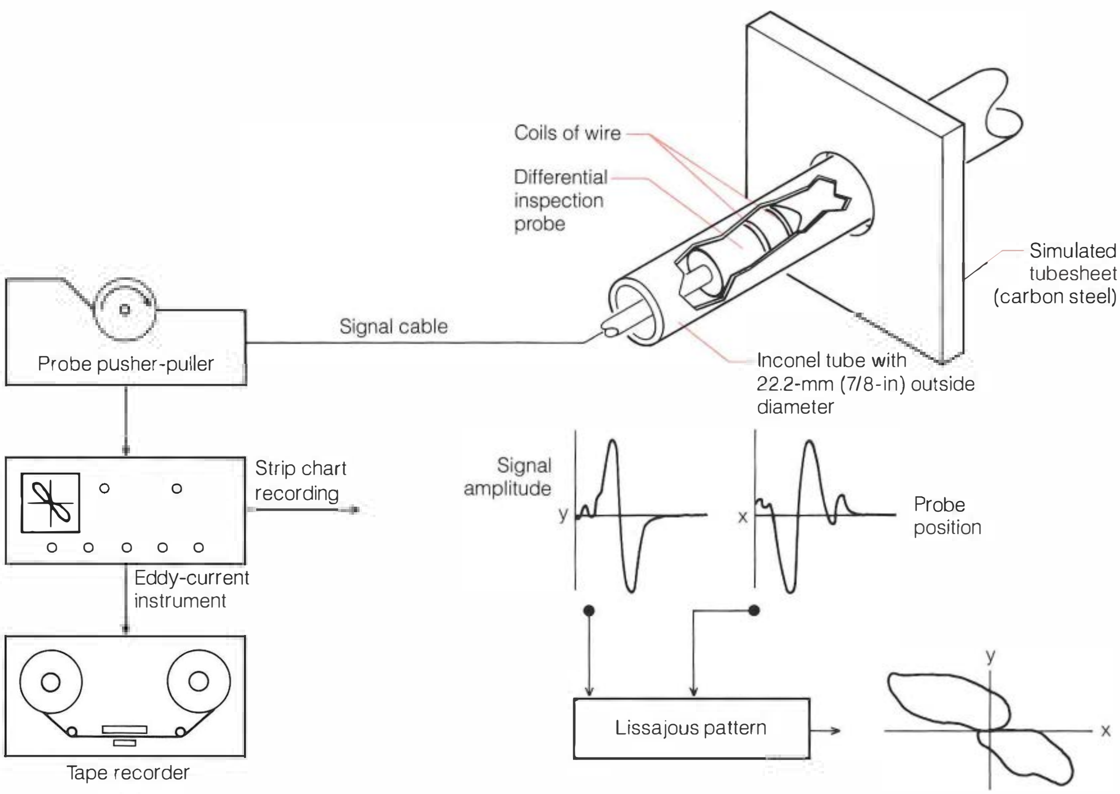
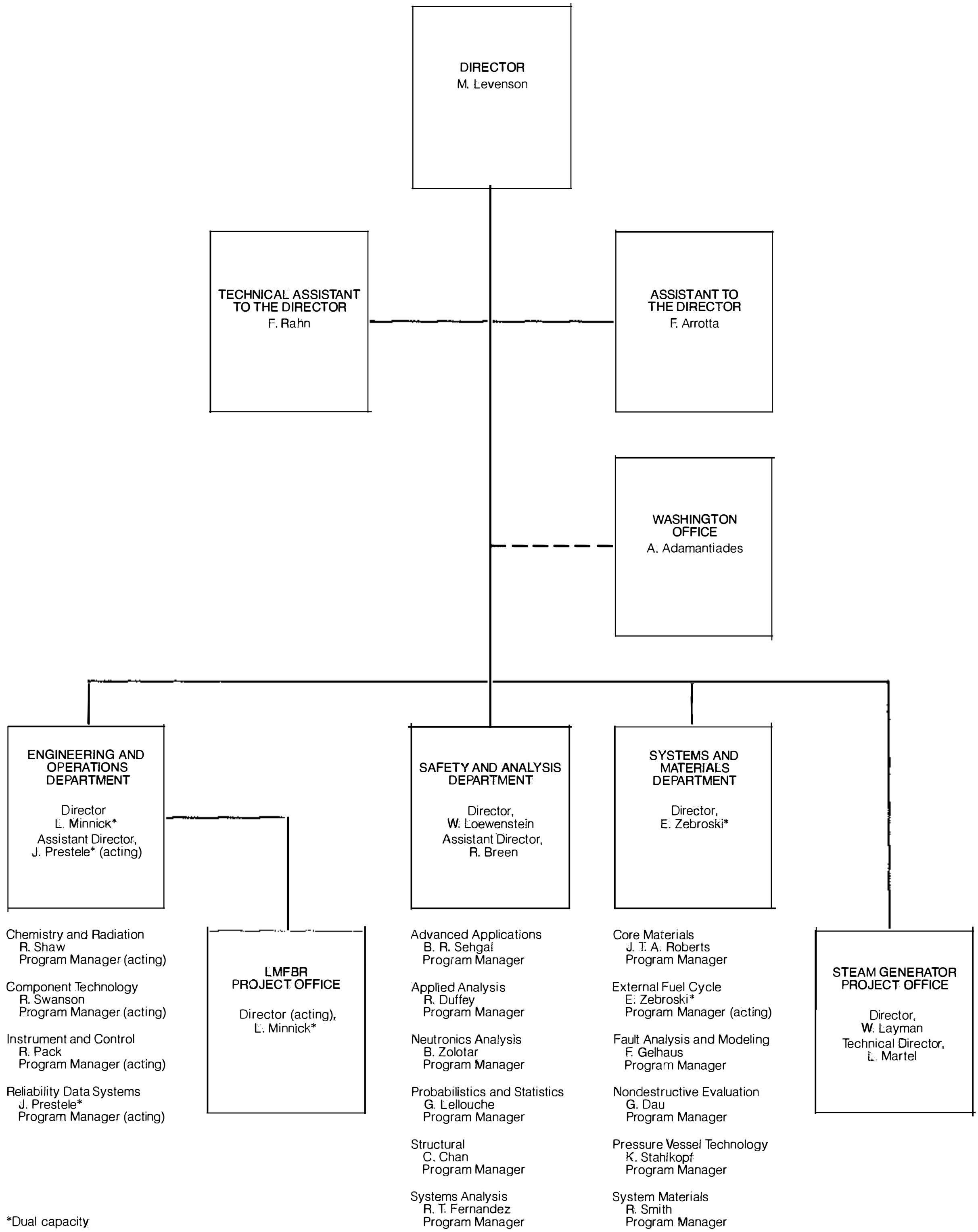


Figure 1 The acquisition of information from steam generator tube inspection is shown in the top part of this illustration. The typical form of the recorded electronic signals is shown by the plots of the x and y channels as functions of probe position. The figure-eight (Lissajous) pattern formed by combining these two signals is used to interpret the data.

ELECTRIC POWER RESEARCH INSTITUTE

Nuclear Power Division



*Dual capacity

needed taxes or exceeds the limits of present ECT practice. (Denting occurs when corrosion products grow in the region between the tube and the tube support plate and force a constriction in the tube diameter.)

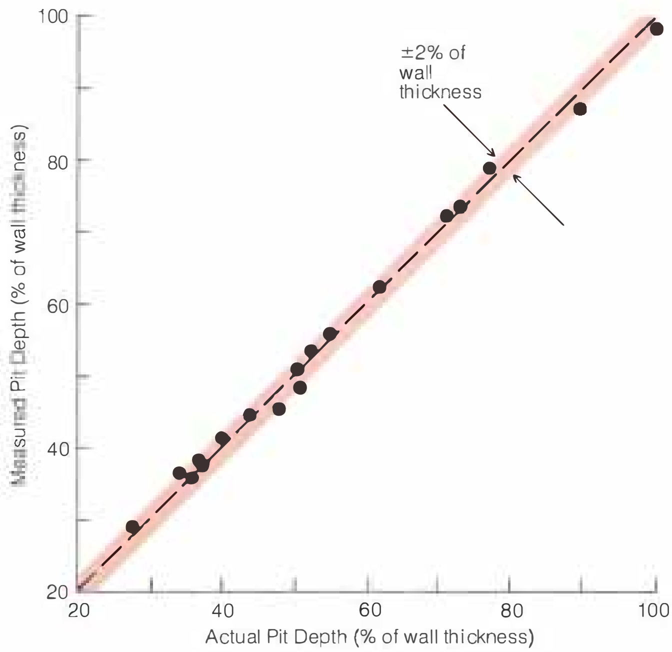
Much work is being done by EPRI and others to optimize probe design and investigate the use of multifrequency excitation to improve tube inspection. However, this EPRI project attacked the problem in a different way (TPS77-723). The basic idea was to use modern computer power and signal analysis concepts to automatically extract more information from the ECT signal than is possible by use of manual methods. A study was initiated to explore the feasibility of using a nonlinear signal-processing concept called the adaptive learning network (ALN).

The development of the ALN is an empirical learning effort whereby all the original signals and a variety of parameters that may be important to the solution are put into a computer. A preprogrammed code is used to select the signal characteristics and parameters that are the most relevant to the solution, determine appropriate combinations of these quantities within the ALN, and assign weighting functions to each combination that is necessary to classify and size the defects. What is unique about the ALN is that it empirically "learns" or identifies the most important signal characteristics and parameters, rejects the others, and "discovers" the necessary linear/nonlinear combination of the important quantities. In normal regression analysis, the analyst, who must select the parameters and assign weights to each, is often hampered by lack of a complete physical description of the process being modeled.

Two sets of tube samples were prepared by Battelle, Pacific Northwest Laboratories. One set had a series of constant-diameter, flat-bottom holes (simulated pits) that extended into the tube wall to depths ranging from 25 to 100% of wall thickness. The second set had electro-discharged machined (EDM) notches (simulated cracks), ranging in depth from 40 to 60% of wall thickness. In both sets, the defects originated on the outside diameter of the tube. Eddy-current signals were recorded as a probe was passed by each defect. Later, the entire process was repeated, but this time a carbon steel plate (simulated tube support plate) was placed over each defect to give the maximum interference with the defect signal. The data were recorded and sent to Adaptronics, Inc., for signal processing.

Adaptronics divided the data for each set into three independent data sets. The first was used to develop an ALN to automatically classify and size the defects according to their unique eddy-current signatures.

Figure 2 The pit depth measured by the ALN method is compared with its actual value. The small amount of scatter (±2%) indicates that the ALN method offers excellent precision and accuracy.



Once an empirical solution was generated from the first data set, a second independent data set was used to ensure that an optimal solution was obtained and that no overfitting occurred (overfitting is the development of a more precise solution than the data warrant). Finally, the third data set was used to provide an independent evaluation of the success of the solution developed from the first and second sets.

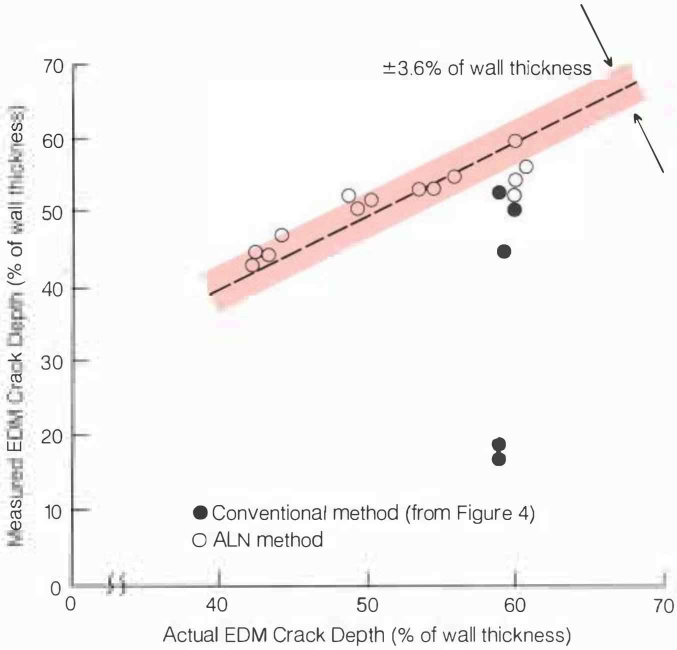
The results from this well-defined feasibility effort show that with use of ALN signal processing of conventional single-frequency (400-kHz) data, it is possible to automatically identify the flaw type and then size it in terms of through-wall penetration. It is significant that these results do not depend on the presence or absence of a tube support plate. Figure 2 is a plot of the data for a pit-type defect (flat-bottom hole), and Figure 3 shows the data for a crack-type defect (EDM notch). Figure 4 shows data obtained with a conventional system (*1*). If sizing were perfect, all points would fall on the dashed center line.

A comparison of results contained in Figures 2, 3, and 4 shows further important facts. (The data for EDM notches from Figure 4 are also plotted on Figure 3 to facilitate comparison.) First, the ALN method sizes the defects with excellent precision (±2.0% for pits and ±3.6% for cracks). Second, the ALN-measured value shows a linear relationship with actual defect size. On the other hand, the conventional data show a considerable variance in sizing ability and also exhibit a nonlinearity in sizing as a function of defect size. This nonlinearity results in an underestimation of the significance of cracklike defects and an overestimation of the significance of wastage-type deterioration.

In summary, the results of this project show that the ALN signal-processing method can considerably enhance the amount and value of information obtained from steam generator tube inspection. Specifically, the data indicate that defects can be identified by type and then sized to a high degree of precision. Furthermore, the accuracy of the measured value is influenced neither by defect size nor by the presence or absence of the tube support plate.

In a follow-on program, prototype hardware is being developed for verification of these laboratory results under more realistic

Figure 3 This plot shows that ALN processing produces good agreement between the measured EDM crack depth and the actual crack depth.



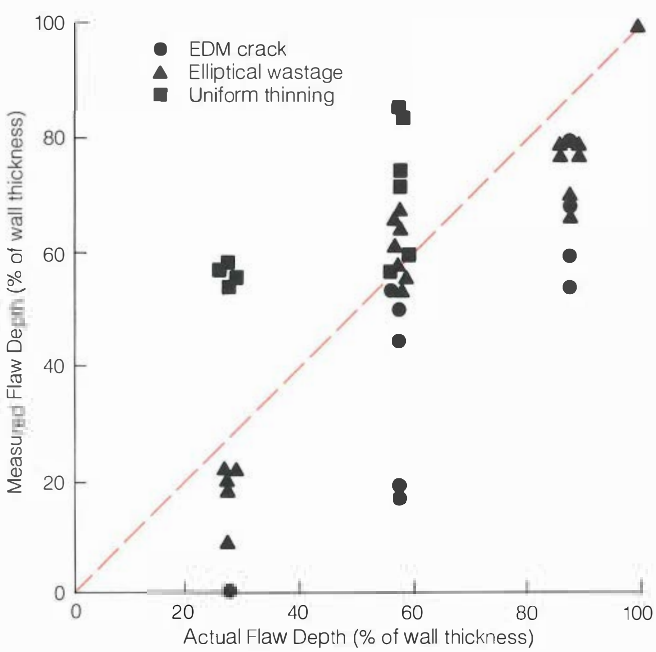


Figure 4 This graph illustrates the lower precision and accuracy of conventional eddy-current inspection. The farther the data points are from the diagonal line, the lower the precision and accuracy.

field conditions. For more information, the reader is referred to the Final Report, *Feasibility of Using Adaptive Learning Networks for Eddy-Current Signal Analysis* (NP-723). *Project Manager: Gary Dau*

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REFLOOD HEAT TRANSFER

A major consideration in the design of engineered safety systems and licensing of LWRs is that sufficient emergency core coolant (ECC) be provided to cool the reactor core in the event of a hypothetical loss-of-coolant accident (LOCA). Historically, the design-basis LOCA calculations have been grouped according to three periods of system response known as the blowdown, refill, and reflood phases.

The reflood phase generally extends from the time that the ECC water reaches the bottom of the reactor core until the core is covered. Calculations from licensing-evaluation models indicate that the fuel cladding heats up to peak temperatures until sufficient coolant is provided to terminate the heat-up transient, quench the fuel rods, and remove the stored and decay heat from the rods. Complex two-phase heat transfer and hydrodynamic phenomena occur during the reflood phase.

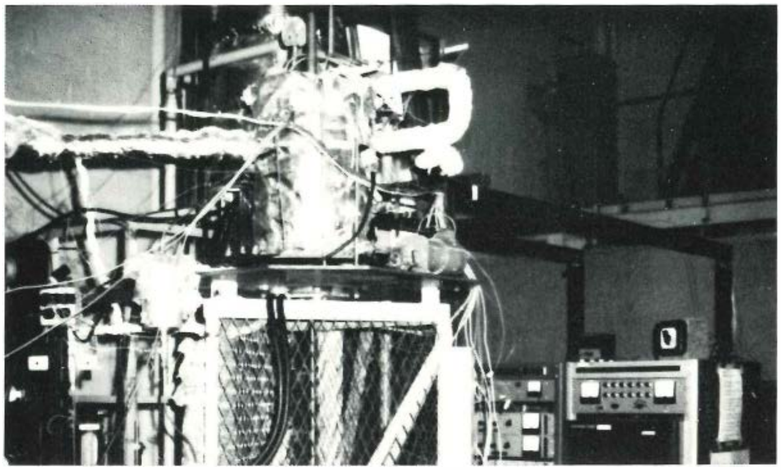
Extensive experiments have been conducted worldwide in recent years to demonstrate the heat transfer effectiveness of reflooding under simulated LOCA conditions. Simultaneously, continued experimental and theoretical efforts have been made to enhance the fundamental understanding of the thermal-hydraulic phenomena that occur during the reflood process and to develop realistic phenomenological models. A project that has been under way since 1974 at the University of California at Berkeley (UCB) is a part of this continuing effort (RP248-1). The scope of the project includes a state-of-the-art evaluation of the phenomena, an experimental program to provide a data base to facilitate model development and model verifications, and development of analytic models to predict thermal-hydraulic performance. Principal investigators were R. Greif, R. Seban, and G. Yadigaroglu.

State-of-the-art evaluation

This evaluation consists of a general review of the heat transfer that takes place during the reflood phase of the LOCA (*1*) and a review of the specific phenomena that govern rewetting and entrainment mechanisms for this phase (*2*).

The general review describes a LOCA in an LWR, ECC systems, and the reflood phase. The Appendix K (10 CFR 50) version of the regulatory requirements that are relevant to the analysis of the reflooding phase is discussed and analyzed. Analytic models and codes for calculating the reflood transients used in the United States for licensing purposes are reviewed, as are developmental computer programs from abroad. A detailed examination is made of all the experimental evidence available from reflooding experiments. Both single-channel and rod-bundle experiments conducted in the United States and abroad are comprehensively and critically reviewed. The state-of-the-art evaluation leads to the conclusion that the current design evaluation models involve some simplistic, physically unrealistic assumptions that can be overconservative for safety licensing evaluations. The need for additional research in this area is obvious, and the potential benefit of further studies can be significant for the utility industry.

The review of the rewetting and liquid entrainment phenomena includes the assessment of existing models and methods for the calculation of quench front propagation rate. The basic assumptions of these models, the numerical values assigned to the various parameters, and the empirical rewetting correlations are discussed. The various mechanisms for liquid droplet entrainment and the analytic formulations of critical gas velocity and of droplet diameter at the onset of entrainment are reviewed. This review concludes that the largest uncertainty in the rewetting models lies in the definition of the rewetting temperature and in the heat transfer mechanisms at the quench front. In addition, further work needs to be done to better characterize the onset of liquid entrainment.



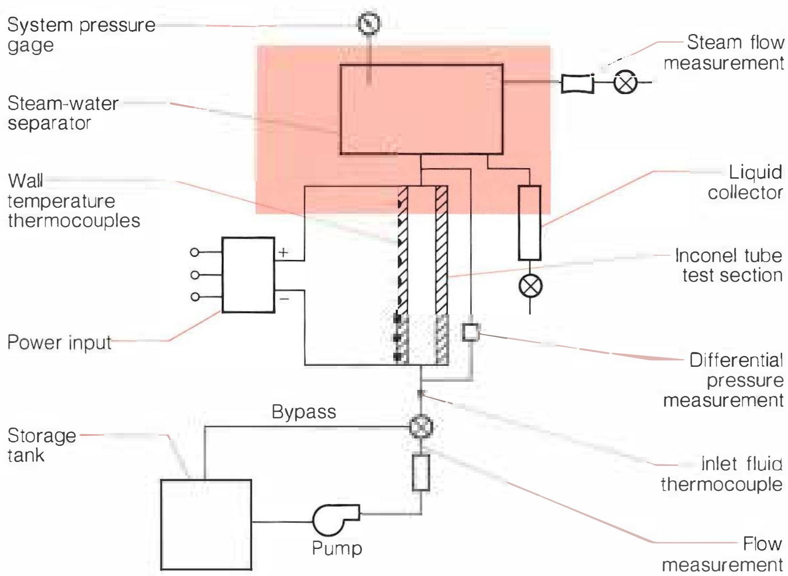


Figure 5 To maintain a basic approach and to minimize the hardware complexities, this single-tube test loop was designed and constructed at UCB for study of the fundamental reflood phenomena during a hypothetical LOCA. The photograph, which corresponds to the outlined section in the schematic, shows the upper portion of the test section (enclosed by screens), the steam-water separator, and the liquid collector, with the data acquisition system in the background.

Experimental studies

To minimize the complexity of hardware and to maintain a basic approach, a single-tube reflood test loop was designed and constructed in UCB's Mechanical Engineering Laboratory (*3*). The schematic of the test loop is shown in Figure 5. The test section was a 3.66-m (12-ft) Inconel tube with an inside diameter of 14.4 mm (0.565 in) and a wall thickness of 0.76 mm (0.030 in). The tube was heated by passing direct current through its wall. When the tube reached a steady-state condition with respect to its surroundings, reflood was initiated by introducing water into the bottom of the tube at a carefully controlled temperature and flow rate. A separator was mounted on the top of the test section to separate water droplets and steam from the two-phase mixture that exited from the tube during the reflooding test.

Temperatures at discrete elevations of the tube, temperature and flow rates at the inlet and exit sections, and system pressure were measured. These measurements led to information on quench front propagation rate, heat transfer coefficient, mass effluent rate, and exit quality. These are the key parameters for the determination of calculated fuel rod temperature transient in design evaluations for licensing.

Tests completed to date cover a wide range of thermal-hydraulic conditions near atmospheric pressure (*4*). The test results are being used as benchmarks for verification of reflood computer methods. Experiments planned for the next two years include a photographic study of the entrainment phenomena, gravity reflood tests to investigate the effect of flow oscillations on reflood thermal-hydraulics, tests with local flow blockage to evaluate the effects of fuel rod ballooning (and the resultant flow area reduction on reflood heat transfer), and forced reflood tests at elevated system pressures.

Analytic studies

The analytic studies consist of two parts—fundamental phenomenological model development and system method development. The former deals with individual physical mechanisms, while the latter incorporates the phenomenological models into a general computer method for the prediction of overall system performance.

An analytic one-dimensional conduction model was developed for the rewetting mechanism during reflood (*5*). Various boiling heat transfer regimes involved in the quenching phenomenon were accounted for in the model.

The phenomenological models under development analyze heat transfer in the vicinity of the quench front and dispersed-flow film boiling. Models planned for the next phase of the study deal with the effects of flow blockage and flow oscillations.

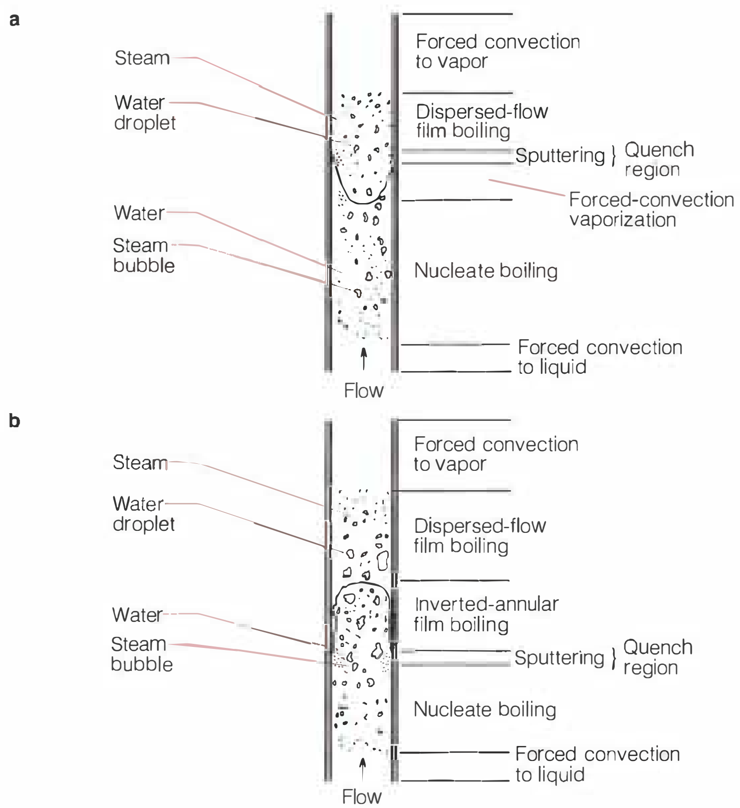
A mechanistic system model to analyze the reflooding of a single-flow channel and its associated fuel rod (or a tubular test section with internal flow) was developed (RP248-1). The computer code UCFLOOD was written to carry out the calculations.

The flow channel is divided into three major volume-control regions according to the prevailing flow regimes—namely, a single-phase region, a continuous-liquid-phase region (bubbly, slug, annular, or inverted-annular flow), and a dispersed-liquid region (Figure 6). The equations for conservation of mass and energy are solved in a fully transient form in the single-phase region, using a Lagrangian description of the flow; in the continuous-liquid-phase and dispersed-liquid regions, these equations are solved in their quasi-steady-state form. Approximations are made for liquid subcooling in the subcooled boiling region and for vapor superheat in the dispersed-flow region. The void fraction distribution is obtained from a drift flux model.

The onset of liquid entrainment is determined by using a simplified criterion based on the instability of the liquid core in the inverted-annular flow regime.

For heat transfer calculations, the channel is also divided into a number of regions,

Figure 6 As the emergency cooling water enters the reactor core during the reflood phase of the hypothetical LOCA, complex thermal-hydraulic phenomena occur. This figure illustrates the concept of the two-phase-flow and heat transfer regions in the reflooding of a vertical channel, for **(a)** low and **(b)** high reflood-rate cases.

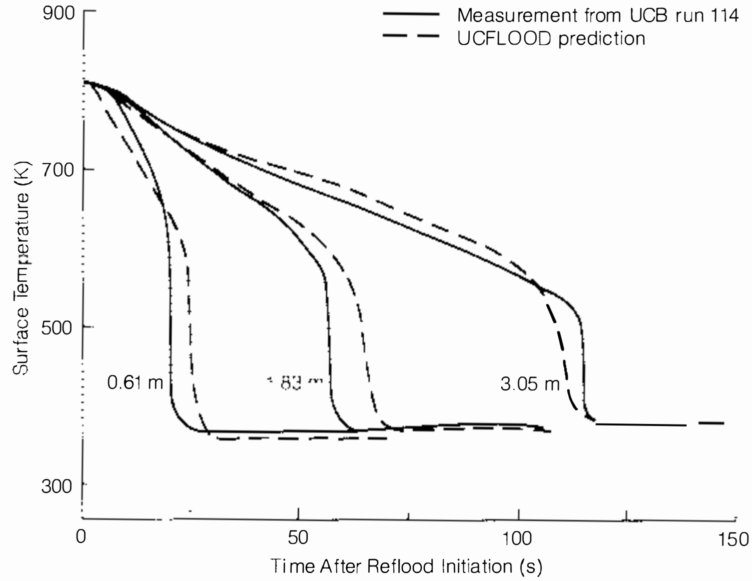


including regions of single-phase heat transfer to the liquid, nucleate boiling and forced-convection vaporization, inverted-annular and transition-flow film boiling, and dispersed-flow film boiling. Heat transfer coefficients in these regions are obtained from correlations available in the literature or extracted from UCB test data. The wall temperature history is calculated by solving the time-dependent radial conduction equation.

The important problem of quench front propagation is treated separately from the overall heat transfer calculations by modeling the narrow quench front region, including the effects of axial conduction. Two methods are available for estimating quench front velocity. The two-dimensional heat conduction equation can be solved using a moving grid technique, or for tubular test sections, a semiempirical correlation can be used.

In summary, the present version of the UCFLOOD code has a general framework that incorporates the current technology. The code subroutines for the individual phenomenological models can be easily modified or updated as more advanced or upgraded models become available. Preliminary results of the UCFLOOD prediction show that the predicted wall surface temperature histories during reflooding agree reasonably well with data from a UCB single-tube test and from a FLECHT (full length emergency core heat transfer) test (Figures 7 and 8). This project is integrated with EPRI's work in facilitating comprehensive and realistic evaluations of reflood concerns. In particular, it is parallel to the large-scale bundle experiment project, FLECHT–SEASET (separate effect and system effect tests), which is jointly sponsored by EPRI, NRC, and Westinghouse Electric Corp. *Project Manager: K. H. Sun*

Figure 7 Composed of a general system framework and the compilation of current analyses of reflood heat transfer, the computer code UCFLOOD (developed at UCB) is shown to predict the wall-temperature histories from the single-tube reflood test.



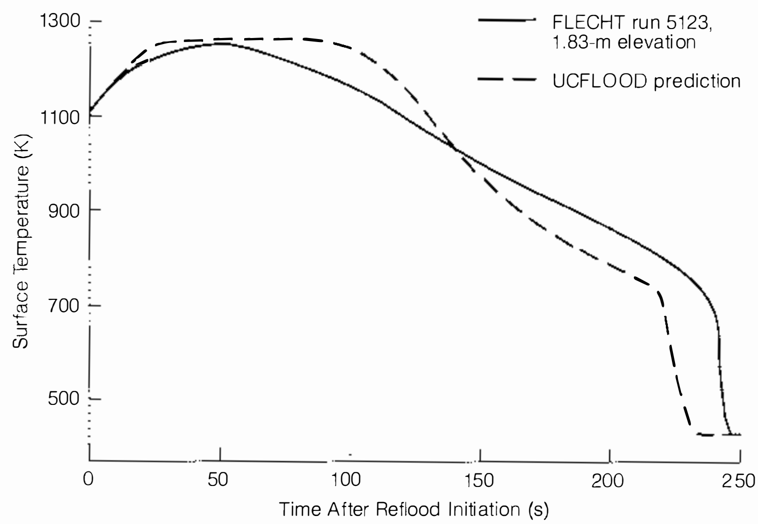


Figure 8 To integrate the results from the fundamental reflood heat transfer project with the existing large-scale bundle experiment program, this work is closely related to the FLECHT-SEASET program, which is jointly sponsored by EPRI, NRC, and Westinghouse Electric Corp. The figure shows reasonable agreement in wall-temperature history between an earlier FLECHT test run and a preliminary UCFLOOD prediction.

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R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

SUBSTATIONS

The bulk of this month's report concentrates on transmission substations. Substations are the gateway for the transfer of all power from generation to distribution, and as such, their reliability is one of our main concerns. Since many substations have to be located in or near populated areas, their esthetic-environmental aspects also carry high priority. There are many fertile areas of investigation (leading to design guides, reference books, and equipment) that offer large benefits to utilities but little commercial incentive to manufacturers.

With the help and advice of utility experts who serve on the task forces or as our industry advisers, we continually update our five-year plan. Most of these experts agree that the more critical areas of R&D still lie before us. The motivation for the plan results from our recognition that:

- The utilities need reliable and economical low-profile substations, such as those with gas-insulated designs.

- The general growth of short-circuit current size resulting from the growth of utility systems represents a major cost and threat to their reliability, forcing solutions that include replacement of some equipment before its useful life is over, splitting of the system, and inclusion of lossy current-limiting reactors. Alternative solutions to these problems are needed.

- Utilities need more information on ways to reduce environmental impact.

- For the sake of efficiency, environment, and economy, transmission voltages of 1200 kV and 1500 kV are expected to be used by the late 1980s. The substations for these voltages should preferably be of a dead-tank, compact design.

- Control and protection systems for transmission substations must take fuller advantage of advances in semiconductor, computer, and digital-optical transmission techniques.

- Reduction of system overvoltages and the resultant lower required insulation levels of the equipment can lead to greater reliability at lower cost.

Since funds are limited, consideration will be given only to high-priority projects in each equipment area. In equipment development, we consider it important to establish commercially acceptable specifications as early as possible so that they accurately reflect the needs of the real world. In many cases, it is important to prove the prototype equipment in a utility system over a trial period. In other projects, limitation of funds precludes any major demonstration, even though such an approach is considered desirable. In those instances we must carry laboratory tests well beyond the proof-of-concept stage.

Overlap of EPRI and DOE funding is avoided by close coordination. This increases the efficiency of our R&D spending and allows more problems to be attacked.

Much of the effort is summarized in the pages that follow, and we welcome any input the industry can offer, from either users or suppliers, so that we can focus our R&D efforts on meaningful results.

Switchgear

One of the key needs in circuit protection is the development of fault current limiters. Limiting the first current peak is especially important. There are basically two types of current limiters. One is a tuned-circuit type, in which a series impedance that is tuned to 60 Hz is detuned during a fault. Although such current limiters are expensive, they are generally fail-safe and may be cost-effective at bus tie locations. We have completed a detailed study of a novel, tuned-circuit current limiter that allows little more than full load current to flow. A 10-kVA model is available for continued study. A bus tie location on a 345-kV system of Consolidated Edison of New York, Inc., has been selected as a model for a design to evaluate cost.

The other way to control fault current is with a switched-impedance device, in which a high-speed switch is opened rapidly to insert an impedance in the circuit. Our approach is to develop a switch that upon opening will generate an arc voltage high enough to transfer current to a capacitor and resistor arranged in parallel. We have made progress in this direction, but until such a switch is available, our interim approach is to transfer current to a silver-sand fuse, which then generates a voltage high enough to transfer current to a resistor. Such a design is being developed by I–T–E Imperial Corp. (a subsidiary of Gould Inc.) for 69-kV application, and a commercially acceptable prototype (RP281) is due to be installed on the Southern California Edison Co. system in 1979 (Figure 1).

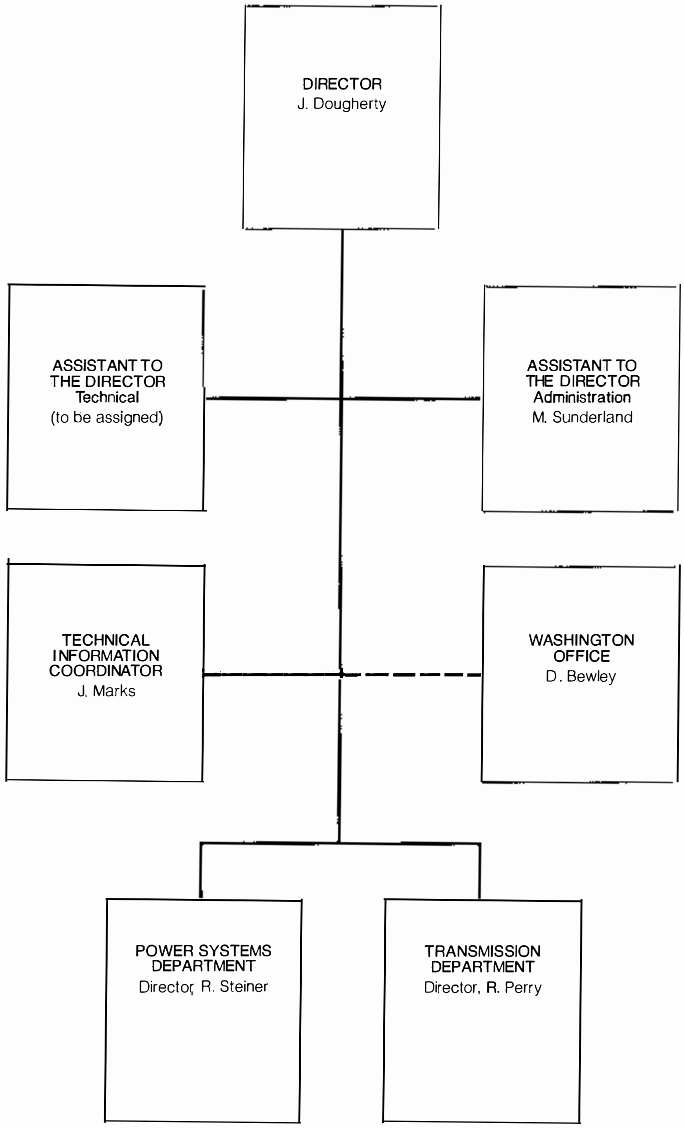
Until fault current limiters are available and generally acceptable, we are developing new circuit-interrupting devices that are simpler, faster, and more reliable than their predecessors. SF_6 gas and vacuum are both important in this endeavor. The objective of our single-pressure, SF_6 interrupter development (RP478) is a dual rating goal of 120 kA at 145kV and 100kA at 242 kV. We have successfully tested both liquid SF_6 and high-pressure SF_6 model interrupters at 75 kA and 145 kV (Figure 2).

A novel concept under development with General Electric Co. exploits the advantages of a diffused arc in a vacuum (RP754). We have established the ability to transfer an arc from moving contacts to fixed electrodes in 1 ms and have maintained the arc in a diffuse mode for currents up to 180 kA peak. We have also successfully tested a triggered-gap vacuum device that will interrupt currents up to 63 kA at 84 kV (Figure 3). This device is probably capable of operating at 63 kA and 100 kV.

Development of reliable disconnects, low-cost interrupters, and advanced interrupters

ELECTRIC POWER RESEARCH INSTITUTE

Electrical Systems Division



Distribution
W. Shula
Program Manager

Power System Planning and Operations
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Overhead Lines (AC and DC)
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Substations (AC and DC)
N. Hingorani
Program Manager

Underground Transmission
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Program Manager

for generator circuit breakers will also receive support.

Transformers

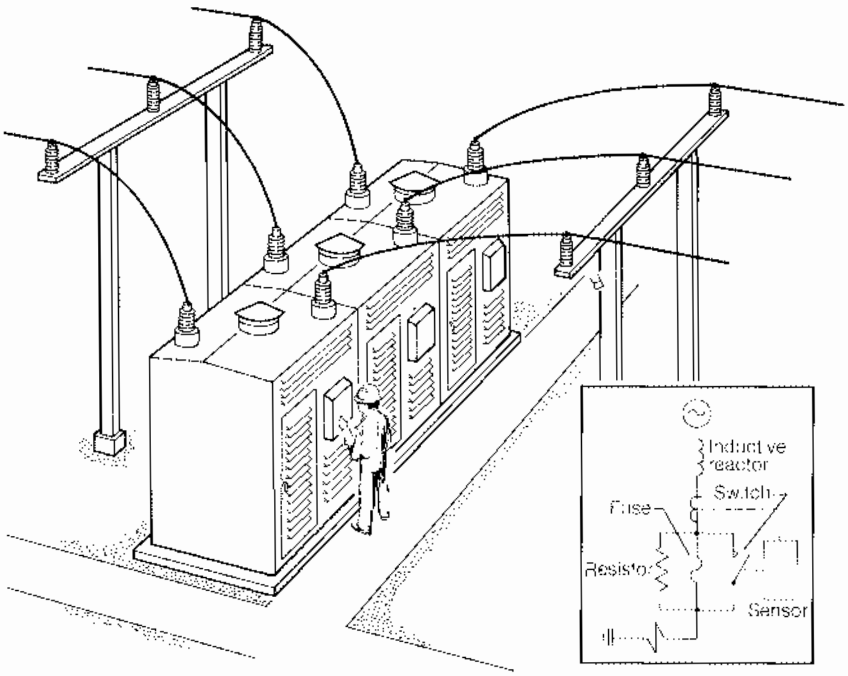
Transformer technology is one area that has several near-term as well as long-term problems. We have projects under way to address the more important of these problems.

For example, two hot spot detector projects should result in reliable detection schemes for directly measuring the hot spot temperature in the windings of transformers (Figure 4). The devices developed for these detection schemes are passive (i.e., require no power supply). An on-line combustible gas-in-oil detector, which will indicate deterioration of transformer insulation, will soon be available for installation on medium-size and large power transformers (RP748). A prototype is under test on Consolidated Edison Co. and Pennsylvania Power Co. transformers (Figure 5). Currently funded work on an acoustic partial-discharge detector for indicating defective transformers should lead to both portable and on-line devices.

Naphthenic-based oil has been used for transformers in the past. Because the supply of this oil from known sources is declining, an in-depth study is being performed of the supply of alternative insulating oils, particularly paraffinic-based oil.

We believe that in the long run there is little to be gained from continued development of oil and paper for insulating and cooling power transformers. Our long-term objec-

Figure 1 Switched-impedance, 69-kV fault current limiter scheduled for installation in late 1979.



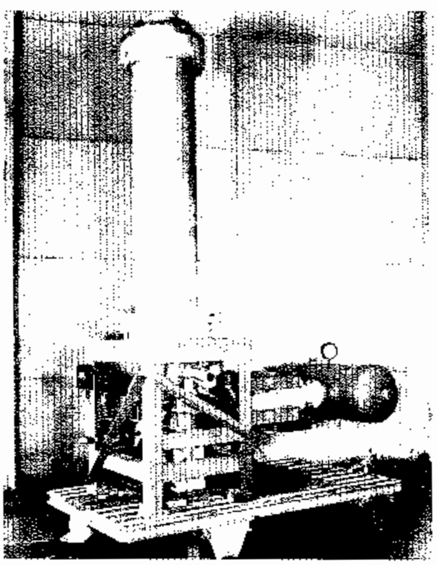


Figure 2 A prototype single-pressure, puffer-type SF_6 interrupter was tested for 75 kA at 145 kV. Based on these tests, a prototype interrupter is being designed for a dual rating goal of 120 kA at 145 kV and 100 kA at 242 kV in Westinghouse's High Power Laboratory, East Pittsburgh, Pennsylvania.

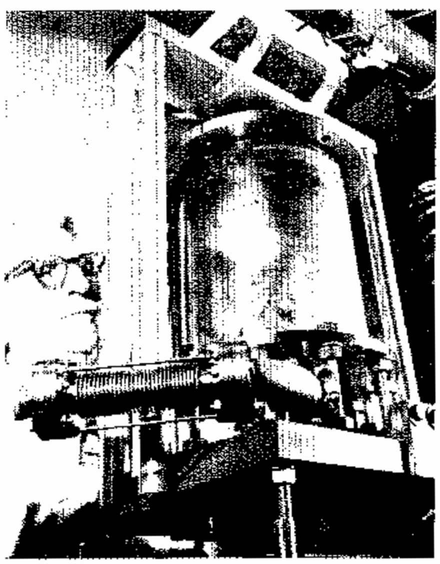


Figure 3 Dr. Rich, a physicist with General Electric Co., prepares to test a diffuse-arc, vacuum interrupter at General Electric Co.'s R&D Center, Schenectady, New York.

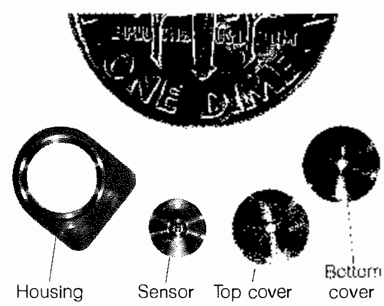


Figure 4 Components of a direct-reading, ultrasonic temperature sensor for transformer hot spot detection.

tive, therefore, must be to exploit alternative dielectrics and cooling systems. In a project jointly funded by EPRI, Niagara Mohawk Power Corp., and Empire State Electric Energy Research Corp., work is already under way at Westinghouse Electric Corp. on gas-insulated, vapor-cooled transformers in the 1–5-MVA range. This project may result in units that compare favorably with oil-filled units, while eliminating the fire hazards associated with oil. Such two-phase cooling concepts may be extended to large transformer ratings, particularly in bulk power substations.

An epoxy bushing with capacitive grading has been developed for transformers and breakers with a 240-kV, 2000-A rating (RP565). The same bushing with a simple heat pipe in its central conductor is suitable for continuous overloads up to 4000 A with no hot spots. These bushings will soon be tested on utility equipment (Figure 6).

The information available to utilities on stresses that contribute to transformer loss of life is inadequate. Work will soon begin to establish the validity of model testing for evaluation of transformer loss of life.

Gas-insulated substations

There is a definite trend toward the use of dead-tank equipment and gas-insulated substations (GISs). This is because GISs take much less space, impose no esthetic problems, present the possibility of lower overall costs (especially at higher voltages), and eliminate electric fields because the equipment is in grounded enclosures. However, utilities are still reluctant to use GISs because of their uncertain reliability and down-time (fault location and on-site repair times are excessive).

Attention is therefore being given to dead-tank, gas-insulated designs, particularly for such major equipment as breakers, arresters, and capacitor banks. Fault location, repair, and test techniques are also being investigated for GISs to reduce the time needed for on-site repair and replacement.

Finally, we are searching for gas mixtures with characteristics superior to SF_6 as insulating and interrupting media. We have already confirmed that epoxy foamed with SF_6 is an excellent material with which to form insulating spacers in GISs.

Reducing environmental effects

Although EPRI's Energy Analysis and Environment Division sponsors biological and medical studies on the effects of fields surrounding electrical equipment, it is the responsibility of the Electrical Systems Division to design equipment that will have a minimal environmental impact. The substation modeling project for predicting field strength prior to construction and the transformer noise abatement projects have been

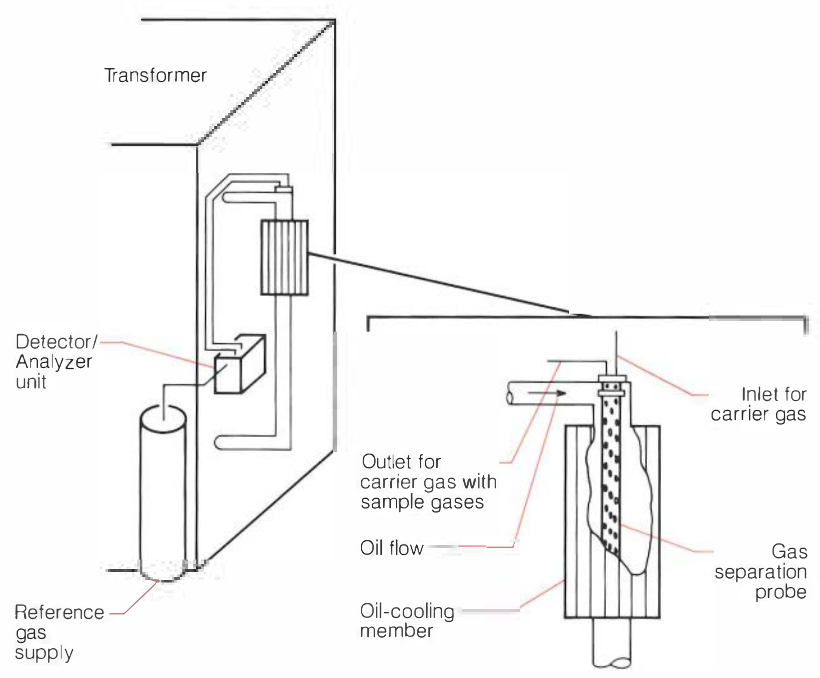


Figure 5 Schematic showing principle of operation for a gas-in-oil detection system soon to be available for testing in medium-size and large power transformers. The thermosiphon principle is used to move oil past the gas separation cell, and carrier gas is used to collect gases to be studied in the analyzer.

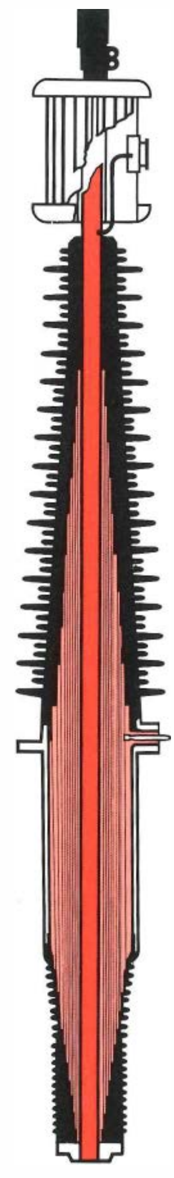


Figure 6 Cast-epoxy bushing with capacitive grading and a heat pipe for cooling. The heat pipe permits an increase in ampacity from 2000 A to 4000 A at 240 kV. The overall length of the bushing is 3.6 m (142 in) and the minimum creep is 5.5 m (217 in).

thoroughly described in previous *Journal* articles. We are presently negotiating with Consumers Power Co. to install a retrofit noise-abatement shell on one of its transformers by the end of this year.

In another area, we are commencing an investigation with I–T–E Imperial and Doble Engineering Co. to identify chemical by-products produced by corona and arcing in gas-insulated substations. As a result of this study, we should be able to furnish utilities with a comprehensive report on the necessary procedures and recommended equipment for handling by-products. In addition, we can furnish manufacturers with data that will enable them to objectively pretest new materials for gas enclosures.

Surge arresters

The new technology of applying metal oxide resistor blocks to surge arresters is producing rewarding developments. The resistor blocks are made with zinc oxide and a small amount of four or five other oxides, which are processed in a complex manner to give a high degree of nonlinearity.

When this technology is applied to power systems, it can result in gapless arresters. Present arresters have gaps in series with nonlinear resistors. These resistors, which are made of silicon carbide, are not nonlinear enough; thus, without gaps in series, the leakage current at normal voltage gets too large and burns up the resistors. With highly nonlinear resistors, gaps can be dispensed with. Without gaps, the arresters have a faster response and are therefore superior for protecting gas-insulated substations and transformers. Projects with

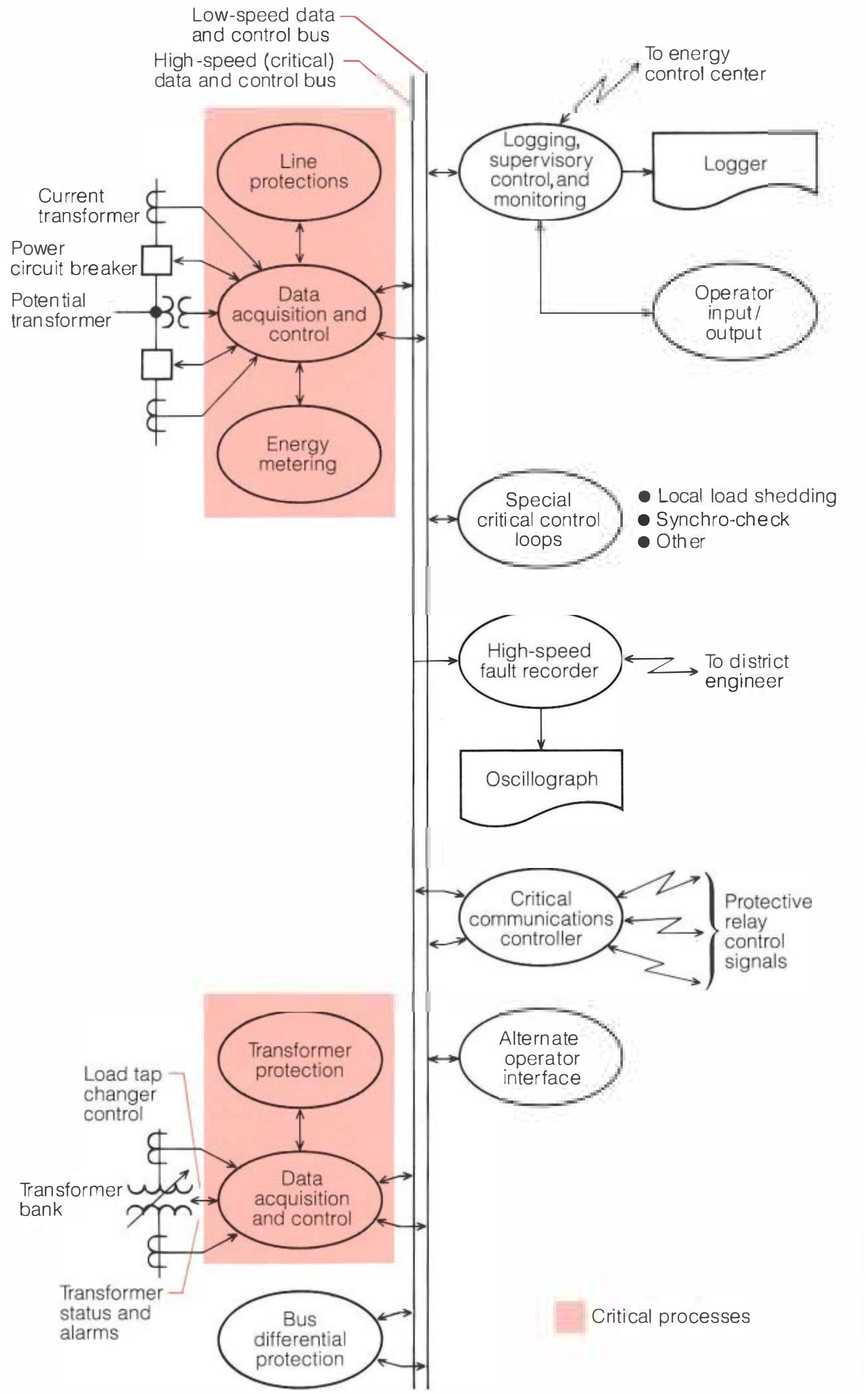


Figure 7 Prototype 500-kV electronic current transducer now installed in Bonneville Power Administration's Ostrander Substation for a one-year field trial of its digital-optical conversion and signal transmission system.

Figure 8 Substation control and protection system that features a common signal bus (center lines) to control recording, comparison, and follow-up actions (right).

McGraw-Edison Co. and Westinghouse are developing a variety of formulas to achieve higher nonlinearity and higher energy dissipation capability. General Electric has already begun to market arresters made with zinc oxide, which have equal or slightly better performance than present arresters.

Our objective is to limit the overvoltage surge on substation equipment to 1.5 per unit of normal voltage. This protective level is so low that surge overvoltage insulation requirements will no longer determine equipment size or cost. In making the blocks, researchers have come reasonably close to our goal. By next year, we hope to test 500- and 1200-kV, air-insulated arresters.

We expect to soon start development of gapless, gas-insulated 500-kV arresters and demonstrate them by early 1980. To attain high energy-dissipation capability, parallel resistor stacks and advanced cooling will also be studied. The metal oxide resistor blocks and their resistor assemblies will become available for many other applications. They are already being developed for series capacitor protection.

Control and protection systems

A commercially acceptable electronic current transducer has been developed that uses digital-optical techniques. It does not require a battery or a power supply from ground and is capable of metering and supporting relays, including high-speed relays. The digital-optical signal, free from electromagnetic interference, is transmitted all the way to the control house. A single-phase, 500-kV unit has been delivered to Bonneville Power Administration for field evaluation (Figure 7). The development of this device facilitates a direct interface with computerized protection and control schemes.

We have also developed a trailer instrumented to monitor fault transients that can gather data needed for design and evaluation of future digital relays, high-speed protection, and current limiters. Staged tests are planned for late this year on the Florida Power & Light Co. system. Analysis of data of this kind will be vital in the development stages of new digital protection concepts.

A comprehensive R&D project on advanced substation control and protection has begun (Figure 8). The study of protective relays will include line protection, bus protection, and transformer protection. The project will be directed toward developing microprocessor-based digital relays capable of interfacing with conventional current transformers and potential transformers and of accepting digital data from the substation yard. Included will be the flexibility to change algorithms and settings. The relays will be self-checking, so that the user will know immediately when a fault occurs. These protective devices could also communicate with substation microcomputer controls capable of providing sequence of events, fault recording, and operator control display. They will also be able to interface upward to the dispatcher's control and downward to the distribution system control.

Capacitors and VAR compensation

Under EPRI funding, a static-controlled reactive power supply has been designed and built and is ready to be tested. It uses thyristor technology for control of current flow through reactors. Fast response, low losses, low maintenance, and low cost make the static VAR generator preferable to rotating synchronous condensers for variable VAR supply on utility systems. The host utility, Minnesota Power & Light Co., has completed extensive system studies related to the benefits and effects of this 40-MVAR, thyristor-controlled reactor in parallel with two switched-shunt capacitor banks (RP669). The main purpose of this project is for the host utility to analyze and demonstrate the benefits of the system to other utilities.

Acceptance tests, to be completed shortly, will be followed by a detailed analysis of the usefulness of this controlled VAR generator. Subsequently, we plan to demonstrate the capabilities of light-fired thyristors by installing one in place of an electronically fired thyristor switch in one phase.

In a joint venture, I–T–E Imperial and ASEA will design, construct, and deliver a compact capacitor assembly (RP996). This project is jointly funded by EPRI and Consolidated Edison. The idea is to enclose modern, non-PCB capacitor units in racks inside a gas compartment. Such a capacitor, when designed to operate at 345- and 500-kV levels, will occupy less than 10% of the volume of an equivalent air-insulated bank. A capacitor of this type should be no more expensive than conventional units.

A three-phase compact capacitor rated 30 MVA for 138-kV systems is expected to be delivered to Consolidated Edison soon, and by early next year, a single-phase, 345-kV, 25-MVA unit will also be delivered (Figure 9).

For the immediate future, we are considering studying the use of highly nonlinear resistors to damp transient and dynamic subsynchronous oscillations. *Program Manager: Narain Hingorani*

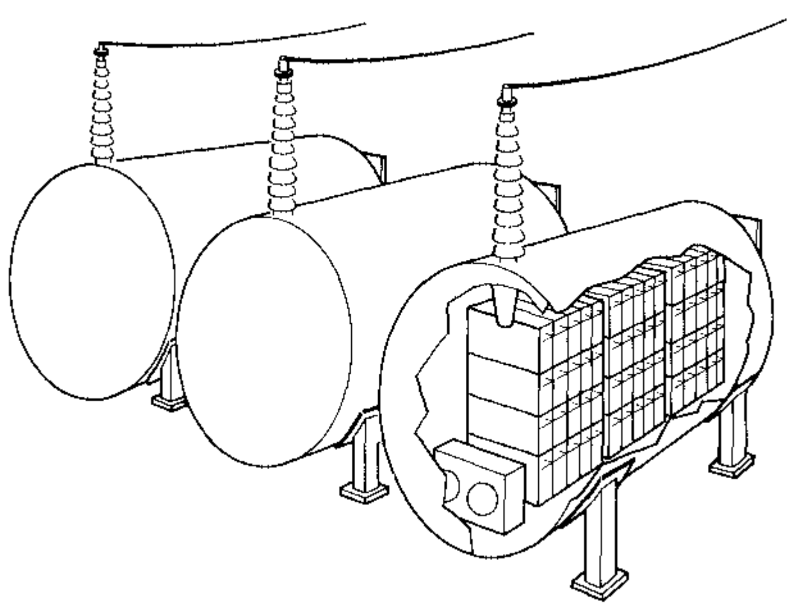


Figure 9 Gas-insulated, compact capacitor bank rated 138 kV, 30 MVA. A 345-kV bank could be expected to be one-tenth the size of its air-insulated counterpart.

UNDERGROUND TRANSMISSION

Gas-insulated cable

The three-conductor, gas-insulated cable that was developed by Westinghouse is now scheduled for field installation and demonstration on an operating utility system (RP7840).

The gas cable system—rated 345 kV, 1200 MVA—will consist of 183 m (600 ft) of three-conductor cable, two trifurcated terminations, and a number of 90° and 45° elbows and offsets, as well as both aboveground and underground modes of installation. The installation will be completely monitored for temperature, voltage (transient and steady-state), and current. Automated telemetry and data analysis systems will be incorporated.

The test program itself is expected to last approximately two years. Two contracts will be written, one with The Detroit Edison Co. and the other with Westinghouse. They will be administered as one project by EPRI. Two final reports will be issued jointly by the contractors, one covering the manufacture and installation and the other dealing with the test program itself. *Project Manager: Ralph Samm*

OVERHEAD LINES

Compact line design

Transmission line designs with reduced phase spacing were developed under RP260, and a design manual was published early this year—*Transmission Line Reference Book: 115–138-kV Compact Line Design.* Two seminars were held during March and April (one in Philadelphia and the other in Palo Alto, California), and over 50 interested utility representatives were informed about application techniques. Using this manual, utilities can confidently plan, design, and erect compact medium-voltage lines that employ existing pole line hardware.

However, the advantage of reduced phase spacing can be more fully realized only if new construction methods and materials are developed. Follow-on studies of bundled circuits should provide utilities with a novel conductor configuration in which a single-phase conductor is replaced with three closely-spaced conductors to form a complete circuit (RP260-2). Six prototype bundled-circuit configurations with bare conductors and one with covered conductors are being tested in the field. Appropriate new support insulation, phase spacers, and hardware should result. *Project Manager: Ernest Ballard*

Dc transmission

Research has been completed by the Hydro-Quebec Institute of Research on dc insulation systems and on power supply requirements for dc insulator pollution testing (RP482-1). Tests were performed to determine the required air-insulation clearances for transmission lines and station buses from ±600 kV to ±1200 kV. The tests were performed with mixed voltages (dc plus impulse) and for various ratios of the impulse to the dc component. The proximity effects of an adjacent line, pole, or bus were also investigated in the study. The results were published in a final report on insulation systems (EL-395).

During this study it was also found that the terminations of columns in a station bus-support system, or clearance between buses, had an appreciable effect on breakdown voltage. A follow-on project (RP430-2) includes an investigation of this effect to determine the behavior of a bus-supporting column arrangement under mixed voltages (e.g., dc plus impulse). Tests are being performed for 2-, 3-, and 4-m-long insulator columns supporting the bus. This research should be completed late in 1979.

Companion research work was done to determine the required capacity (stiffness) of a dc power supply used for flashover tests of contaminated insulators (RP430-1). It was found that the flashover voltage of contaminated insulators depends on the dynamic voltage drop, the smoothing capacitance, and the resistance on the ac and dc sides of the rectifier. It was further concluded that the most economic rectifier for insulator pollution testing is a half-wave cascade rectifier with a high-speed control circuit (EL-397).

In accordance with the conclusions of RP430-1, one of the aims of RP430-2 is to determine the required circuit elements of a cascade rectifier and to develop a high-speed control circuit to compensate for the rectifier voltage drop. *Project Manager: Ernest Ballard*

DISTRIBUTION

Treating in-service wood poles

Oregon State University is the contractor for a project on the use of volatile chemicals to control biological deterioration in wood poles (RP212). These efforts, which were started before the establishment of EPRI, are now cofunded by EPRI, Pacific Power & Light Co., and the contractor. Specific objectives are to:

- Develop methods for predicting the need for supplemental treatment of wood poles in service
- Develop effective formulas and methods of application of fumigants
- Determine the fate and residual fungitoxicity of selected fumigants and their decomposition products in wood
- Determine the role of microorganisms in the reinfestation of fumigant-treated wood poles and the influence of nondecay organisms on the reestablishment of decay fungi

Of critical concern in this project is the development of reliable methods for determining both the degree of fumigant penetration and the effective retention period. Thus, research has been initiated to evaluate several methods for detecting the concentrations of fumigants in poles: biological methods, a gas-sampling device, and an electrical resistance device.

Field evaluation of fumigant effectiveness and retention has now reached the eighth year, with chloropicrin, Vorlex, and Vapam controlling decay fungi in Douglas fir poles for that period. The continued presence of chloropicrin and Vorlex vapors in the wood up to 2.4 m above the groundline indicates that with these chemicals, no re-treating will be needed for at least 10 years. No Vapam vapors were detected, but no fungi reinfestation was present either. A four-year test showed that smaller amounts of Vorlex (0.25 liter) and chloropicrin (0.13 liter) were as effective as 0.5 liter of Vapam.

Allylalcohol, a relatively low-cost chemical found to be highly effective for controlling decay fungi in wood blocks, was selected as an additional chemical to be tested in decaying wood poles.

Five methods for detecting internal decay were evaluated by comparison with the examination and culturing of increment borer cores.

An Interim Report (EL-366) covering the first three years of this contract was completed in early 1977 and is available on request. *Project Manager: Robert Tackaberry*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

FOREIGN ENERGY SUPPLY

World energy supply will continue to have a substantial influence, directly or indirectly, on the U.S. economy and on U.S. energy supply for the foreseeable future. At present we depend on other nations for about 50% of our petroleum liquids supply and 5% of our natural gas supply. Without energy imports, the U.S. economy would be in dire straits. However, the cost of these imports adds to the balance of payments problem and helps undermine the value of the dollar.

This dependence has triggered various reactions. For example, the federal government and many state agencies are pressing hard for energy conservation. There is government interest in increasing domestic supply, but as yet there is no clear resolution of the factors constraining supply increases. Electric utilities are being pressured to phase out their use of oil and natural gas. Research, development, demonstration, and commercialization efforts on new technologies for producing oil substitutes are receiving increased attention.

However, even under optimistic conservation and domestic supply scenarios, energy imports a decade from now are likely to be at or above today's levels. Moreover, there are strong indications that world oil prices and (in the more distant future) world natural gas prices will set the level of domestic oil and gas prices. Domestic coal and uranium prices, while not directly tied to world oil prices, are related to them through economic mechanisms.

A particularly important fact from EPRI's standpoint is that world energy prices will tend to set the level of permissible costs of output from new technologies being developed for use by the electric utility industry. Similarly, world energy prices will affect the prices of other forms of energy that compete with electricity. Although it is unlikely that the OPEC cartel will dissolve and that world oil prices will shift to cost-based prices, the impact of such a price break on federal energy R&D budgets would be disruptive.

Thus there is a strong incentive for EPRI's Supply Program to analyze foreign energy supply. Two relatively small but significant studies of foreign supply have been completed. One examines the prospects for foreign uranium output; this is now of particular significance to utilities because prohibitions on domestic use of foreign uranium are being phased out. The other study deals with free-world oil in a context of world energy demand and supply. Both studies focus on the period to 1990, with some analysis extending beyond this date.

In a study of foreign uranium supply (EA-725), known uranium resources are analyzed, using data on geologic setting, production plans, and possible mining, environmental, and political obstacles to production and export. The study focuses on uranium supply in Australia, Canada, southern Africa, France, and French-speaking Africa. To date, these countries have done 100% of the foreign contracting with U.S. utilities and represent over 90% of the potential for future foreign purchases by U.S. utilities. Other free-world producers are considered in less detail.

Maximum production capability for these countries is projected through 1990 on the basis of reasonably assured resources. The undeveloped component of these resources is assumed to be translated into production capability according to current plans and prospects, limited only by engineering and geologic difficulties. These maximum capabilities are then reduced to more realistic figures by taking ore grades and the possibility of construction delays into account. In some countries and for some mines, the obstacles to bringing on new production capability will prove greater than discussed and in other nations, less. Consequently, the percentage uncertainty in the total capability should be less than in the capabilities of individual countries. The 1990 figures are conservative because the discovery and development of new resources is not considered.

Under RP883, NUS Corp. estimated foreign free-world uranium capability (Table 1). For comparison, the NUS estimates of U.S. production capability and foreign and U.S. uranium demand are shown in Table 2, although these were not the subject of the study. Foreign demand is based on a projection of 850 GW installed capacity by the year 2000. U.S. demand is based on a projection of 380 GW installed capacity by 2000.

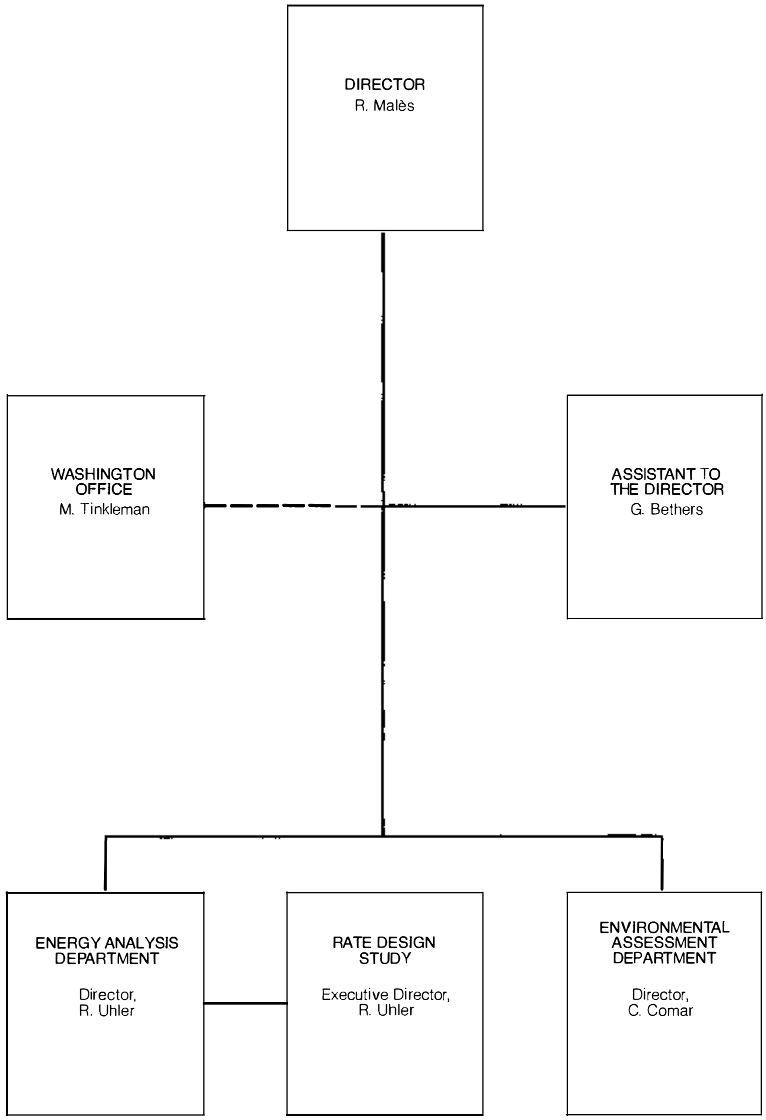
The extent to which production capability and demand will be in balance depends on the extent to which utilities and others decide to hold inventories in advance of actual demand. Assuming that (on the average) two years of inventory is held, supply and demand come into balance by 1980–81. If no inventories beyond minimum working inventories are held, foreign production capability will exceed demand until 1985. For the United States, the balance will be reached in 1982, and for the combined (foreign and U.S.) supply, the balance will occur in 1985. The projections show production capability well below demand in 1990 in both the United States and the rest of the free world. This situation may be remedied in part by discovering and bringing into production new uranium resources, or the demand may be reduced if the number of nuclear plants actually needed is smaller than now projected.

In the study on world oil supply and demand (EA-745), energy demand in the free world is projected for three energy demand growth scenarios. The various growth rates to 1990 (i.e., 4.1%, 3.7%, and 3.3%) represent different combinations of assumptions about economic growth and energy-GNP ratios. The demand growth rates are deliberately set on the high side of expectations to test the capability of the supply system.

From these growth rates, estimates of energy consumption in 1980, 1985, and 1990 are derived. After expected energy

ELECTRIC POWER RESEARCH INSTITUTE

Energy Analysis and Environment Division



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Systems
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Biomedical Studies
L. Sagan
Program Manager

Ecological Effects
R. Goldstein
Program Manager (acting)

Health Effects
J. McCarroll
Program Manager

Physical Factors
R. Perhac
Program Manager

Table 1
FREE-WORLD U_3O_8 PRODUCTION CAPABILITY (U.S. EXCLUDED)
(10^3 t)

	1977	1978	1979	1980	1981	1982	1985	1990
Australia	0.7	1.0	1.0	1.2	1.6	3.7	13	24
Canada	7.2	8.4	8.9	9.4	10.6	11.5	12	11
Southern Africa*	6.5	9.0	9.9	10.4	11.4	11.8	13	11
Other	5.7	7.9	9.1	11.5	12.6	12.3	12	11

*Southern Africa comprises the Republic of South Africa and South-West Africa (Namibia).

Table 2
COMPARISON OF PROJECTED FREE-WORLD U_3O_8 DEMAND AND PRODUCTION CAPABILITY
(10^3 t)

	1977	1978	1979	1980	1981	1982	1985	1990
oreign Free-World								
Production capability	20	26	29	33	36	39	50	57
Demand								
Case A	14	17	20	24	27	32	49	86
Case B	20	24	27	32	37	43	61	108
nited States								
Production capability	16	20	23	23	24	23	27	35
Demand								
Case A	11	12	15	17	19	23	29	43
Case B	15	17	19	23	25	27	34	51
otal Free-World								
Production capability	36	46	52	56	60	61	77	92
Demand								
Case A	25	29	35	41	46	55	78	129
Case B	35	41	46	55	62	70	95	159

ote: Demand Case A assumes 0.2% enrichment tail assays and minimum working inventories held by utilities and others.
emand Case B assumes 0.2% enrichment tail assays and two additional years' inventory held to allow for supply uncertainties

Table 3
FREE-WORLD DEMAND FOR OIL

Demand Growth Case	Demand (10^6 bbl/d) 1976	1980	1985	1990	1976–1990 Annual Demand Growth Rate (%)
High	47.6	55.6	66.0	80.6	3.8
Medium	47.6	54.2	61.6	72.0	3.0
Low	47.6	52.7	57.4	64.2	2.2

Table 4
FREE-WORLD DEMAND FOR OPEC OIL

Demand Growth Case	Demand (10^6 bbl/d) 1976*	1980	1985	1990	1976–1990 Annual Demand Growth Rate (%)
High	30.1	33.6	41.1	51.7	3.9
Medium	30.1	32.2	36.6	43.1	2.6
Low	30.1	30.7	32.8	35.8	1.2

*Preliminary.

production from sources other than oil is subtracted, three cases for estimated oil requirements can be estimated (Table 3). The free-world oil demand shown in Table 3 is reduced by subtracting non-OPEC oil production in order to yield estimates for OPEC production (Table 4). The crucial questions are: Will OPEC be able to produce these amounts? Will OPEC want to produce them? What price will OPEC set?

The contractors for this project, John Lichtblau of Petroleum Industry Research Foundation, Inc., and Helmut Frank of the University of Arizona, conclude that from a resource-base point of view, even the high case is achievable. From a technical point of view and because of OPEC conservation policies, the high case for 1990 is unlikely to be attained. The medium-growth case can be achieved in 1990 if the Saudi Arabian government is willing to permit a modest but steady expansion in production capacity and output throughout the 1980s.

In the low-growth case, considered by the contractors to be slightly more probable than the medium-growth case, the FOB price of OPEC reference crude (i.e., Saudi Arabian light) would remain near its present price of $12.70/bbl in real terms through 1990. In the medium-growth case, real prices are likely to remain fairly constant until 1983 or 1984 and then rise from $12.70 to $15–$17/bbl by 1990. In the high-demand case, a real price of $16–$18/bbl is likely by 1985 and $21–$23 by 1990. The report cautions that these figures are very speculative and should be viewed more as trend indicators than exact price levels. *Program Manager: Milton F. Searl; Project Manager: Thomas E. Browne*

REDUCTION OF LARVAL FISH ENTRAINMENT LOSSES

Section 316-b of the Federal Water Pollution Control Act states, "Any standard established . . . applicable to a point source shall require that the location, design, construction, and capacity of cooling-water intake structures reflect the best technology available for minimizing adverse environmental impact." This section was included in the control act because of concern about the potential ecological impact resulting from fish eggs and larvae passing through the intake screens of thermal power plants and being carried through the condensers, where the eggs and larvae can be subjected to thermal, chemical, mechanical, and pressure stresses. The process by which aquatic organisms pass through the power plant is called entrainment.

A new component of the Environmental Assessment Department's overall effort on thermal power plant cooling system effects (*EPRI Journal*, October 1977) is the development of intakes and cooling systems that reduce entrainment losses to fish populations. The design of such devices and the testing of their biological effectiveness require a combination of engineering and biological expertise. Hence the Environmental Assessment Department works with the Water Quality Control and Heat Rejection Program (Fossil Fuel and Advanced Systems Division) in this area.

There are several research approaches to reducing entrainment losses. One is to reduce the number of organisms entering the cooling system by the application of various diversion and screening devices. A second is to reduce the mortality rate among those organisms passing through the cooling system by minimizing the stress to which they are subjected.

At present, EPRI is initiating two projects on reduction of entrainment losses. One is to be undertaken by New England Power Service Co. and takes the first research approach mentioned above (RP1181). Its objective is to evaluate the feasibility of using the porous dike intake concept to reduce entrainment (Figure 1). Dike filler material of suitably sized rock is being sought so as to provide relatively free flow of water with low potential of flow reduction due to biofouling. In addition, it is hoped that the dike will create a flow field that allows fish larvae to avoid being entrained. Field experiments will be conducted at a test facility constructed in the existing outside wall of the discharge canal at New England Power Co.'s Brayton Point electric generating station in Somerset, Massachusetts. The station is located on Mount Hope Bay, an arm of Narragansett Bay. The field experiments will measure how well porous dikes with fillers of various rock sizes will exclude zooplankton, fish larvae, and post-larval to adult fish and will quantify the susceptibility of these porous dikes to biofouling. Larval behavior and avoidance will also be studied in laboratory flumes. This project is being jointly managed by the Water Quality Control and Heat Rejection Program and the Environmental Assessment Department.

The second project is to be undertaken by Oak Ridge National Laboratory and takes

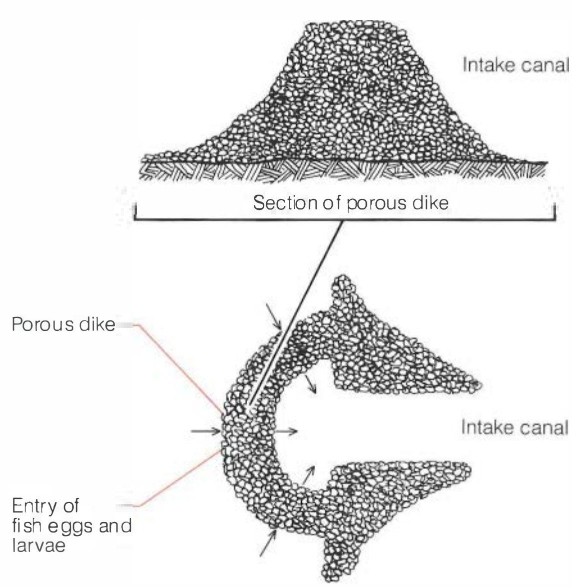


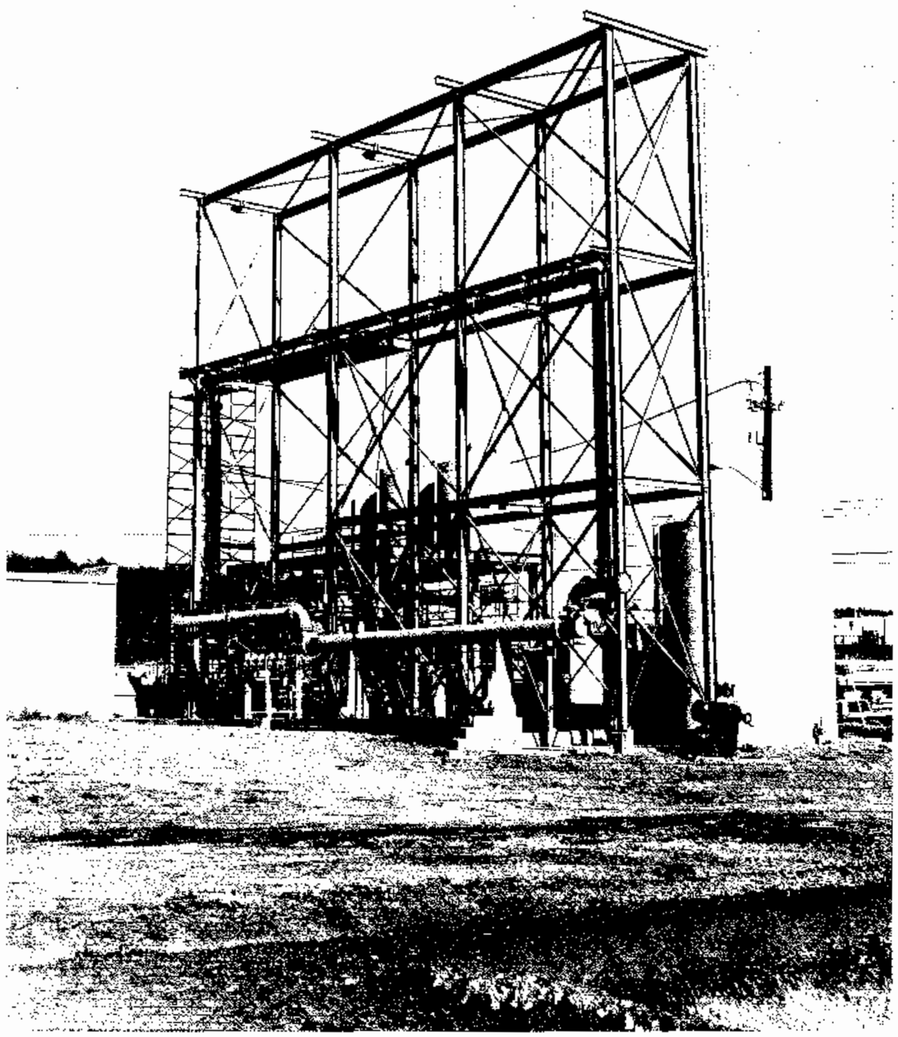
Figure 1 Porous dike designed to prevent fish larvae from entering the cooling-water intake at a steam electric generating station. The effectiveness of such a facility is being studied by New England Power Service Co.

the second research approach previously described (RP1183). The overall objective of the Oak Ridge effort is to define biological and engineering parameters that can damage entrained organisms and to define the effects of this damage on organism survival in order to determine the feasibility of reducing entrainment losses through redesign of cooling systems. The project will focus on stresses associated with pumps, temperature, and vacuum conditions. Experiments will be conducted with a cooling-system simulator (Figures 2 and 3). The apparatus, which is a closed loop, is constructed so that organisms can be introduced into the system on either side of the pump, allowing evaluation of stresses associated solely with the pump. The adjustable elevation of the return piping allows control of the vacuum to which larval fish are exposed. Experimental species include gizzard shad, threadfin shad, channel catfish, cyprinids, white sucker, bluegill, yellow perch, freshwater drum, and striped bass for freshwater experiments; and menhaden, spot, anchovy, and naked goby for saltwater experiments. This work is also being supported by EPA and DOE. Within EPRI, the project is managed by the Water Quality Control and Heat Rejection Program in consultation with the Environmental Assessment Department.

To evaluate the research status of various design concepts for prevention of larval fish entrainment, EPRI, Southern California Edison Co., and Argonne National Laboratory cosponsored a larval exclusion system workshop on February 7 and 8 in San Diego. The workshop was attended by approximately 80 biologists and engineers representing electric power companies, government, consulting firms, and manufacturers. Some of the concepts covered were artificial filter beds, wells, porous dikes, fine-mesh screens, perforated pipes, single entrance–double exit screens, and woven slot screens.

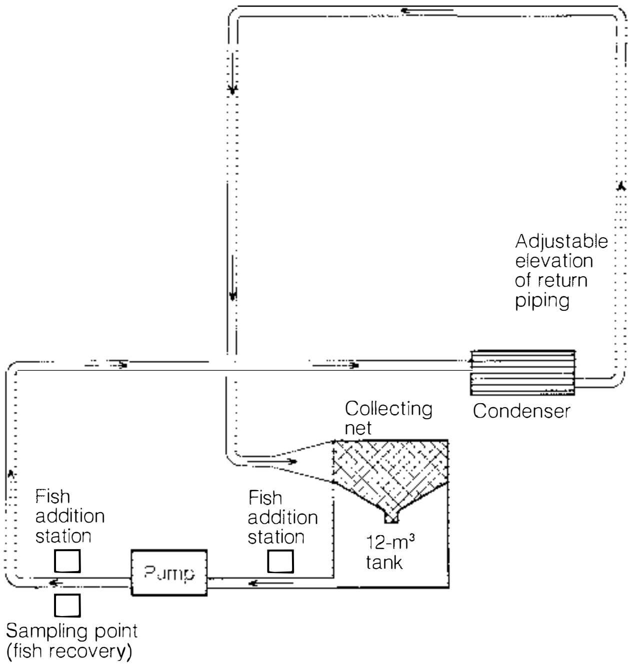
It was clear at the workshop that substantial progress is being made in understanding larval behavior and avoidance. Several years ago, it was usually assumed that fish larvae were completely planktonic—that is, that they exerted no control over their positions in the water body. However, recent experiments indicate that fish larvae are capable of swimming and actively avoiding certain objects. Films demonstrating this were shown at the workshop.

Figure 2 This power plant cooling-system simulator designed by Oak Ridge National Laboratory will be used in a study to define biological and engineering parameters that cause damage to entrained organisms. *Courtesy Oak Ridge National Laboratory*



A report on the workshop's proceedings is being prepared for publication. The report will specify the most promising domain of applicability (e.g., coast, estuary, lake, river; once-through cooling system, off-stream cooling system) for each larval exclusion concept and will review the status of current research on the engineering and biological effectiveness of each concept. This information will be used to guide EPRI's future research plans on the reduction of larval entrainment losses. *Project Manager: Robert A. Goldstein*

Figure 3 Schematic of the Oak Ridge National Laboratory power plant cooling-system simulator. Heat load is applied to the 12-m³ (4000-gal) tank. The mixed-flow impeller pump is similar in hydraulics to power plant pumps.



New Technical Reports

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

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

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ENERGY ANALYSIS AND ENVIRONMENT

An Appraisal of Energy Analysis

EA-504 Final Report (RP760-1)

Energy analysis can be a useful complement to economic analysis in technological assessment and public policy decision making. This report by Criterion Analysis, Inc., presents a review and evaluation of the literature on methods and applications of energy analysis. *EPRI Project Manager: Rex Riley*

A Survey of Econometric Models of the Supply and Cost Structure of Electricity

EA-517-SR Special Report

This special report reviews studies on economic aspects of the electric power industry, including a general description of the industry, a discussion of the concept of aggregation, and summaries of studies on generation, transmission, and distribution. In addition, the report discusses the economic theory of production technology (including derived demands, technical change, and duality) and the economic characteristics of the process technologies of generation, transmission, and distribution. Finally, industry supply models and informal price models are reviewed and critiqued. *EPRI Project Manager: Rex Riley*

Energy and the Economy

EA-620 Final Report, Vol. 1 (RP875)

EPRI set up the Energy Modeling Forum to improve the usefulness of energy models. This report compares six models of energy and the economy. The comparison illuminates the structures of the models and identifies the importance of a few key elements in determining the nature of the feedback from the energy sector to the remainder of the economy: the value share of energy, the potential for substituting capital and labor for energy, and the interaction between energy availability and capital formation. The strengths and weaknesses of the models as applied to the study of energy and the economy are discussed, with emphasis on contribution to improved communication between decision makers and energy modelers. *EPRI Project Manager: Stephen Peck*

Demand 77: The EPRI Annual Energy Forecasts and Consumption Model

EA-621-SR Special Report, Vol. 1

EPRI's forecasts of end-use consumption of electricity, petroleum, natural gas, and coal for the years 1980–2000 are based on an econometric model whose equations represent the energy consumption of each form of energy in each end-use sector. The forecasts are updated and modified annually by the staff of EPRI's Demand and Conservation Program. *EPRI Project Managers: Larry Williams, James Boyd, and Robert Crow*

FOSSIL FUEL AND ADVANCED SYSTEMS

Technical Assessment of NO_x Removal Processes for Utility Application

AF-568 Final Report (RP783-1)

The Tennessee Valley Authority conducted a state-of-the-art review of 48 processes being developed for the removal of nitrogen oxides (NO_x) from power plant stack gas, including dry NO_x processes, dry simultaneous NO_x-SO_x processes, wet NO_x processes, and wet simultaneous NO_x-SO_x processes. Eight of these processes were recommended as candidates for preliminary economic analysis in the next phase of the study. *EPRI Project Managers: Donald Teixeira and Navin Shah*

Influence of Dispersed Refractory Oxides in Retarding Catalyst Sintering

EM-624 Interim Report (RP371-1)

The molten carbonate fuel cell anode consists of a high-surface-area, porous nickel powder compact. This anode is subject to loss of surface area (and therefore to loss of catalytic activity) through a process known as sintering. Refractory oxides dispersed on the surface of the nickel provide a means for retarding the rate of nickel sintering.

In this project, which was initiated with Northwestern University in 1974, studies were made of sintering on idealized sinusoidal surfaces that simulate the geometry of porous compacts, and the results were compared with those obtained on actual porous compact surfaces. *EPRI Project Manager: Arnold Fickett*

Catalyst Sintering Studies

EM-661 Interim Report (RP583-1)

Phosphoric acid fuel cells use platinum catalysts dispersed as small crystallites on carbon supports. These crystallites are metastable and, because of surface free-energy considerations, tend to grow to a larger size (sinter) with a lower surface area. Exxon Research and Engineering Co. studied methods of retarding the loss of catalyst surface area and the resultant loss of catalytic activity in phosphoric acid fuel cells. The factors controlling surface energy were manipulated to improve platinum crystallite stability. These factors included the catalyst preparation method, nature of support substrates, addition of adsorbed cations, and addition of potentially stabilizing components. *EPRI Project Manager: Edward Gillis*

Liquids From CO and H_2 for Energy Storage

AF-689 Final Report (RP541)

The University of Connecticut investigated the Fischer-Tropsch synthesis for producing liquids from CO-H_2 mixtures manufactured by coal gasification. The objective was to develop a model for a large-scale reactor based on this technology.

A thorough literature review was used to define the most promising commercial catalysts for experimental evaluation. These experiments showed that promoted, nitrided fused-iron ammonia synthesis catalysts showed good activity and stability, while cobalt-silica catalysts showed the highest activity. *EPRI Project Manager: Howard Lebowitz*

Assessment of Fuels for Power Generation by Electric Utility Fuel Cells

EM-695 Final Report, Vols. 1 and 2 (RP1042)

An assessment was made by Arthur D. Little, Inc., of the technical and economic feasibility of alternative fuel options for dispersed and baseload utility-scale fuel cell power plants. The study covers coal-derived and petroleum-derived fuels and assesses near-term and advanced fuel conversion and fuel cell technologies.

A forecast of international crude oil prices for the period 1980–2000 was developed. Projections of product demand slates and domestic refining capacity were used along with landed crude prices to determine prices for various petroleum products under regulated and world parity crude price scenarios. *EPRI Project Manager: Edward Gillis*

Characterization of Fly Ash and Related Metal Oxides by Using Auger Electron Spectroscopy

FP-708 Final Report (RP631-3)

It has long been recognized that the behavior of fly ash in electrostatic precipitators is strongly influenced by the surface properties of the ash. Unfortunately, conventional methods of ash analysis (e.g., wet chemical method, neutron activation, atomic absorption spectroscopy) measure bulk rather than surface composition.

The major objective of this project by Stanford University was to complete a study of fly ash and its basic metallic constituents, with emphasis placed on a determination of surface properties. Auger electron spectroscopy (AES) with high spatial resolution ($\sim 3\ \mu m$), which was the primary technique employed, enabled the analysis of the outermost atomic layers of individual fly ash microparticles. By the simultaneous use of AES and ion-sputtering, the variation of chemical composition with depth into the ash was obtained. Ash topography was analyzed by scanning electron microscopy, and surface composition analysis by X-ray photoemission spectroscopy, and secondary ion mass spectrometry was also performed.

A significant result of this study is that sulfur appears to be highly concentrated—probably as a sulfate—in the surface region (the outermost 0.01–0.03 μm; 100–300 A) of the coal fly ash samples studied. Such elemental surface predominance suggests that the behavior of coal fly ash in particulate hardware, as well as its impact on health and the environment, may be different from that predicted by conventional bulk analysis.

In addition to communicating specific results, the present report is intended to serve as a guideline for the characterization of fly ash by Auger spectroscopy and to inform the general reader about the Auger technique and related modern surface spectroscopies. *EPRI Project Manager: Owen Tassicker*

Emission Characteristics of Paraho Shale Oil As Tested in a Utility Boiler

AF-709 Final Report (RP779-11)

Combustion tests of crude Paraho shale oil (0.7% sulfur and 2% nitrogen) were conducted in a 45-MW Combustion Engineering, Inc., boiler at Southern California Edison Co.'s Highgrove Generating Station. Shale oil was blended in various proportions with low-sulfur oil before its combustion in the boiler so that the sulfur content of the fuel blend did not exceed 0.5%. Emission of air contaminants was determined for (1) oil blends burned in all burners (tank blending), and (2) oil blends burned in the lower boiler elevation only, with low-nitrogen fuels burned in the upper elevations. The segregation of the high- and low-nitrogen fuels into two independent fuel systems was originated by Southern California Edison and termed dual fuel combustion. *EPRI Project Manager: Ronald Wolk*

Economic Screening Evaluation of Upgrading Coal Liquids to Turbine Fuels

AF-710 Final Report (TPS76-666)

The objective of this study by Mobil Research and Development Corp. was to estimate the cost of upgrading coal liquids to turbine fuels. Processing requirements were based on experimental fixed-bed hydroprocessing data developed by Mobil. Costs were estimated for a hydrotreater (including waste water treater and sulfur plant) using both utility and equity methods of financing. The economic bases were supplied by EPRI so that results would be consistent with other EPRI coal liquefaction plant evaluations.

The costs of upgrading the five coal liquids from the H-Coal and solvent-refined coal (SRC) processes varied from \$0.34 to \$2.59/10^6 Btu of liquid fuel product with utility financing (1976 dollars, 0%/yr inflation) and \$0.36 to \$2.87/10^6 Btu with equity financing (1980 dollars, 5%/yr inflation). Cost depends on the quality of the raw coal liquid and the severity of the hydroprocessing necessary to achieve a given product quality. Approximately one-half of the processing cost is for hydrogen input; the other half is about equally divided between capital recovery and operating costs. Estimates for capital investment ranged from \$39 million to \$273 million for utility financing (1976 dollars) and from \$45 million to \$308 million for equity financing (1980 dollars). *EPRI Project Manager: Stanley Vejtasa*

Phoenix House: Solar-Assisted Heat Pump System Evaluation

ER-712 Final Report (RP924-1)

Kaman Sciences Corp. made a study of how a utility's costs of supplying energy to its customers are influenced by the configuration of the solar heating and cooling components used in their homes. Of several configurations studied over a 7-yr planning period, a solar-assisted heat pump system resulted in the lowest per-unit cost of energy supplied (over a range of market penetration levels). Structure and storage tank heat losses are also discussed in the report. *EPRI Project Manager: James Beck*

Evaluation of Three 20-MW Prototype Flue Gas Desulfurization Processes

FP-713-SY Final Report,
FP-713, Vols. 1, 2, and 3 (RP536-1)

The two 40-MW Babcock & Wilcox Co. pulverized-coal-fired boilers at the Scholz Electric Generating Station of Gulf Power Co. were retrofitted with three 20-MW prototype flue gas desulfurization processes. This report by Southern Company Services, Inc., summarizes the performance of these processes during an evaluation program that was conducted in 1975 and 1976. *EPRI Project Manager: Stuart Dalton*

Preliminary Evaluation of Potential NO_x Control Strategies for the Electric Power Industry

FP-715 Final Report, Vols. 1 and 2 (RP836)

Flow Resources Corp. conducted an investigation of strategies for the control of nitrogen oxides emitted by fossil-fired power plants. The study focused on meeting the current annual NO_2 primary national ambient air quality standard (100 $\mu g/m^3$) through the year 2000. It included four sets of nuclear/coal growth scenarios and three sets of assumed emission restrictions and centered on 20 critical air quality control regions (AQCRs), chosen for their potential for being in NO_2 noncompliance during the study. Reviews were conducted of federal and state NO_x regulations and of photochemical diffusion modeling (the latter done under subcontract by Systems Applications, Inc.).

The principal conclusion of this study was that in most critical AQCRs, reduction of coal-fired power plant NO_x emissions below 0.3 lb/10^6 Btu appears to offer little leverage for further substantial reduction of annual ambient concentrations of NO_2. This result, however, varies among AQCRs and may necessitate a more detailed evaluation of control strategies. *EPRI Project Manager: Stephen Baruch*

Dual Energy Use Systems Workshop

EM-718-SR Special Report

Results of EPRI's Dual Energy Use Systems (DEUS) Workshop held September 19–23, 1977, in Yarmouth, Maine, are presented in this short report. Electric utility industry representatives, industrial and other consumer experts, government representatives, academicians, and equipment manufacturers met to discuss and evaluate the various options for using thermal and electric energy produced from a common source.

Work sessions based on formal presentations and group discussions resulted in a list of 32 research, development, and demonstration projects of potential interest to state and federal program managers as well as to utility personnel. The complete proceedings, which should be useful to utilities in the process of developing programs related to DEUS, is available free of charge (EM-718-W). *EPRI Project Managers: Deborah Dougherty and Quentin Looney*

NUCLEAR POWER

Transient Deformation Properties of Zircaloy for LOCA Simulation

NP-526 Final Report, Vols. 2 and 3 (RP251-1)

Battelle, Pacific Northwest Laboratories determined the creep/creep rupture anisotropic properties of Zircaloy and used analytic techniques to compare these properties with ramp-pressure and ramp-temperature test results. Biaxial and uniaxial testing modes were used to evaluate the anisotropic deformation behavior. The combination of test results and predictive analysis techniques will make it possible to predict the transient deformation of reactor fuel cladding during simulated LOCA conditions. *EPRI Program Manager: Adrian Roberts*

Development of Adaptive Learning Networks for Pipe Inspection

NP-688 Final Report (RP770)

Unambiguous discrimination between cracks and geometric reflectors has been achieved in sample welded sections of type-304 stainless steel pipes, using nonlinear signal processing of ultrasonic pulse echoes via the adaptive learning network (ALN) methodology.

To follow closely actual procedures for preservice and in-service inspection of BWR piping, this study by Adaptronics, Inc., was directed to (1) record pulse-echo data around the pipe circumference (using a transducer-scanning apparatus) and automatically locate suspicious regions via an ALN preliminary classifier; (2) collect an ensemble of pulse-echo data by moving the transducer over small angular increments at each suspicious location; and (3) automatically classify the ensemble pulse-echo data into crack or nondefect (i.e., geometric reflector) classes via an ALN crack classifier.

Results of the study demonstrated the practical possibilities of an NDE processor that can perform in-service inspection in a nuclear environment more accurately, reliably, quickly, and safely than human operators. *EPRI Project Manager: Gary Dau*

CAT: A Computer Code for the Automated Construction of Fault Trees

NP-705 Interim Report (RP297-1)

System reliability analysis has become widely recognized as an integral part of design safety evaluation for nuclear power plants. Analysis of fault trees and event trees to quantify reliability of systems and subsystems has been extensively applied by both the industry and regulatory agencies. The analysis generally involves the construction and evaluation of system logic models, which describe various interconnections between components and their operation requirements.

Several computer codes have been developed for the numeric evaluation of a given logic model. Model construction has remained a manual task, which usually consumes most of the time spent in a probabilistic system analysis. The University of California at Los Angeles has developed CAT, an automated algorithm for constructing the logic models of fault trees. This algorithm could probably speed up reliability analysis. Several other concepts have been examined for computerized fault tree construction; it appears that the CAT code approach could provide an improved modeling capability to nuclear systems and subsystems. *EPRI Project Manager: Boyer Chu*

EPRI–NASA Cooperative Project on Stress Corrosion Cracking of Zircaloys

NP-717 Final Report (RP455)

A 30-month program of research was undertaken by SRI International and NASA, Ames Research Center to improve understanding of the stress corrosion cracking (SCC) mechanism considered responsible for pellet-cladding interaction (PCI) nuclear fuel failures. PCI failures originate at the fuel side of the Zircaloy cladding, and therefore the major objective was to define the SCC mechanism of Zircaloy in environments similar to those at the inside surface of operating fuel cladding. *EPRI Project Managers: Adrian Roberts and Howard Ocken*

Feasibility of Using Adaptive Learning Networks for Eddy-Current Signal Analysis

NP-723 Final Report (TPS77-723)

In a feasibility study by Adaptronics, Inc., eddy-current signal responses were generated, recorded, and digitized from several simulated pits and cracks in samples of nuclear reactor steam generator tubing. Using adaptive learning network (ALN) flaw classification and ALN flaw-size models, unambiguous discrimination and accurate sizing of simulated pits and cracks were obtained for both single- and multiple-frequency eddy-current data. The error rates for sizing flaws were 2.4% for pits and 3.6% for cracks. *EPRI Project Manager: Gary Dau*

Power Plant Data Systems

NP-736 Final Report (RP826)

As the cost of electric power rises and reserve margins dwindle, pressure is put on the industry to make generating units more productive. Historical data are needed to aid in the improvement of deficient units and the design of new ones. Holmes & Narver, Inc., undertook this study to determine the kind of data needed and the way in which information can best be provided.

The existing data-gathering activities of the power industry and government agencies are described. Two plans are presented for acquiring a single, nationwide generating unit data system that would satisfy both the needs of the power industry and the requirements of government agencies. *EPRI Project Manager: William Lavallee*

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