Nuclear Safety After TMI

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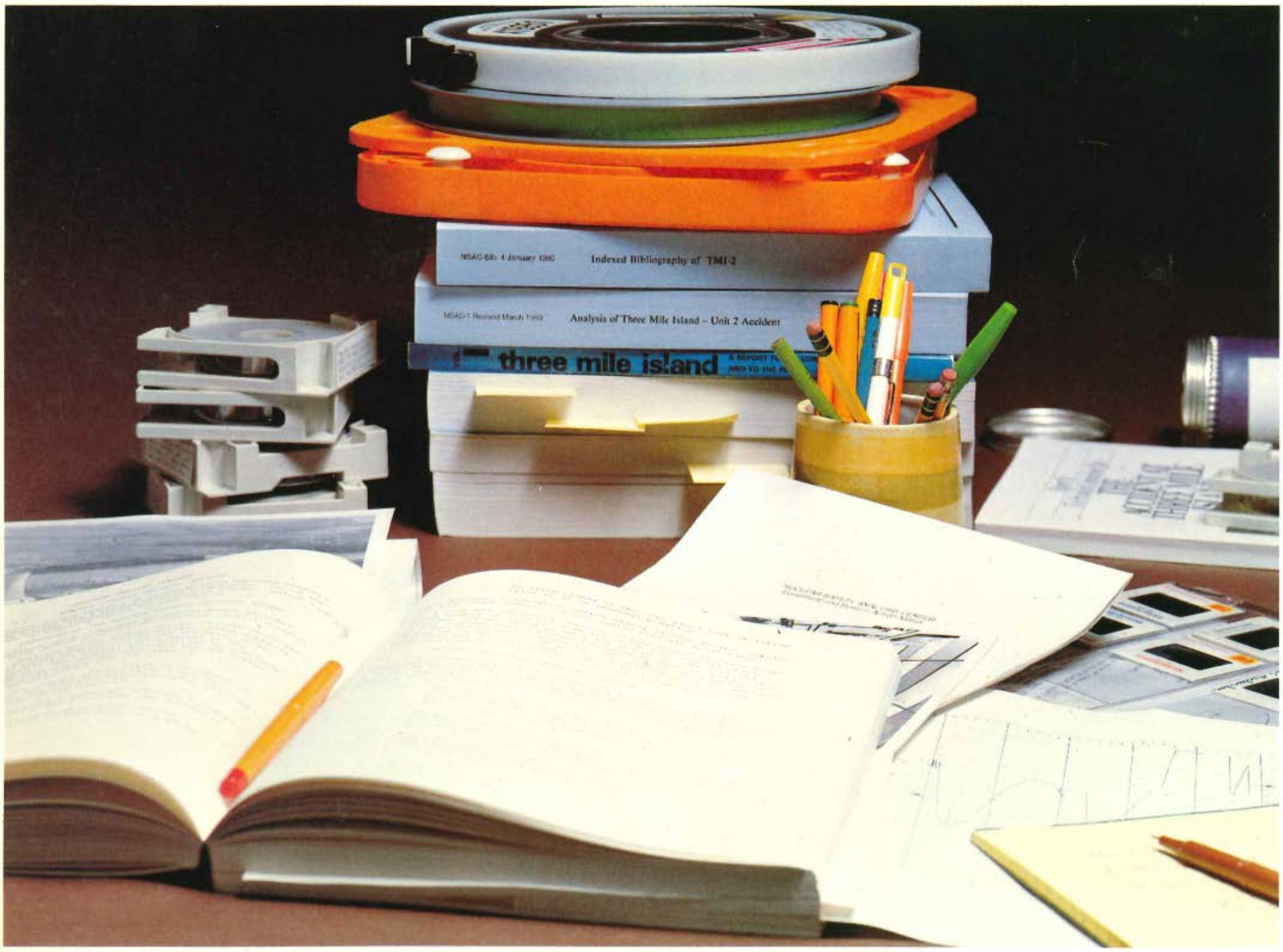

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Cover: Reports represent the outcome of
15 months of intensive effort by industry and
government to analyze and learn from the
accident at Three Mile Island.

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Well over a year has passed since the accident at TMI-2 first captivated national headlines with the threat of an impending nuclear disaster. That accident on Wednesday, March 28, 1979, is now fully understood, and subsequent analysis has shown that it was not as perilous an event as it once seemed. But first impressions linger.

Many people still believe that a major catastrophe was only narrowly averted, the nature of the accident is still undecipherable, and the health effects are unknown and unpredictable. None of this is valid. Moreover, few people know what is being done by the nuclear industry to prevent similar occurrences in the future. There is a pressing need to bridge this communications gap and to update earlier accounts that were often spotty, inaccurate, or incomplete. In this issue the *EPRI Journal* takes a comprehensive look at the accident, drawing on 15 months of painstaking analysis by technical and scientific experts. It also looks at the fixes. The purpose is to explore how the accident has affected the course of nuclear power.

The industry response has been positive and long term in nature, as evidenced by the creation of two major institutions, the Nuclear Safety Analysis Center and the Institute of Nuclear Power Operations, to deal specifically with the technical and operational aspects of nuclear safety. The work of these two groups has accelerated safety analysis and shifted the focus to the more probable accident sequences, as well as to the problems of man-machine interactions. Their efforts have already raised the level of nuclear safety.

This issue describes the accident sequence, summarizes the institutional response, and provides a broad assessment of the technical, health, and economic consequences of the accident as they are now understood from the perspective of time and detailed study. All this is a springboard to understanding the future, and in the last article, the *Journal* reports how nuclear plants are now being made safer. *Brent Barker, Editor*

Authors and Articles

The consequences of Three Mile Island continue to flow. How, then, to get behind a story that is not yet behind us? For the *Journal*, the authoritative avenue was to work with more than a dozen staff members of the Nuclear Safety Analysis Center and the Nuclear Power Division. Our objective in this special-focus issue is to be inclusive, yet brief and comprehensible to the many whose interests and expertise are outside the field of nuclear power.

Brent Barker, editor of the *Journal*, consulted with Edwin Zebroski, director of NSAC, and Milton Levenson, director of the Nuclear Power Division, and organized a group of writers to shape material prepared by the NSAC staff.

Before his appointment as director of NSAC, Zebroski was director of the Systems and Materials Department of EPRI's Nuclear Power Division for 5 years. Zebroski's career in nuclear engineering and research management dates from 1947, successively at General Electric Co.'s Knolls Laboratory (7 years), SRI International (3 years), and General Electric Co. (17 years), where he became manager of design review for the Nuclear Energy Division.

Levenson has directed EPRI's Nuclear Power Division since it was established. Before 1973 he was with Argonne National Laboratory for 26 years, becoming its associate director for energy and environment. Earlier, Levenson worked in gaseous diffusion technology and spent 4 years in fuel cycle research at Oak Ridge National Laboratory. At Argonne, he held project engineering responsibility for a sodium-cooled reactor fuel cycle facility (EBR-II) and later was director of the EBR-II project.

Robert Breen, deputy director of NSAC, was with EPRI's Nuclear Power Division for 4 years (including 2 years on loan from Westinghouse Electric Corp., where he had worked since 1955). From 1955 to 1973, Breen was a scientist and research manager at Bettis Atomic Power Laboratory, and thereafter a program manager for the Advanced Reactors Division.

William Lavallee joined NSAC as a project manager after 5 years with EPRI's Nuclear Power Division, where he developed new systems for the acquisition and analysis of plant performance data. Lavallee graduated in electrical engineering from the University of Mississippi and served in the U.S. Navy for 5 years in a nuclear power training program and as a nuclear submarine engineering officer.

William Layman, associate director of NSAC, was previously with EPRI's Nuclear Power Division in two capacities, first as a program manager in the Engineering and Operations Department, then as director of the Steam Generator Project Office. A 1947 Annapolis graduate, Layman was in the U.S. Navy until 1961, including 9 years in nuclear submarine reactor operations. He was later with General Public Utilities Corp. (7 years) and AEC (7 years), involved in utility reactor R&D management, utility power generation management, and federal water reactor development and safety research.

Miles Leverett is a consultant and acting department manager in NSAC, continuing a professional career begun in 1931 and associated with nuclear engineering since 1942, when he was involved in chemical process and reactor design for the Manhattan Project. Leverett subsequently was with General Electric Co. for 24 years, retiring in 1976 as safety and quality assurance manager in the Nuclear Energy Division.

Walter Loewenstein is director of the Safety and Analysis Department in EPRI's Nuclear Power Division. He came to the Institute in 1973 after 18 years at Argonne, where he was director of the applied physics division and, earlier, was associate director and then director of the EBR-II sodium-cooled reactor project. Loewenstein held a research and teaching fellowship at Ohio State University for 4 years while earning a PhD in physics.

James Mallay is a project manager for NSAC, on loan from Babcock & Wilcox Co., his employer since 1961. In 1971, after he had been manager of safety analysis in B&W's Nuclear Power Generation Division for 3 years, Mallay became manager of licensing, manager of LMFBR components, and program manager for European operations, responsible for engineering and marketing services to a B&W subsidiary and other companies in the European nuclear power industry.

Alan Miller, a project manager for NSAC, previously worked in radiation control and radioactive waste management research for EPRI's Nuclear Power Division. With General Electric Co. from 1973 to 1978, he supervised the development of automated systems for the monitoring, sampling, analysis, and control of nuclear reactor water chemistry. Miller holds BS and PhD degrees in chemical engineering from Iowa State University and the University of Wisconsin.

Frank Rahn joined EPRI's Nuclear Power Division as a project manager in 1974 and became technical assistant to the division director 2 years ago. For 9 years after earning MS and DEngSci degrees at Columbia University, Rahn specialized in nuclear cross-section measurement and analysis and in reactor safety analysis, working successively for General Electric Co.'s Knolls Laboratory, Columbia University, Mathematical Applications Group, Inc., and Burns & Roe, Inc.

Leonard Sagan has been with EPRI's Energy Analysis and Environment Division since 1978 as comanager of the program for health effects and biomedical studies. Since graduating from the University of Chicago medical school and completing his residency in internal medicine in 1961, he has focused on radiation studies and risk analysis. He spent 3 years in Nagasaki as medical department chief for the Atomic Bomb Casualty Commission, another 3 years as a research physician in nuclear medicine with AEC, and 10 years with the Palo Alto (California) Medical Clinic, where he became associate director of environmental medicine.

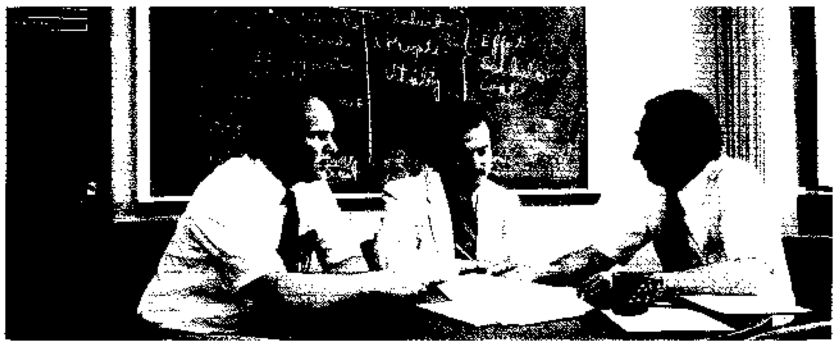
William Sugnet, NSAC program manager for probabilistic risk assessment, is on loan from Westinghouse, where he worked for 6 years in the Nuclear Technology Division, becoming manager of safety standards, with responsibility for reactor safety evaluations and licensing matters. He was previously in the U.S. Navy's nuclear power program for 6 years as a nuclear submarine engineering officer and as an instructor in reactor plant operations, heat transfer, and fluid flow. He is a mechanical engineering graduate from the University of Notre Dame.

Harvey Wyckoff, an NSAC project manager on loan from Commonwealth Edison Co., has handled special assignments for half of his 32-year career with the Illinois utility. From 1959 to 1966 he was responsible for research at Commonwealth; he had earlier spent 2 years with the Nuclear Power Group in feasibility studies of nuclear power generation and later was on loan to General Electric Co. (10 years) for breeder reactor study and various design projects. Wyckoff was also on the utility team that organized Project Management Corp. for the design and construction of the Clinch River breeder reactor and was assistant to the PMC general manager for 3 years.

This month's Washington Report, *Nuclear Emergencies: Coordinating the Federal Response* (page 39), reviews the structure of the Federal Emergency Management Agency and its new responsibilities as recommended by the Kemeny commission and approved by President Carter.

Loewenstein Levenson Rahn

Sagan



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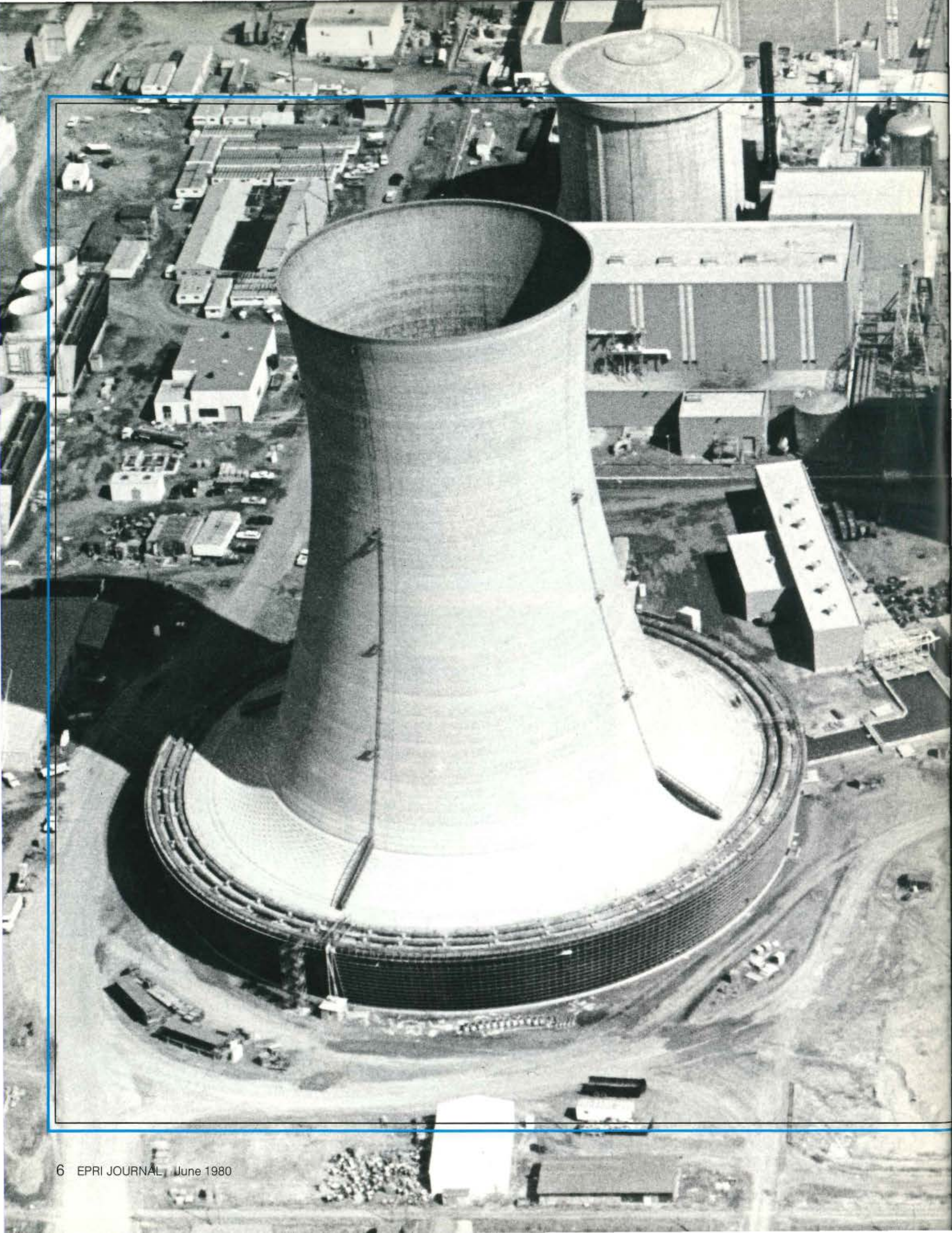
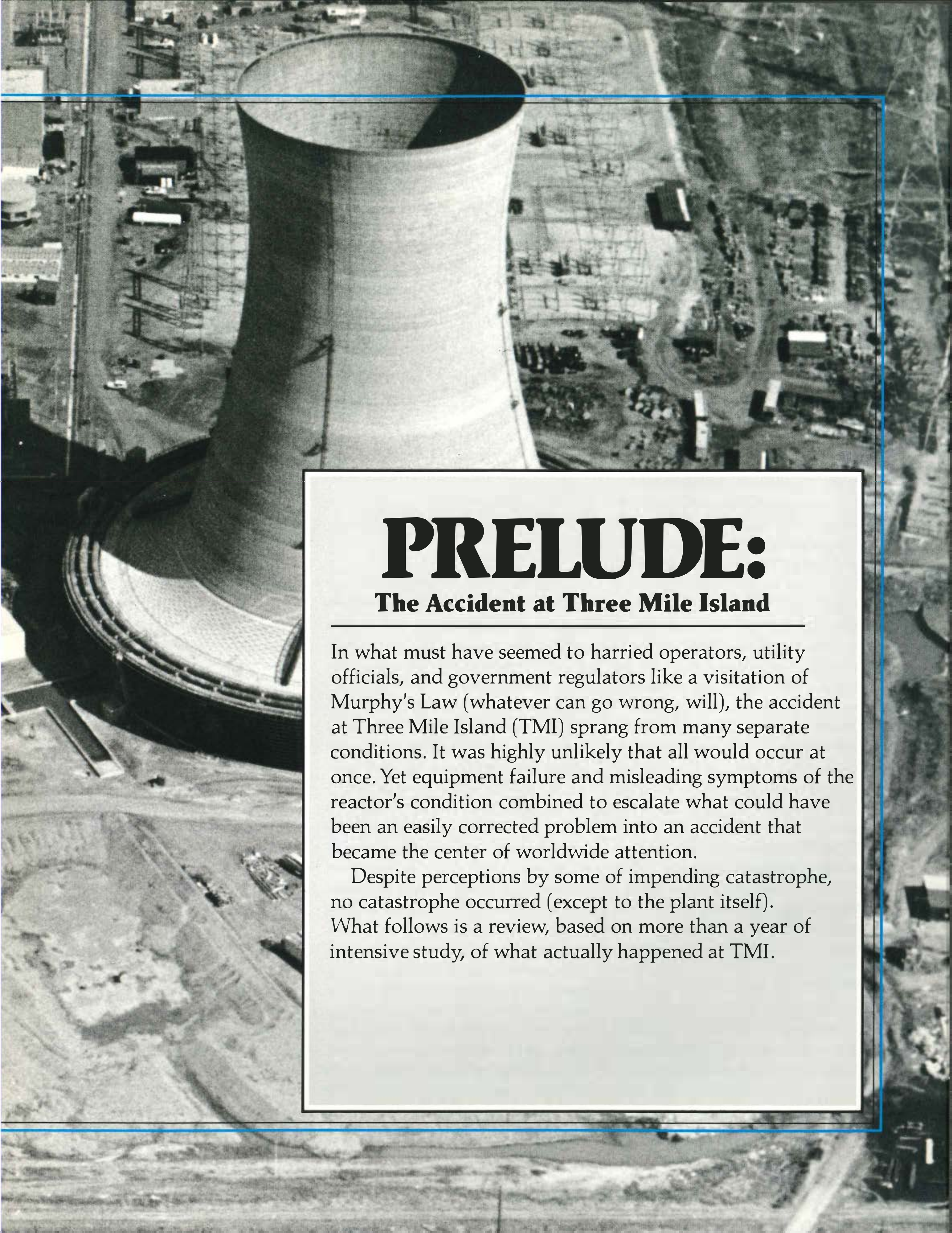




PRELUDE:

The Accident at Three Mile Island

In what must have seemed to harried operators, utility officials, and government regulators like a visitation of Murphy's Law (whatever can go wrong, will), the accident at Three Mile Island (TMI) sprang from many separate conditions. It was highly unlikely that all would occur at once. Yet equipment failure and misleading symptoms of the reactor's condition combined to escalate what could have been an easily corrected problem into an accident that became the center of worldwide attention.

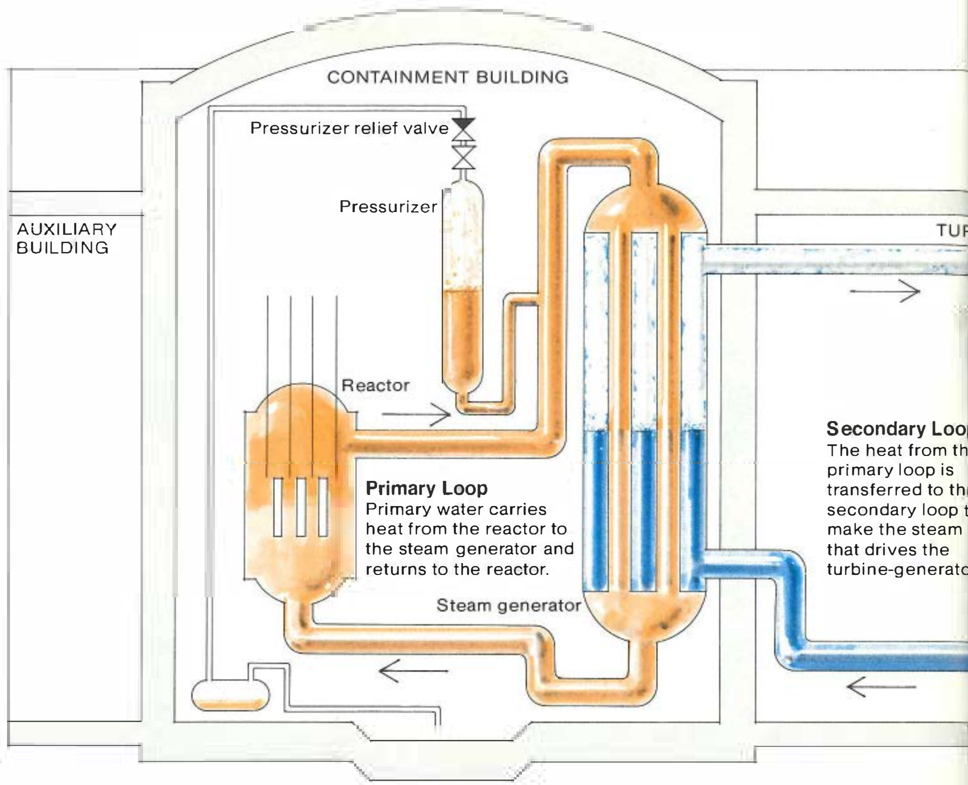
Despite perceptions by some of impending catastrophe, no catastrophe occurred (except to the plant itself). What follows is a review, based on more than a year of intensive study, of what actually happened at TMI.

Nuclear reactors at the TMI power station, like all the nation's commercial reactors, are built around a uranium core. Here, in the heart of the reactor, nuclear fission of the uranium fuel occurs, liberating precisely controlled amounts of heat energy that eventually becomes electricity. To transfer the heat safely from the core and convert it into electricity, water, the most versatile and well-known coolant, is used.

Very simply, what happened at TMI was a gradual loss of the cooling water that is pumped through the reactor's heat-producing core. This shut the reactor down very quickly but eventually left insufficient water to remove all of the core's afterheat. When the quantity of water became low enough to allow the metal cladding of the fuel rods to partially melt and chemically react with the reactor water, a relatively small quantity of radioactive material was released from the damaged fuel rods into the reactor cooling-water circuit.

Risk assessment studies for plant licensing had heretofore focused on hypothetical pipe-bursting scenarios as potentially the most damaging type of water-loss event. This is one of the ironies of TMI. The loss of water did not come from a dramatic rupture. Instead, the water slowly leaked out of a stuck-open valve—an event that had been analyzed, but was not given the attention paid to the spectacular loss-of-coolant accident used as the basis for NRC licensing.

TMI-2, like some two-thirds of the nuclear units now operating in the United States, is a pressurized water reactor (PWR). So to understand what went wrong, we should know how a PWR works.



PWR basics

The water in a PWR is the transfer medium by which heat from the core is carried to the electricity-producing parts of the plant. To accomplish this, a plant is built with three independent but interlocking sets of loops (systems) in series.

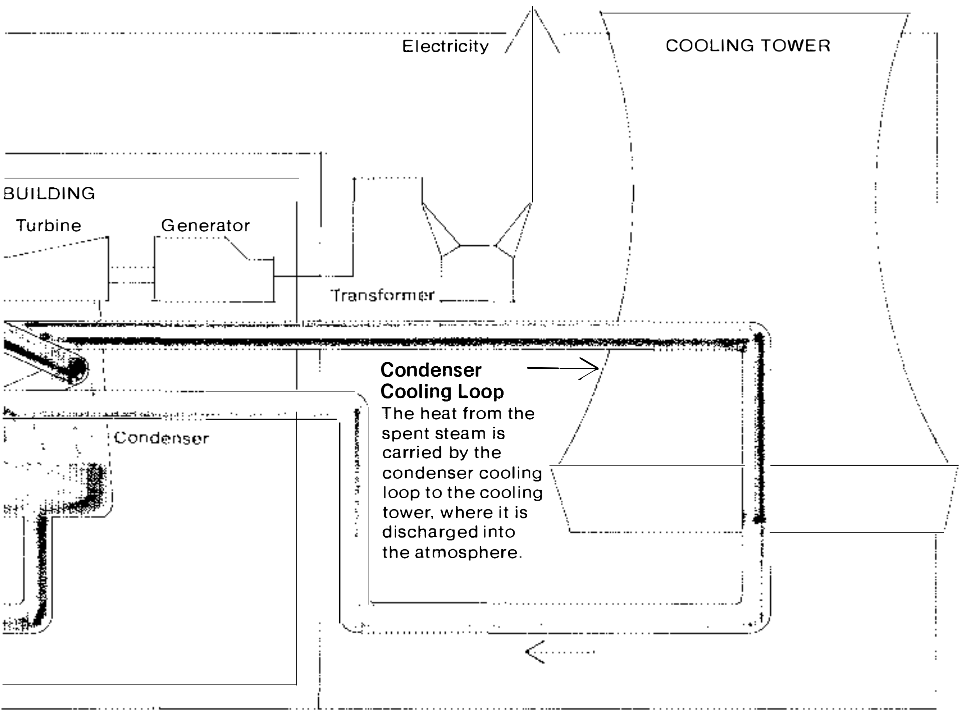
Water in the first, or primary, system circulates through the reactor core, picking up heat from the fission reaction. This water, under pressure to prevent boiling, is then pumped to heat-exchanging steam generators, 35-ft-tall tanks in which the primary water passes through a large number of small tubes. The steam generators are the boundary between the primary system and the secondary system. At this boundary, the primary system transfers the heat picked up in the core to the secondary system, where the water boils to steam in the steam generators.

The hot steam is piped to a turbine, where it drives the turbine rotor and turns a shaft that connects to an electric generator.

The spent steam, having delivered its energy to the turbine rotor, goes to a condenser under the turbine. Here, the third system enters the picture. To condense the steam leaving the turbine, the third loop brings cooled water to the condenser, and this water picks up the steam's heat through tube walls. The water from the condensed steam is pumped back to the steam generators, and the cycle is repeated.

In systems like the one at TMI, the third-loop cooling water pumped into the condenser comes from a cooling tower, to which the water eventually returns. These cooling towers and their cloud of water vapor, far removed from the reactor and radioactivity, have become symbols of nuclear power to the public, even though they are equally essential to disposing of the low-temperature heat from fossil plants.

Besides the three normal cooling systems, a nuclear reactor is equipped with emergency core-cooling systems. These safety systems force water directly into the primary loop to prevent overheating of the core if there is leakage from the primary loop. The emergency core-cooling systems have their own water supplies and their own pumps. At TMI, one system, with redundant loops, can force water into the reactor at high pressure. A separate system, with redundant loops, can force larger quantities of water into



the reactor at lower pressure. And a multiple-loop core-flood system can flood the core, forced by static gas pressure (without the need for pumps or pumping power). These emergency core-cooling systems come on automatically to protect the reactor, or if necessary, the reactor operator can activate or deactivate them.

In a PWR, boiling is suppressed in the core. But how can water held at such high temperatures (usually about 600°F, 316°C, in the primary loop) be prevented from boiling? The answer is pressure—the pressure that gives the PWR its name. The water in the primary loop is held at a pressure of about 2200 psi (15.2 MPa), which prevents it from vaporizing to steam even while removing heat from the core.

The component where this high pressure is created and closely controlled is called the pressurizer, a large vessel connected to the primary loop. The bottom half of this tank is filled with water heated by electric heaters, and the top half, with the resulting high-pressure steam. As the water in the primary loop heats or cools, it expands or contracts by several hundred cubic feet, raising or lowering the water level in the pressurizer. A rising water level squeezes the steam cushion at the top and increases the pressure exerted by the steam on the water's surface. So increased temperature creates increased pressure in the primary loop to maintain the water in its liquid state.

This mechanism tends to be self-regulating; it is fine-tuned by electric heaters and cooling sprays, which are controlled to regulate the amount of steam and hence the pressure in the pressurizer and primary loop. In the event the temperature and consequent pressure in the vessel become too high, a relief valve atop the pressurizer opens automatically to release steam. Since valves sometimes stick open, the relief valve has a backup block valve in series with it. In addition, two large safety valves provide added protection against overpressure.

The relief valve played a critical role in the events at TMI. This was the valve that stuck open and allowed the primary pressure to drop to the point where, over a period of two hours, the primary system water boiled away until it no longer covered the reactor's core. To follow this development, we have to review the events at TMI in the order they occurred.

The accident sequence

On the morning of March 28, 1979, at 4 a.m., the Three Mile Island Nuclear Power Station Unit 2 was producing just under its full output of 900 MW (e). But the stage was set.

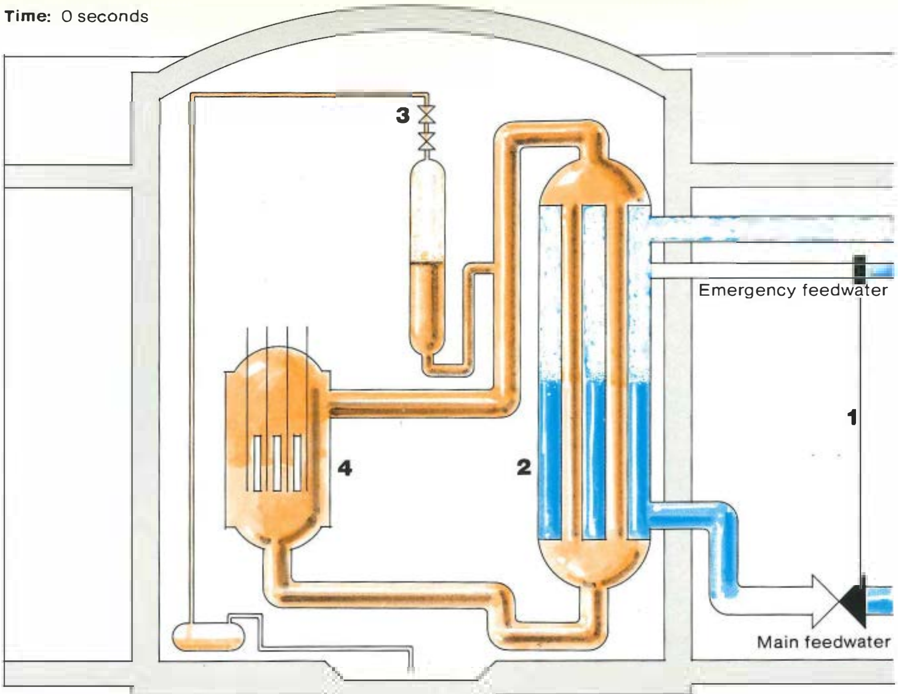
First, there was a slight weeping of steam from the pressurizer relief valve. It was being channeled to a safe holding area (the reactor drain tank). The water level and the pressure in the pressurizer remained normal, and the leak was not considered serious because relief valves often weep. What later proved to be serious was the fact that the small leak heated a temperature-measuring device in the exit pipe from the valve and prevented it from signaling a change when the relief valve stuck open.

Second, sometime during the preceding two days, two valves in the secondary loop's emergency feedwater supply pipes were left in the wrong position: Supposed to be open, they were closed. This meant that an automatic emergency flow of cool feedwater to the steam generator would be blocked when needed.

Third, workers were trying to fix a malfunction in the secondary loop's water purification system. This is the kind of routine maintenance normally needed in a power plant. But this time it caused feedwater supply pumps to shut down automatically. It was this small event with normally minor consequences at precisely 4:00:37 a.m. that marked the first step in the accident sequence at TMI.

Once triggered by the feedwater pump shutdown, events moved automatically. Almost instantaneously, a safety device shut down the turbine-generator. With the main feedwater cut off, the emergency feedwater pumps should have

Time: 0 seconds



1 As a result of maintenance work, the main feedwater pumps trip. Emergency feedwater flow is blocked by two valves that inadvertently had been left closed sometime during the previous two days.

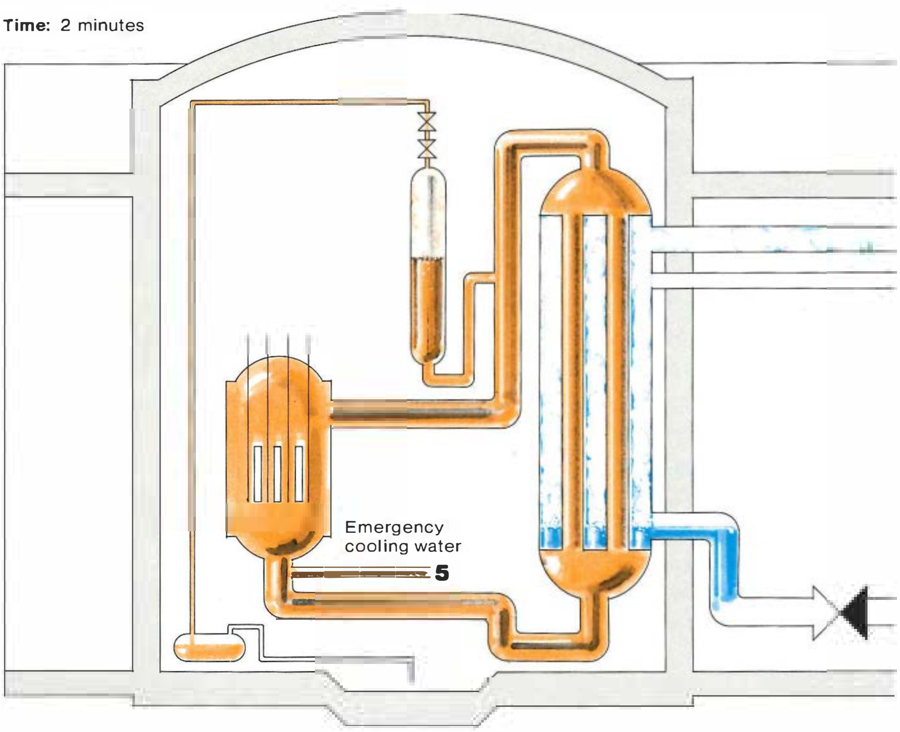
2 When feedwater flow stops, heat removal from the primary system decreases.

3 At 3 seconds, relief valve on the pressurizer opens to reduce momentary overpressure but fails to close when pressure drops. Operators are unaware valve is open.

4 Reactor shuts down at 8 seconds.

5 Pressure in primary system continues to fall and triggers automatic injection of emergency cooling water into the core. At 5 minutes this is throttled by operators, who believe the system is overfilled with water because the pressurizer is full.

Time: 2 minutes



been able to supply the water now needed by the steam generators. But on this occasion the water could not get through because the two valves already mentioned were closed.

Because of this loss of feedwater to the steam generators, temperatures began rising in the primary loop. The primary coolant water was picking up more heat from the reactor core than it could discharge in the steam generator because the cool feedwater to absorb much of the heat from the primary loop was no longer available. The heat transfer that would normally occur in the steam generator was greatly reduced, leaving the primary loop with a steadily increasing buildup of temperature and pressure.

Only 3 seconds passed before the next step took place: The pressurizer's relief valve opened. Then, at 8 seconds, the automatic protective system shut down the reactor because opening the relief valve was insufficient, by itself, to reverse the pressure buildup.

With the reactor shut down, primary system water temperature and pressure soon began to fall, as expected. At about 12 seconds, pressure returned to normal. At this point, the relief valve atop the pressurizer should have closed automatically. But, for reasons still unknown, it did not. (Relief valves very infrequently stick open for a variety of reasons.) And here the real trouble began.

Plant operators, having an indication that the signal had been sent for the relief valve to shut, assumed it had done so. They had no direct indication of the valve's position and did not realize that reactor coolant was still escaping through the open valve.

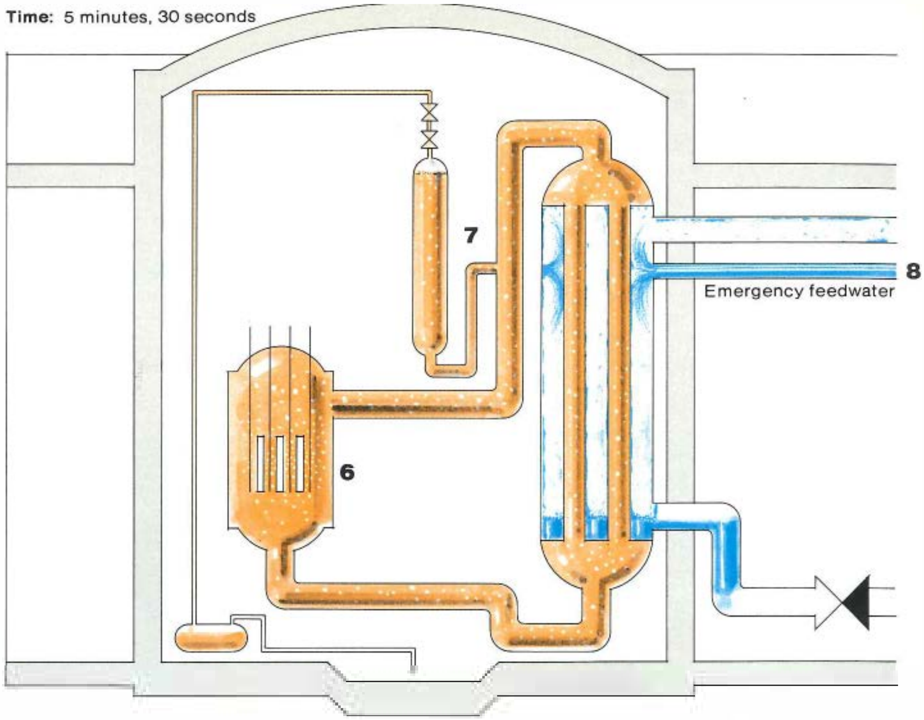
High temperature in the pipe leading from the relief valve to the drain tank signaled the presence of escaping steam or hot water. But operators thought the reading was due to the minor, known leak and the expected residual heat from the automatic opening of the pressurizer relief valve. These camouflaged the much more pressing problem that had now developed with the relief valve.

Pressure, temperature, and level in the drain tank increased as water poured into the tank through the open relief valve. A reading of these gages would have suggested the true volume of coolant that was escaping. But the indicators were out of sight, on a board behind the main control room panels, and there were no recorders to save this information and show the operators the trends.

Operators were busy watching the strange behavior of the water level in the pressurizer and attempting to get water into the steam generators. The pressurizer normally has the only free water surface in the primary loop. The level of this surface indicates how full the primary system is. The pressurizer's water level and the primary system's pressure level normally rise or fall together, but now the water level in the pressurizer began to rise while the pressure continued to fall. This situation was not covered by the operators' training and procedures.

What was happening was that the loss of water and the drop in pressure were allowing primary-loop water to boil in the core. The boiling water produced steam, which formed pockets that took up space in the primary coolant loop. These steam voids forced water into the pressurizer and raised its water level, creating the false impression that the reactor system had too much water.

As the pressure continued to fall, it reached the point (about 1600 psi; 11 MPa) that triggered the automatic emergency core-cooling system. Cool water began flowing into the core from high-pressure injection pumps, which was just what was needed to cool the core and turn the tide. But here a major misstep occurred. The operators, watching the rising water level in the pressurizer and trained never to let the pressurizer "go solid" (fill completely with water, leaving no cushion of steam for pressure control), reduced the emergency core cooling water flow. By this action, an early opportunity to avert the subsequent damage to the reactor core was missed. But at this point, the core was still intact,

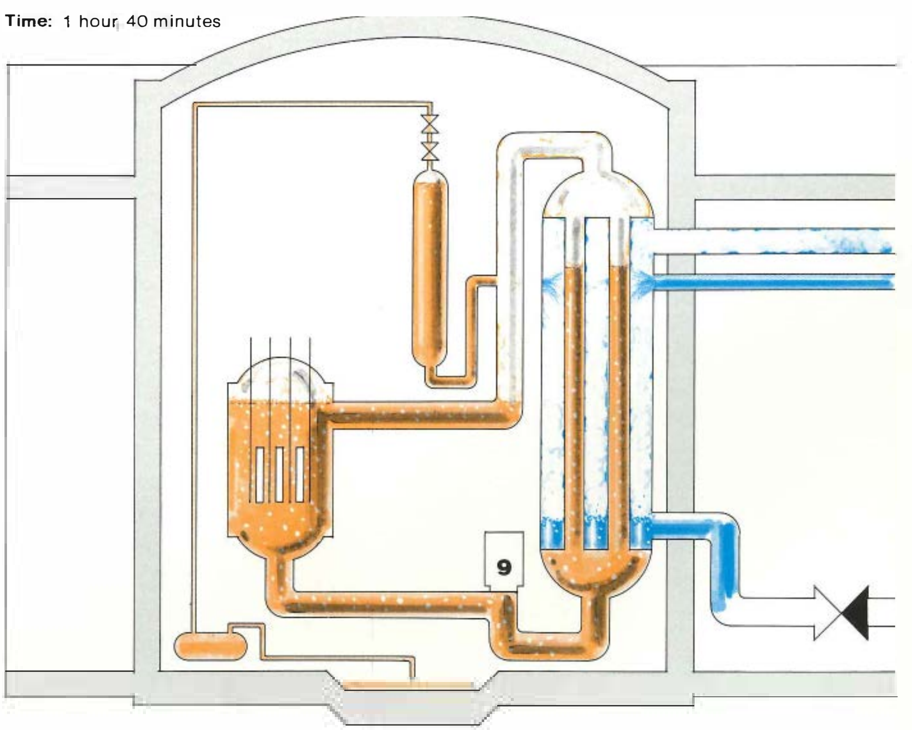


6 Water begins to boil in the core.

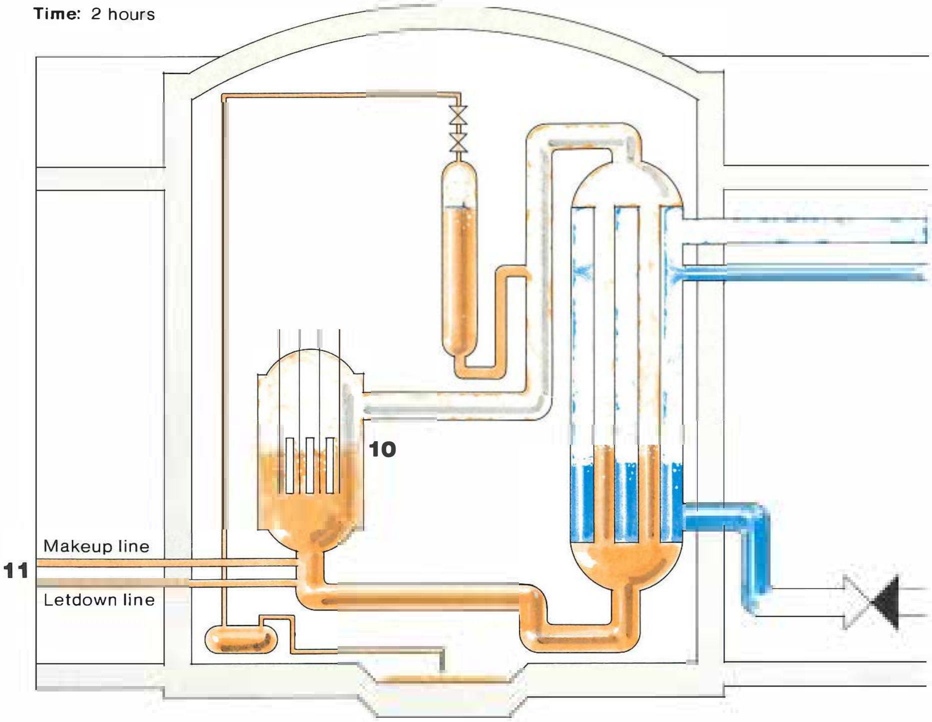
7 Increasing steam volume forces water into the pressurizer. The high water level in the pressurizer continues to mislead operators into believing the primary system is overfilled.

8 Operators discover the closed valves in the emergency feedwater lines and open them at 8 minutes.

9 Insufficient water remains for proper operation of reactor cooling pumps. Pumps begin to vibrate excessively. Last two pumps are shut off at 1 hour, 40 minutes.



Time: 2 hours

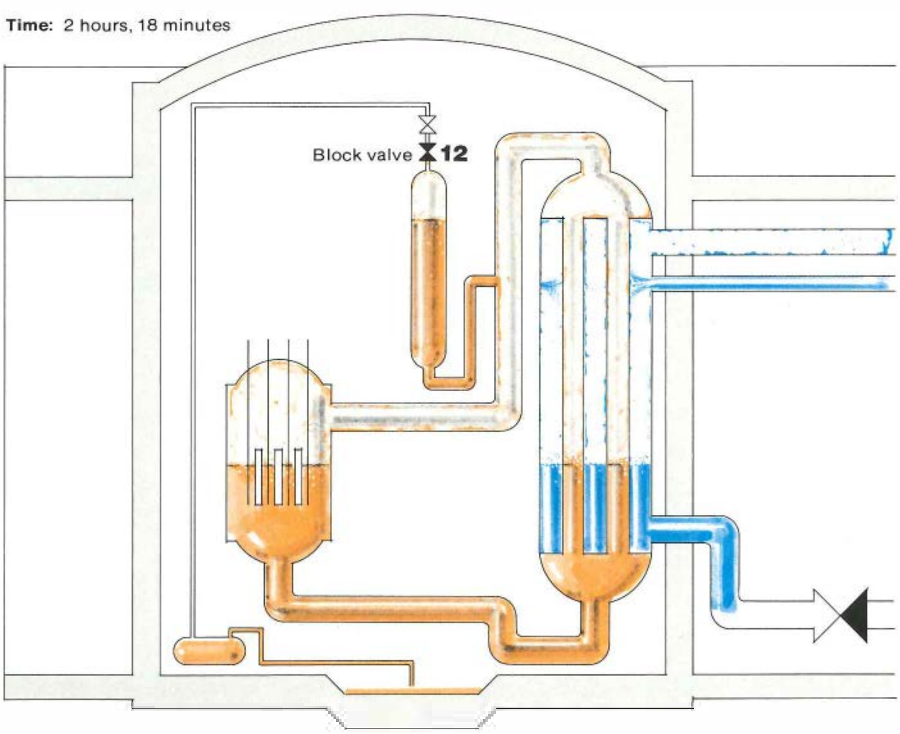


10 After the pumps are shut off, the core begins to overheat. Fuel cladding begins to fail.

11 A small fraction of the radioactive gases from the fuel travel with the primary system water to the auxiliary building through the piping (letdown line) of the level control and purification system.

12 Operator closes the block valve to stop flow through the stuck-open pressurizer relief valve. The loss of primary system water is stopped.

Time: 2 hours, 18 minutes



and nothing really serious had happened.

From that point, which occurred about 4–5 minutes into the accident sequence, things went steadily downhill. With the emergency coolant flow reduced, more and more of the water in the core boiled to steam and escaped through the still-open relief valve. Eventually, there was so much steam in the primary loop and so little water that the reactor coolant pumps were pumping a mixture of water and steam and began to vibrate excessively. So the operators, concerned that a pump seal might fail and leak primary system water, shut off the pumps. Two reactor coolant pumps were stopped at 1 hour 13 minutes into the accident; the other two, at 1 hour 40 minutes.

The core uncovers

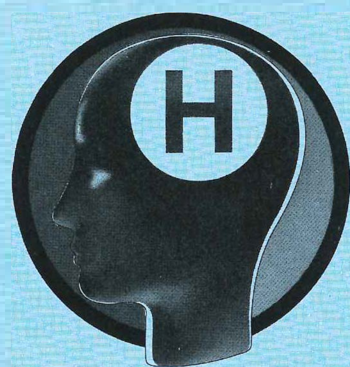
The shutdown of the reactor coolant pumps was one of the critical points. Up to this time, the pumps continued to force the remaining water, mixed with steam, through the core. This provided good cooling and prevented core damage despite the loss of coolant through the stuck-open valve. But now the coolant stopped circulating, the water settled out from the water-steam mixture, and the upper part of the core was uncovered.

At a high temperature and exposed to superheated steam, the Zircaloy cladding that encased the nuclear fuel began to deteriorate, allowing radioactive gases to leak from the fuel and into the primary system. Mixed with the hot water and steam, some of the radioactive gases then escaped through the open relief valve and into the containment building, where they were retained. A small fraction of these radioactive gases from the fuel became dissolved in the primary system water that circulates through the reactor water level control and purification system located in the auxiliary building. While passing through this system's process equipment, the gases came out of solution and escaped through leaks (and possibly pressure relief valves) into the auxiliary building atmosphere and ultimately to the environment.

The open pressurizer relief valve was finally blocked off 2 hours and 18 minutes after the accident began. Had this occurred even a half hour earlier, there would have been little or no damage to the reactor core and relatively little radioactivity would have escaped from containment. Postaccident analyses indicate that serious damage to the core did not begin until after 1 hour and 40 minutes into the accident—the time when the last two circulating pumps were turned off. If the pressurizer relief valve had been closed and the core covered with water before this damage occurred, the core would not have overheated and only the minor amount of radioactive materials that are normally present in the water would have escaped from the primary loop to the containment building.

This marked the end of the undetected loss-of-coolant phase of the accident. By the night of March 28, some 16 hours after the accident began, a reactor coolant pump was restarted and forced core cooling was reestablished. The most crucial phase of the accident at TMI had ended, but the controversy it would spark was just beginning. ■

THE HYDROGEN BUBBLE SCARE



For the public, the hydrogen bubble scare was one of the most disturbing developments that occurred during or after the accident. It arose from a mistaken judgment by NRC personnel that both hydrogen and oxygen might be accumulating in the reactor and primary system. The fear was that with sufficient oxygen present, the hydrogen might burn, or within a week, it might build up to levels that could explode.

Actually, a little hydrogen in a PWR is normal. Hydrogen is added routinely to react with the excess oxygen and prevent an accumulation of oxygen in the water, which might otherwise corrode the system's metal parts. But at TMI, accident conditions generated hydrogen far in excess of the normal amount. This excess hydrogen formed when the reactor core uncovered and the superheated steam swirling through it began to react chemically with the Zircaloy cladding of the fuel rods to form hydrogen. Some of this hydrogen dissolved in the reactor water, but most of it mixed with steam and either escaped into the containment building through the stuck-open relief valve or stayed to form the infamous bubble.

The part that escaped eventually ignited, because there was the normal oxygen present in the air to support combustion. This burn did cause a sharp, short jump in the containment building pressure but did not threaten the integrity of the building because it had been designed to withstand pressures at least double those generated by the hydrogen combustion.

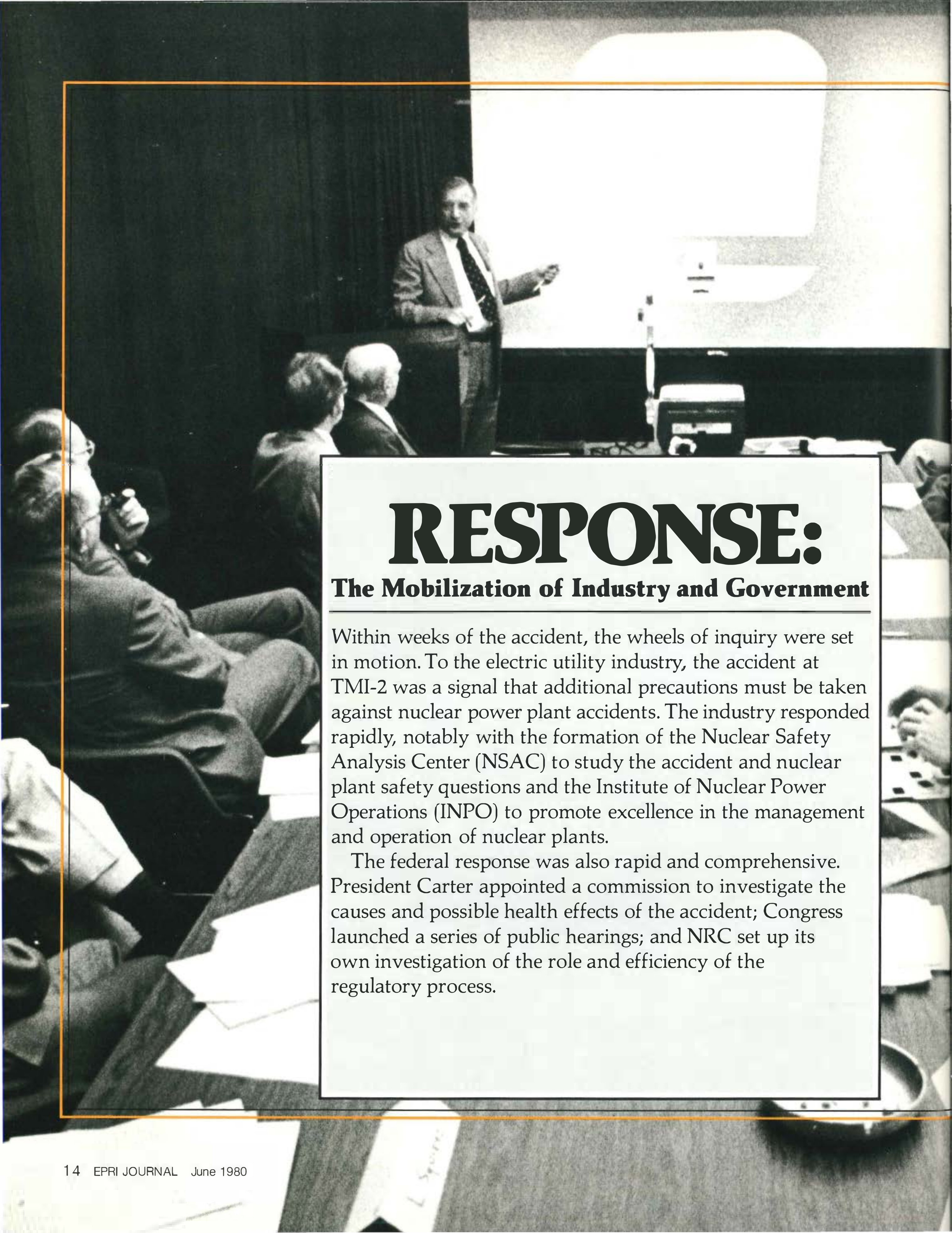
More serious would have been ignition inside the reactor vessel. Yet the fact is that the bubble in the reactor vessel could not have ignited because there was never sufficient oxygen present inside the vessel to support combustion, and the hydrogen would continue to combine with any excess oxygen, forming water.

NRC's Rogovin report later indicated that a number of NRC personnel realized that radioactivity in the system might be freeing oxygen molecules from the coolant water. This view was confirmed by calculations available to NRC, but these calculations neglected the known presence of hydrogen. Industry judgments, on the other hand, factored in the presence of the hydrogen and determined that oxygen was recombining with the hydrogen as fast as it was formed.

The worry about the possibility of the exploding bubble was caused by the worst-case scenario used by NRC. This worst case required three assumptions, each contrary to the actual situation or to well-established engineering knowledge.

- Oxygen would increase in the reactor's bubble. (The method of intentionally adding hydrogen to prevent oxygen accumulation by radiation was known.)
- A mixture of hydrogen with 5% oxygen in the presence of steam might explode. (A flame is possible above 5% oxygen, but 10% oxygen is required for detonation when excess steam is present.)
- A pressure vessel would fracture from a brief overpressure from a hydrogen burn. (These vessels are specially made of tough ductile steels, which are tested to large margins of safety in shock resistance, strength, and ductility to withstand large deformations.)

Unfortunately the debate within NRC went on for several days before it was announced that the bubble was gone, and in any event, it could not have burned or exploded. But the psychological trauma caused by the fiction of a possible exploding bubble is hard to erase. For much of the public, a myth persists that an explosion and public disaster were only narrowly averted. This, of course, is not true.



RESPONSE:

The Mobilization of Industry and Government

Within weeks of the accident, the wheels of inquiry were set in motion. To the electric utility industry, the accident at TMI-2 was a signal that additional precautions must be taken against nuclear power plant accidents. The industry responded rapidly, notably with the formation of the Nuclear Safety Analysis Center (NSAC) to study the accident and nuclear plant safety questions and the Institute of Nuclear Power Operations (INPO) to promote excellence in the management and operation of nuclear plants.

The federal response was also rapid and comprehensive. President Carter appointed a commission to investigate the causes and possible health effects of the accident; Congress launched a series of public hearings; and NRC set up its own investigation of the role and efficiency of the regulatory process.

Immediately after the accident sequence began, an ad hoc committee of top utility executives convened. At its request, EPRI set up NSAC. By mid-April, NSAC had started work. Its tasks were extensive.

▫ NSAC was charged with obtaining a full and documented understanding of the technical and operational factors that contributed to the onset, ramification, damage, and consequences of the accident. The idea was to provide a basis for remedies and improvements, not to place blame.

▫ NSAC was to identify the generic elements that contributed to the accident and could lead to improvements in equipment, operation, and management for all types of U.S. power reactors.

▫ NSAC was to provide assistance to General Public Utilities Corp. (GPU) in the recovery from the accident and to work with others, including EPRI's Nuclear Power Division, to obtain useful technical information on this operation.

▫ NSAC was to act as an information exchange for 60 utilities, 6 reactor-owner groups, and NRC, providing, for example, information on plant operating problems and solutions. NSAC was also directed to collect data (jointly with the State of Pennsylvania Department of Health) on any health effects from the accident.

▫ NSAC was to develop recommendations for practical, evolutionary improvements in reactor safety and to be responsible for responding to NRC actions, particularly those of a generic nature.

NSAC is headed by Edwin Zebroski, former director of EPRI's Nuclear Systems and Materials Department. It has a staff of 50, including 35 technical experts in nuclear plant design, operation, and safety analysis. Its work is guided by two utility committees and is reviewed by distinguished and experienced nuclear, space, and medical experts as members of the Utility Safety Advisory Committee. NSAC reports directly to the president of EPRI, Floyd Culler.

After the accident at TMI, an EPRI team led by Milton Levenson, director of EPRI's Nuclear Power Division, and Edwin Zebroski was called to the site to direct and participate in the Industry Advisory Group, which was set up at the request of GPU and NRC to advise GPU.

NSAC produced the first detailed event sequence of the accident, followed by a second-by-second reconstruction of the events and the scientific and engineering basis for understanding the phenomena that occurred. Many of the corrective actions that NRC and industry subsequently proposed were based on these analyses.

The findings of these analyses were published as a report, NSAC-1, in July 1979, with supplements in September and October and a major update in March 1980.

NSAC provided data to the president's commission (the Kemeny commission), to NRC's own investigative group (the Rogovin commission), and to the congressional staff study of the accident.

At the request of the Kemeny commission staff, NSAC studied what would have resulted at TMI if the accident had not been terminated when it was. The conclusion was that contrary to some widely publicized opinions, numerous countermeasures were available to prevent continuation of the accident. It was shown that even in the extreme event of a gross core melt and reactor vessel penetration, reliable means existed to keep the containment building intact.

NRC responded to the TMI investigations with an action plan, which included well over 200 proposed safety requirements. These requirements varied as to effectiveness, complexity, and cost, but their number, nature, and short schedules were overwhelming to the industry, particularly as there was no indication of their relative value to safety.

When NRC invited the utility industry to suggest methods for determining values and priorities, NSAC joined with participants from Atomic Industrial Forum (AIF), the Edison Electric Institute, the utilities, reactor suppliers, architect-engineers, and consultants to develop a ranking method that took account of the following factors.

▫ How effectively each proposed requirement could increase safety and its relative importance to other safety-related issues

▫ Whether a proposed requirement might have adverse side effects that could offset beneficial safety effects

▫ Whether other proposed, committed, or already accomplished requirements had the same objective

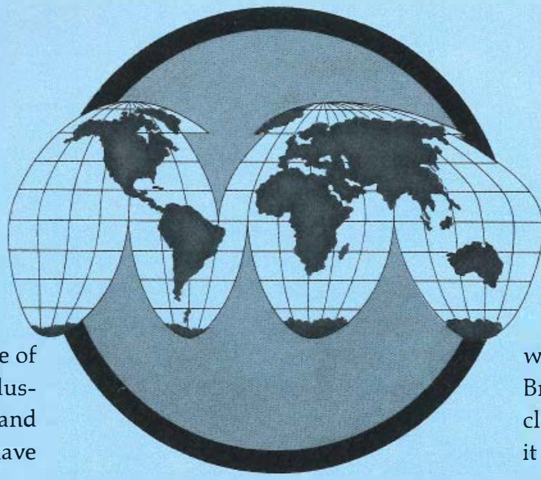
▫ Whether a proposed requirement could reasonably be fulfilled within NRC's schedule and with the available resources

The set of evaluations that resulted were presented to NRC and to its Advisory Committee on Reactor Safeguards. Reviews within NRC are clarifying the intent and ordering the importance of the items covered in the master plan.

In another instance, NRC was concerned about the possibility that an instantaneous, guillotine rupture of plant steam lines might damage cables or electrical equipment in the auxiliary building, producing an unsafe reactor condition. NSAC and AIF responded by jointly setting up an industry workshop, at which NSAC and EPRI supplied technical data showing that even under extreme circumstances, steam pipes made to current nuclear plant specifications either survive or develop leaks that enlarge only gradually. Time is thus available to shut down the reactor before the increasing temperature or humidity would affect essential instruments or controls.

On a different occasion, NSAC assisted the utilities by providing decision methods and technical evaluations of some of the NRC requirements for emergency planning.

THE INTERNATIONAL RESPONSE



The TMI accident produced a wave of concern that reached most industrialized countries of the world and those developing countries that have civilian nuclear energy programs.

Initial accounts of the accident reported in Europe were drawn from some of the more wildly lurid stories in the American press. But as better information became available, the European press published more temperate and accurate reports.

Some countries that supply nuclear power plants were quick to respond publicly that their nuclear plants were of a different design than TMI-2 and their installed safety systems precluded the possibility of a TMI-type accident. Nevertheless, many of them proceeded to reevaluate their operating practices, safety designs, and training programs.

Most of the countries with significant civilian nuclear programs set up investigative commissions to analyze the relevance of TMI to them. Also, in many countries, task groups from utilities and government regulatory bodies reviewed the design, operating practices, and safety features of their existing and planned reactors.

Governments in Japan, France, West Germany, and Great Britain made it clear that nuclear power is essential to their energy mix as a way to avoid relying too heavily on imported oil. Most foreign nuclear programs went ahead without pause, but in Sweden fuel loading of two new plants was delayed for 10 months, pending the result of a national referendum on nuclear power expansion that was held in March 1980. The result of the referendum was to support the full program of plants in operation and those committed to construction.

In spite of some local reaction, the governments of Switzerland, Belgium, and the Netherlands also decided to go forward with nuclear power, although the Dutch program may place at least a temporary limit on expansion beyond that already approved.

The British government is still considering a program of designing and building PWRs, although of a somewhat different design than TMI-2. The British have also reviewed their nuclear safety record, ascertaining that it has been excellent, except for a serious 1957 accident in a reactor at Windscale, which released over 1000 times more radioiodine to the environment than the TMI accident. For several weeks after that accident, it was necessary to dump milk produced in the nearby region because of the pickup of radioiodine from cattle forage.

The Danish nuclear program, in which some reactor construction was scheduled to begin in the late 1980s, has been indefinitely deferred, partly because Denmark could, if necessary, tap nearby North Sea oil.

Many other countries continue to expand their national laboratories and the development and operation of small reactors. They are training a nucleus of engineers and scientists in readiness for large-scale nuclear power projects in the 1980s and 1990s.

Although the trend abroad has been to go ahead with nuclear power, albeit with more emphasis on ensuring adequate safety, the TMI-2 accident has strengthened the position of antinuclear groups. It has also focused greater public attention on the plans of large utilities and their government regulators.

CHRONICLE OF EVENTS: 1979-1980

April

TMI insurers pay $500,000 to evacuees.

A New York *Times*–CBS poll following the TMI accident finds U.S. public support for nuclear power dropped from 69% to 46%.

The utility industry directs EPRI to provide recovery assistance at TMI, analyze the accident sequence, and assess generic safety implications.

EPRI establishes NSAC to carry out these assignments.

Babcock & Wilcox Co. engages in an intensive review to determine whether its plant design is too "unforgiving" from an operator's standpoint.

The president of AIF, Carl Walske, predicts no new reactor orders until financial questions about nuclear power that arise from TMI-2 are resolved.

NRC issues first signals of delay on new reactor licensing.

NRC orders shutdown of all Babcock & Wilcox reactors for safety modifications.

The President's Commission on the Accident at Three Mile Island, headed by the president of Dartmouth College, John Kemeny, holds its first meeting.

NRC's authorizing subcommittee in the House defeats a proposal for a six-month moratorium on issuance of construction permits.

May

Senate nuclear regulatory subcommittee begins a year-long inquiry into TMI accident.

HEW Secretary Joseph Califano says the effects from the TMI accident will be less than one fatal cancer and one nonfatal cancer during the next 20 or 30 years, with an estimated dose of 3500 person-rem.

GPU tells the Pennsylvania Public Utility Commission that denial of rate relief will jeopardize $450 million in short-term credit the company needs to stay in business. Replacement power costs to make up for two TMI units are $24 million per month.

NRC announces a three-month de facto licensing moratorium and formation of a lessons-learned task force.

The House Subcommittee on Energy and the Environment releases transcripts of interviews with TMI operators, which show their apparent errors in perception and judgment during the damage-producing phase of the accident.

June

An NSAC analysis indicates core damage could have been prevented by the proper use of available water supplies for up to two hours after the TMI accident began.

A *Nucleonics Week* survey of U.S. utilities that build nuclear plants finds the construction pace has not been slowed by the TMI accident.

July

NRC decides to hold full adjudicatory hearings on the restart of undamaged TMI-1; this will delay operation for a year or more.

Babcock & Wilcox reactors are returned to service, except for the TMI units.

Bechtel Corp. estimates the cleanup and recovery of TMI-2 will take four years and cost $400 million. GPU estimates another $100 million to cover core replacement and uncertainties.

August

NRC issues its lessons-learned requirements.

The nuclear utility industry lays out plans for a three-pronged approach to enhanced safety. It features the Nuclear Safety Analysis Center, the Institute of Nuclear Power Operations, and a mutual insurance pool for partial recovery of replacement power costs in the event of accident-related outages.

September

The largest fund-raising event in antinuclear annals is held in New York's Madison Square Garden and attracts nearly a quarter-million persons.

October

A waste treatment unit for cleaning up TMI-2, Epicor II, is approved.

Metropolitan Edison Co. is fined $155,000 by NRC for alleged violations at TMI.

The Kemeny commission releases its findings and concludes that there are serious deficiencies in the regulation and operation of nuclear power plants, but it does not endorse a moratorium on nuclear development.

November

NRC invokes a continued licensing pause of indeterminate length.

Intervenors in TMI-1 restart proceedings raise psychological distress as a reason not to resume operation.

December

The House approves the NRC FY80 authorization bill and defeats an amendment calling for a further six-month moratorium on issuance of new construction permits.

President Carter responds to his TMI commission's report, and he calls for strengthened management of NRC within the present commission structure and for giving the Federal Emergency Management Agency authority over emergency planning.

Carter installs John Ahearne as interim chairman of NRC, replacing Joseph Hendrie.

NRC, noting the need for domestic energy supplies, indicates its plans to resume licensing within six months.

January

NRC staff concludes that TMI did not qualify for designation as an extraordinary nuclear occurrence.

The National Academy of Science's Committee on Nuclear and Alternative Energy Systems concludes that coal and nuclear power are the only near-term, large-scale alternatives to oil and gas for electricity production.

NRC's Rogovin commission calls for more-remote siting of nuclear plants, more emphasis by NRC on monitoring reactor operations and utility management, and a single head for NRC.

Representative Morris Udall introduces a nuclear energy bill calling for an increase in liability for accidents to $5 billion; a three-year moratorium on new construction permits and operating licenses, unless NRC determines certain safety improvements are in place; and top priority to health and safety protection in siting.

Utilities comply with first deadlines for nearly all modifications in operations and equipment stemming from TMI.

February

The TMI commission set up by the governor of Pennsylvania urges NRC to expedite the TMI cleanup. The panel is unopposed to controlled venting of krypton gas into the atmosphere.

An accident at Florida Power Corp.'s Crystal River-3 nuclear unit leads to the spilling of 43,000 gallons of slightly radioactive water into the containment building. Operator training and procedures resulting from TMI-2 prevent any damage to the reactor fuel.

TVA's Sequoyah-1 becomes the first U.S. nuclear unit since the TMI accident to be licensed to begin operation, but is limited to low power.

March

NRC staff recommends the controlled venting of krypton gas from the TMI-2 containment building, noting the infinitesimal effect it will have on the environment relative to natural background radiation and the benefit of avoiding an uncontrolled release.

Another contribution was the preliminary scoping of a program ordered by NRC to test relief and safety valves. This program is now being implemented in cooperative projects by the Nuclear Power Division of EPRI, various utilities, and the reactor vendors. Phase 1 testing has started.

From the outset, one of the tasks of NSAC has been to suggest improvements in the safety of nuclear systems, based on experience. NSAC is tackling the task with two programs.

In the first, called significant-event evaluation, NSAC contractors are reviewing all Licensee Event Reports (LERs). (These are compulsory reports sent to NRC on safety-significant events at nuclear plants.) Because many of these LERs cover relatively minor events, the first step is to systematically single out those events that have true safety significance and are generic in nature. These are then studied in depth, and significant findings are communicated to the utilities concerned. This task is truly a massive one—there are about 300 LERs filed each month.

LER review is, and for some time has been, one of the responsibilities of NRC. But the TMI accident revealed that NRC's review was very slow in many cases, and the information derived was not communicated rapidly to the industry. The utilities had no system of their own, and reactor manufacturers responded only when called upon by owners and NRC. No one was making full use of the information in LERs. Currently, NRC has restructured its LER review function, but NRC analysts will have, in part, different objectives from those of the utilities and NSAC. INPO and NSAC will work together to review LERs with an eye toward the procedures and training programs of INPO and the physical plant technology and safety studies at NSAC.

NSAC is interested in studying events at nuclear plants that indicate generic safety problems applicable to many reactors. An example of such an in-depth study occurred in February 1980 when a temporary loss of power to non-safety-related instruments and controls at the Crystal River plant in Florida caused the reactor to shut down and cooling water from the reactor circuit to be discharged into the containment building. With the agreement of the plant operator, NSAC and INPO promptly sent a team of engineers to the plant to analyze the problem. A report of that analysis was sent through Florida Power Corp. to other utilities that might experience a similar situation. The report was also submitted to NRC.

Access to information of this type and to current safety-related data is speeded considerably by NSAC's Notepad system of rapid electronic communication. More than 130 Notepad stations are operating at 42 utilities that own reactors. Portable terminals, no larger than a small portable typewriter, provide full access to current information from any telephone. There is also a microfilm library containing more than 100,000 items related to nuclear safety. This library is continuously updated by the NSAC staff, the Nuclear Power Division of EPRI, and others, and it is accessible through an electronic search system called Zytron. A hard-copy library of reports, including many safety analysis documents, is in place at NSAC and can be accessed by all utilities. NSAC has electronic access to repositories of nuclear safety data at the Nuclear Safety Information Center in Oak Ridge and at other sources in the United States.

To provide information on the effects of low-level radiation on human health, NSAC is sponsoring continuing work on radiation effects through EPRI's Health Effects Program. A report on this important subject, summarizing information in commonly understood terms, is being prepared.

Perhaps one of the most important functions of NSAC is to evaluate and comment on new regulations, criteria, and standards that are issued by NRC, the Federal Emergency Management

Agency (FEMA), and state and local agencies.

In the future, the significant-event evaluation program and responding to new licensing and regulatory actions will take an increasingly large share of NSAC's effort. Safety analysis attention to the generic aspects of regulation and licensing problems in the industry will be shared with the Nuclear Power Division of EPRI, where appropriate. For instance, NSAC will be responsible for technical and equipment analyses and for system performance. In this area, NSAC will continue to call on the experts and the broad scientific programs in EPRI's Nuclear Power Division. Where new R&D efforts are necessary to understand nuclear systems safety, the Nuclear Power Division of EPRI will be responsible. An example of a program that is the responsibility of EPRI's Nuclear Power Division is the planning and coordination of data collection during the cleanup at TMI.

Institute of Nuclear Power Operations

TMI emphasized again the importance of operation and management to nuclear safety. The utility industry recognized the necessity to improve the level of excellence here, as well as in the physical plant.

To fill this need, the nuclear utilities established INPO. Plans for its formation were announced on June 28, 1979, and Chauncey Starr, vice chairman of EPRI, was asked to develop the basic plan for its organization. With the help of the EPRI staff and the advice of training and management experts from many areas, including industry, the U.S. Navy's nuclear program, NASA, and airline safety programs, this organization plan was completed in the early fall of 1979.

By October a board of directors had been selected, chaired by William Lee, president of Duke Power Co. By November Atlanta had been selected as the headquarters, and by January 1980 Eugene P. Wilkinson had been confirmed as the president of INPO. (Wilkinson was the first skipper of the first nuclear submarine, the USS *Nautilus,* and retired from the navy as vice admiral.)

The focus of the new institute is to establish standards of excellence in the management and operation of nuclear power plants. INPO will regularly evaluate operating practices at nuclear plants to help utilities meet the standards. INPO will also set criteria for training programs and instructors, and it will review and analyze operating experience, emergency preparedness, and the human aspects of plant systems design.

The utilities recognized the importance of getting INPO to function quickly, and task forces prepared standards for excellence in operation, training, management, and emergency planning. INPO is now being staffed and will grow to an estimated staff of 200 professionals. The new president and the staff are developing close working relationships with individual utilities, other industry organizations, and NRC. The 1980 budget, subscribed to by member utilities according to the size of their nuclear programs, is $11 million. All nuclear utilities are now members of INPO.

The establishment of INPO is decidedly a new direction for the electric utility industry, in particular for the nuclear utilities, and its program of self-improvement draws on 25 years of reliable operating experience. INPO's philosophy of helping utilities help themselves recognizes that resolving an operating problem at one nuclear plant can help avoid a similar problem at many other plants. That INPO is operating after only nine months from the proposal for its establishment reflects the intensity and urgency with which the utilities view the accident at TMI-2.

Report to the president

Full details of NSAC's and INPO's progress in improving nuclear safety were presented in *Report to the President and the American People: One Year After Three Mile Island.* The report was delivered to the White House on March 25, 1980, by a delegation of five: Floyd Lewis, chairman of the board of EPRI and of Middle South Utilities, Inc., as well as chairman of the industry's oversight committee; Edwin Zebroski, director of NSAC; Carl Walske, president, Atomic Industrial Forum; John Selby, president, Consumers Power Co.; and Robert Partridge, executive vice president, National Rural Electric Cooperative Association.

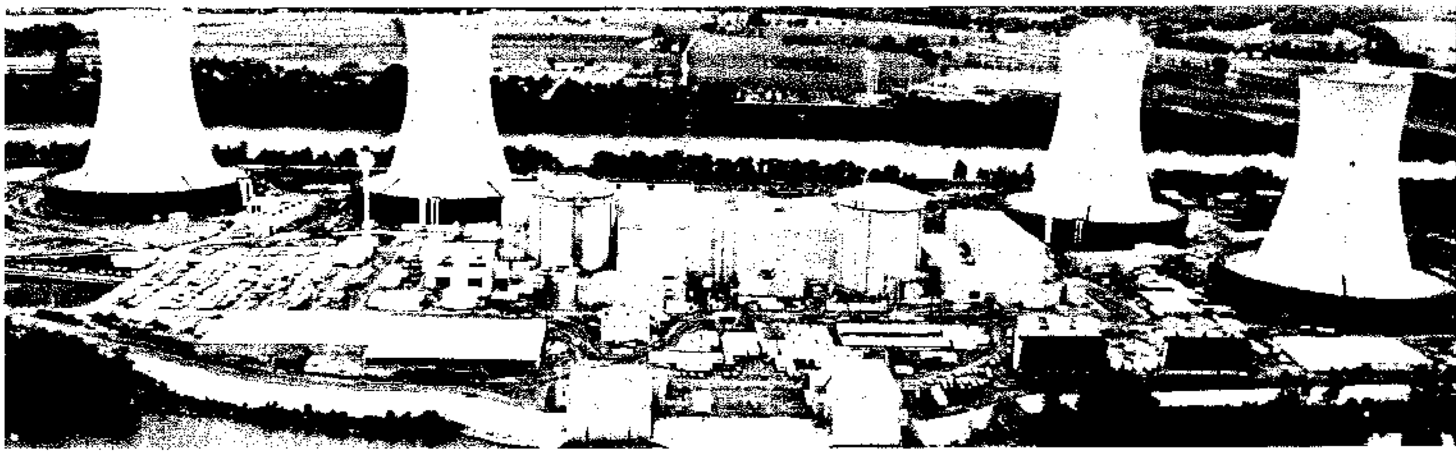
Several themes were stressed in the report. First, the TMI-2 accident was serious but not highly dangerous; official reports show that many of the fears at the time were largely based on misinformation. Second, the U.S. electric power industry has responded quickly and forcefully to the accident by revising procedures and training in nuclear power plants, making equipment changes, and establishing major new organizations to correct the inadequacies indicated by the accident. As a result, nuclear power plants are even safer than they were a year ago. Third, it has been demonstrated since the TMI-2 accident that not having nuclear power puts a heavy cost burden on the utilities and on the nation as a whole.

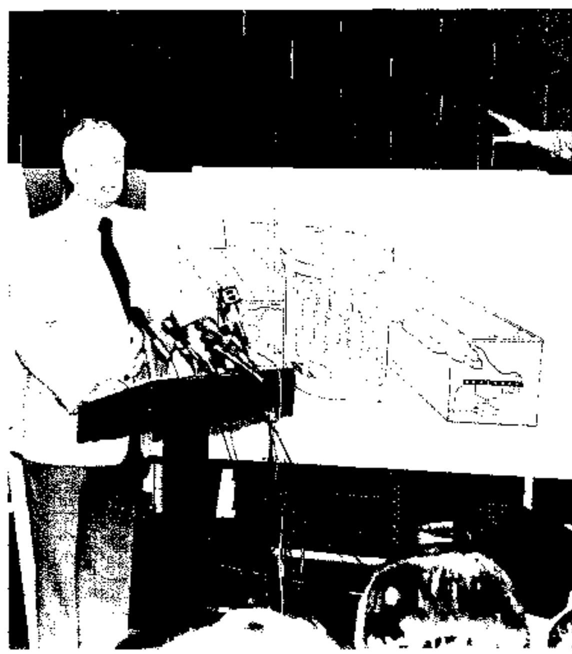
Government reaction

The federal government acted swiftly in the weeks immediately after the TMI accident. While the operators at the plant were still working out plans for long-term stable conditions for the plant, Congress launched a series of public hearings. The president and NRC also moved to seek the factors that contributed to the accident and to provide the basis for steps that could help prevent another of similar gravity.

Two weeks after the accident, President Carter appointed a 12-member commission, charging it to make a comprehensive investigation. More specifically, he instructed the members to assess the event, its causes, and its possible impact on the health and safety of the public and the personnel at the plant. Members were to analyze the managing utility's role and evaluate the emergency preparedness and response of government

In the crisis environment of the first few days, industry and government officials and nuclear experts—along with the national press—converged on the plant site at TMI.





Temporary offices were established for technical personnel, and a nationally organized effort was set in motion to help with the recovery operations.

agencies. Further, they were to evaluate NRC's licensing, inspection, operation, and enforcement procedures and give their opinion on how the public's right to information was served in this event and how it should be served in any future event. Then they were to make appropriate recommendations based on their findings.

The commission, led by its chairman, John Kemeny, president of Dartmouth College, initiated a wide-ranging investigation of the TMI-2 accident. In its report, published on October 31, 1979, it recommended that NRC be restructured with the control in the hands of one person rather than five. It concluded that serious deficiencies marked the regulation and operation of nuclear power plants, though it did not endorse a moratorium on nuclear development.

The report was commended by NRC, the nuclear industry, and others as accurate, lucid, and imbued with depth of perception, despite the complexity of the issues involved.

Commenting on the report, NRC's chairman, Joseph Hendrie, said that based "on the results so far of our own internal reviews of the accident, we have generally found that the actions recommended by the president's commission . . . are necessary and feasible."

Five weeks later the president, too, expressed his support for the recommendations: "We cannot shut the door on nuclear energy. We must take every possible step to increase the safety of nuclear power produced. I agree fully with the spirit and intent of the . . . recommendations." At that time, the president appointed John Ahearne as temporary chairman to replace Hendrie.

In June 1979, three months after the accident, NRC set up its own inquiry group, headed by attorney Mitchell Rogovin, to investigate the way in which its regulatory processes functioned in licensing the TMI plant and in handling the accident. Many of those who testified before the Kemeny commission also gave evidence before the Rogovin group. Although the Rogovin commission was not meant to duplicate the efforts of others (among them, the Kemeny commission), its charge was to determine what happened and why, to assess the actions of utility and NRC personnel, and to identify deficiencies in the regulatory system.

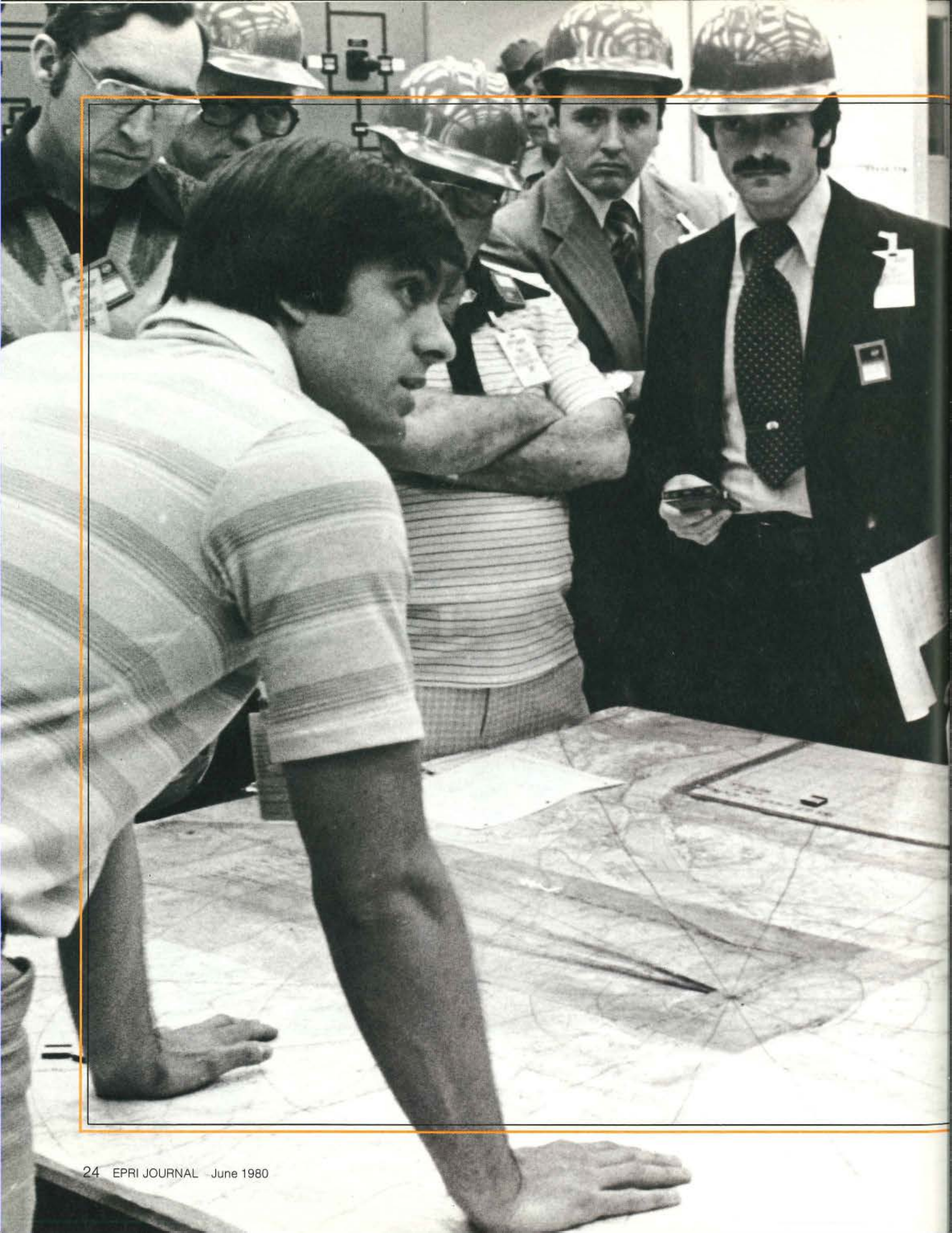
The result was a report in two volumes: the first in popular, dramatic language; the second, more technical. It appeared on January 24, 1980, but received less attention because it echoed many of the Kemeny commission's findings published almost three months earlier.

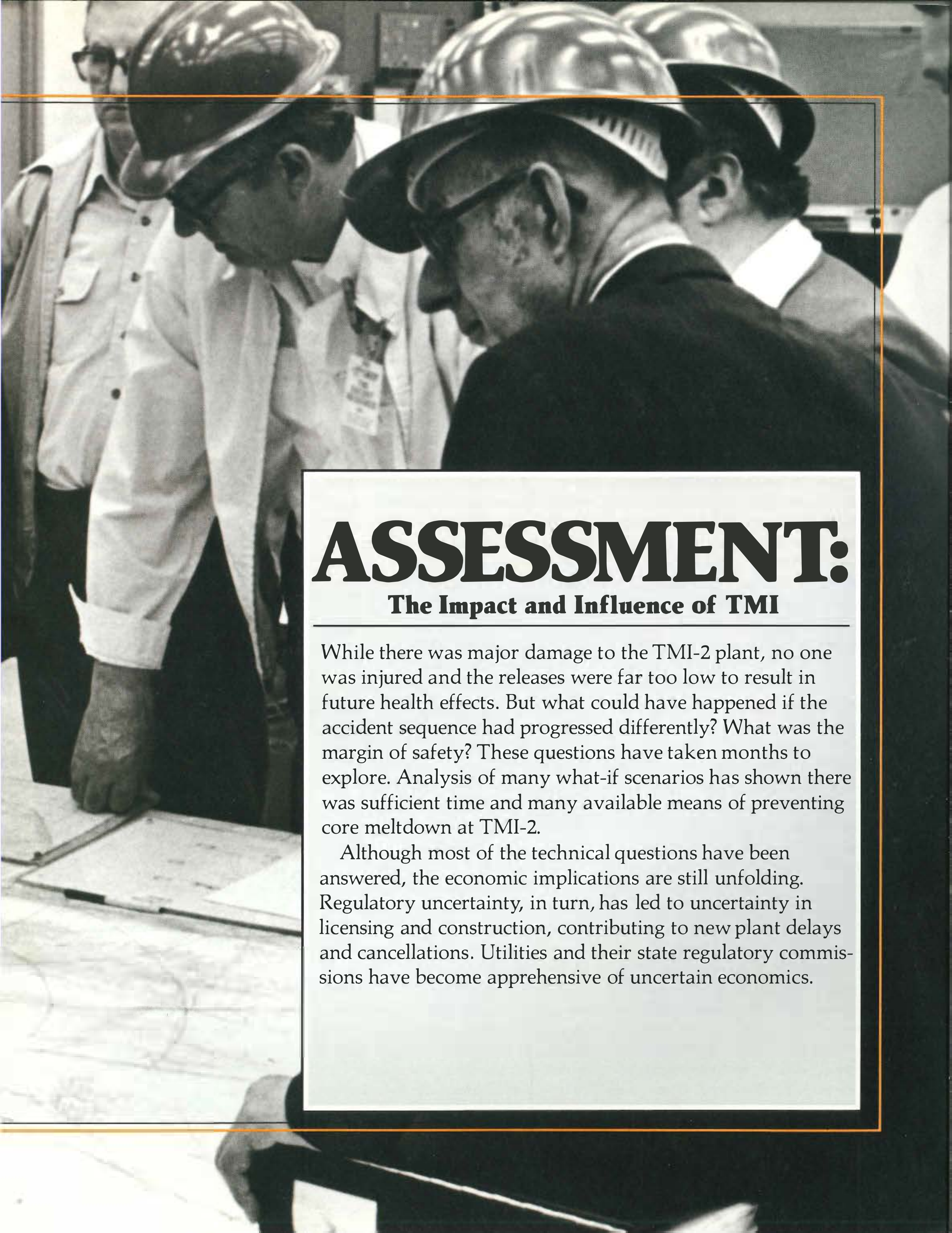
During the time the two investigative groups were digging for facts, Congress was listening to testimony from scores of witnesses. For example, a series of hearings was held by Representative Morris Udall, chairman of the House Subcommittee on Energy and the Environment. As a result, he introduced a comprehensive bill in Congress on January 31, 1980, that covered licensing, nuclear wastes, and insurance.

Senator Gary Hart, chairman of the Senate Subcommittee on Nuclear Regulation, indicated he would present his findings on TMI-2 in June 1980, when his subcommittee completed the hearings it began in June 1979.

Several other congressional committees also held hearings on the accident. For example, Representative Mike McCormack, chairman of the Subcommittee on Energy Research and Production, held hearings on reactor safety in May 1979. Representative Toby Moffett, chairman of the Subcommittee on Energy, Environment, and Natural Resources, held hearings in which he criticized the lack of better emergency plans. These hearings further alerted NRC to these concerns, and subsequent NRC actions and requirements seem to support the ideas suggested. Significantly, the earlier call for a moratorium on nuclear plant operation never found its way into law, and both Senator Hart and Representative Udall have recently spoken of the need to maintain the nuclear part of the U.S. energy supply mix.

Despite the actions taken by the president, the Congress, the utilities, and the investigating committees, there are indications of public uncertainty about the adequacy of the institutional structure in dealing with nuclear safety. That this feeling is not universal is substantiated by a poll taken this spring in cities near TMI, which indicates 58% of the respondents favor a restart of the undamaged TMI-1 reactor. The challenge nevertheless remains to ease concern and increase confidence in the safety of nuclear systems by broadly based changes in the regulatory agencies and in the utilities' attitudes toward safety. ■





ASSESSMENT:

The Impact and Influence of TMI

While there was major damage to the TMI-2 plant, no one was injured and the releases were far too low to result in future health effects. But what could have happened if the accident sequence had progressed differently? What was the margin of safety? These questions have taken months to explore. Analysis of many what-if scenarios has shown there was sufficient time and many available means of preventing core meltdown at TMI-2.

Although most of the technical questions have been answered, the economic implications are still unfolding. Regulatory uncertainty, in turn, has led to uncertainty in licensing and construction, contributing to new plant delays and cancellations. Utilities and their state regulatory commissions have become apprehensive of uncertain economics.

Damage to the TMI-2 core is severe. In addition, equipment in the containment building is contaminated by radioactivity and is suffering the effects of standing idle for more than a year in a wet environment. In the sense that they must be cleaned for renewed plant operation, the pumps, piping, and tanks in the auxiliary building are also damaged. By all these measures, the plant itself experienced disaster. Restoring TMI-2 to service means "rebuilding the engine."

No one was killed or injured by the accident, and except at the plant, there was no physical damage. Several million curies of radioactivity escaped, mostly as inert gases, and there were also traces in waste water released to the river. Fortunately, measurements and analyses both confirm that exposures off-site were much smaller than the natural background radiation in Pennsylvania, even smaller than the variations of background in different geographic regions. (Natural background radiation in Denver, for example, is about twice as high as that in Pennsylvania.) Thus, the Kemeny commission concluded that exposures resulting from TMI will not produce a measurable direct effect on public health.

Economic damage to Metropolitan Edison Co. and its service area is substantial. For the utility itself there is a $1.5 billion investment (TMI-1 and TMI-2) idled for a matter of years, with cleanup and repair costs of TMI-2 estimated to exceed $400 million. To offset this, insurance coverage stands at $300 million.

The extra cost of replacement power is a burden on both Metropolitan Edison and its customers, amounting to nearly $1 million a day as long as TMI-2 and the undamaged TMI-1 are shut down. The fuel-related cost of coal-based electricity is nearly twice that produced by TMI; for oil-based electricity, it is 5–10 times greater. Until a partially compensating rate increase was granted by the Pennsylvania Public Utility Commission, the utility absorbed this cost and for a time faced the prospect of bankruptcy.

Reactor core ruined

For nearly 2 hours after a condensate pump tripped out in one of the secondary water loops at TMI-2, the accident was only a sequence of temperature, pressure, and flow changes in the reactor vessel, the primary coolant loop, and the secondary loop. It was serious because of the unrecognized leakage through the pressurizer relief valve that had stuck open. But truly irreversible damage occurred only when water ceased to flow in the core. The water level then dropped; the upper half of the core began to boil dry as a result of its own decay heat, which was then about 0.3% of the full power level.

With the top of the core in an atmosphere of superheated steam, essentially all the fuel rods would be expected to rupture. This was the source (not immediately evident) of the radioactive gases that escaped from the containment building and, ultimately, from the plant. The path was a loop of makeup and letdown water circulating between the reactor and the auxiliary building, a loop used to maintain the quantity and quality of water in the primary system. This flow was maintained during the evolving accident, both compensating for leakage and continuing to provide the flow required for pump seals. Some of the radioactive gas dissolved in this water, passed through this loop, and escaped through vents from the auxiliary building.

The high fuel temperatures also caused oxidation of about half the Zircaloy cladding of the fuel rods. According to current estimates, the upper half of the core is severely oxidized across about two-thirds of its diameter, and the rest of the core is oxidized to a lesser degree. Temperatures in the most severely damaged parts of the core were high enough to melt some metal parts, as well as cladding that had not already oxidized. Some uranium oxide fuel would be expected to dissolve in this cladding. In this limited sense, there probably was localized fuel melting; but this does not imply damage to the containment structure (or serious environmental effects), as has been widely conjectured.

Outside the core itself, there is believed to have been little or no structural damage. The reactor vessel and the primary piping are probably intact, but both will need to be thoroughly examined before there is any consideration of putting the unit back into service.

The lower levels of the containment and auxiliary buildings were contaminated during the accident because a substantial fraction (roughly half) of the volatile fission products were released or leached from the rupture-exposed fuel. Except for the inert gases (xenon and krypton), this radioactivity now remains mostly in the sump of the containment building.

For a time it was surmised that much of this building's interior, even above the operating deck, was grossly contaminated, which would add to the difficulty and cost of cleanup and repair. Material samples cut from the building and instrument probes have now established that residual radiation levels are low enough (except in the sump) for workers to enter and operate cleanup equipment. Preparations for regular entry are being made, and it will be possible for crews wearing air masks and protective clothing to go into the containment for limited working periods even before the remaining krypton gas is removed.

As this is written, the containment building is estimated to contain about 50,000 curies of radioactive krypton, and the decision on the rate of venting is pending with Pennsylvania and NRC officials. If the gas is released over a period of about 50 days when the weather is favorable, the ground level exposure for anyone will be less than 5% of natural background radiation, more likely, less than 1%. For perspective, background levels in the counties around TMI vary from one another by more than 300%.

Analysts of the TMI-2 plant, who are continually monitoring its status, are anxious to complete this step soon, noting that air circulation fans and other equipment inside the containment have now been running without maintenance for more than a year. Should these fans stop, normal solar heating of the still air in the structure would raise its pressure (now less than the air pressure outside) and create a possible problem of small leaks. It is possible these leaks might result in larger concentrations of krypton in the environment than would occur with controlled venting when the weather is good. In neither case are the releases hazardous.

Radioactivity accidentally released

During the earliest hours and days, the acute phase of the accident, several million curies of radioactivity escaped from TMI-2 as intermittent leaks of two inert gases, xenon and krypton. Between 10 and 20 curies of radioiodine also escaped as vapor that evolved from solution in the auxiliary building tanks. By their natures these gases pose distinctly different hazards. Being inert means that xenon and krypton do not react chemically and thus are not retained as compounds in biologic systems. At TMI, therefore, a radiation dose from this source could occur only during the brief passage of a gas plume. The highest momentary dose rate (equivalent to about 1300 millirem per hour) was recorded by helicopters flying in the plume at 200-ft altitude, just above the vent stacks. At ground level immediately next to the plant, such dose rates probably did not exceed 20 millirem per hour.

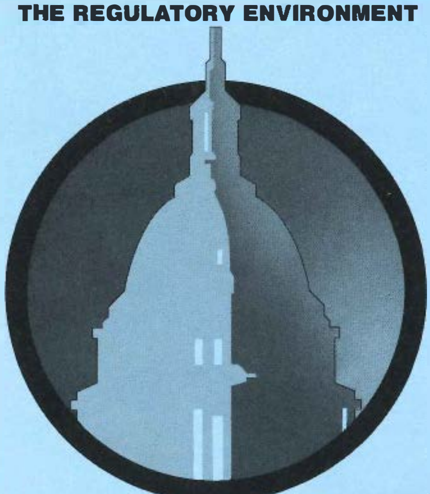
Possibly the most exposed person was a man working on a nearby island in the Susquehanna River, and his highest cumulative dose (whole body) is believed to have been less than 40 millirem.

Radioiodine is a greater potential danger because unlike the inert gases, iodine is absorbed into tissue and is concentrated in the thyroid. But fortunately, the amount released at TMI was very small and occurred over a period of about two weeks. Special charcoal filters and the water in the containment held the radioiodine emissions to the atmosphere to about 10% of what was produced.

The highest estimated thyroid dose from radioiodine at TMI, possible for an individual remaining close to the site for several days, was less than 10 millirem.

For perspective on these doses, the maximum hypothetical whole-body exposure of anyone near TMI was about equivalent to a single chest X ray or to the natural background radiation experienced in a few months simply by living in Pennsylvania. (On average, natural background radiation amounts to a whole-body dose of about 100 millirem in a year.) Medical use of radioiodine in scans for diagnostic purposes involves doses of 20,000–50,000 millirem to the thyroid. Sparingly administered, such scans have not been found to produce ill effects, even though the dose level is

THE REGULATORY ENVIRONMENT



The year following TMI has seen marked changes in the nuclear regulatory environment, both for the utility industry and for NRC itself.

From the point of view of the industry, the changes have been mainly an intensification of regulatory pressures of all kinds. Almost immediately after the accident, NRC announced that it would cease to consider construction permits for new plants or operating licenses for plants nearing completion in order to allow it time both to probe the causes of the accident and to devise regulatory measures to prevent a similar recurrence and other serious accidents.

Several months later, NRC issued its *Short-term Lessons Learned* report containing a number of detailed recommendations that it quickly translated into requirements to be complied with on a time scale so short, in some cases, as to be impractical.

About nine months after the accident, NRC issued a detailed draft of its proposed post-TMI action plan consisting of over 200 items. The plan was submitted for industry review.

This review, as well as those by NRC's Advisory Committee on Reactor Safeguards and by the NRC commissioners themselves, was critical of the action plan on the grounds that no distinction was made between the important tasks and the unimportant ones, and many tasks were aimed at the same objective. Resources required to execute the plan in the near term were beyond the capabilities of the industry. In a joint AIF–NSAC working group, a substantial effort was made to provide recommendations to NRC on scopes, priorities, schedules, and resources for these items.

NRC's pause in licensing is being eased by degrees, but licensing for many reactors will take at least a year longer than otherwise and may be further delayed by new requirements still to be implemented.

2000–5000 times greater than the highest at TMI.

Perspective on TMI radioactivity as a nuclear power accident phenomenon is provided by an accident in 1957 at England's Windscale plant. About 20,000 curies of radioiodine escaped there and passed up the food chain from hay to cattle to milk, yielding human thyroid doses up to 13,000 millirem. After the Windscale accident, milk produced in the vicinity was dumped for several weeks. Surveys of the area and its people for 20 years thereafter detected no public health consequences.

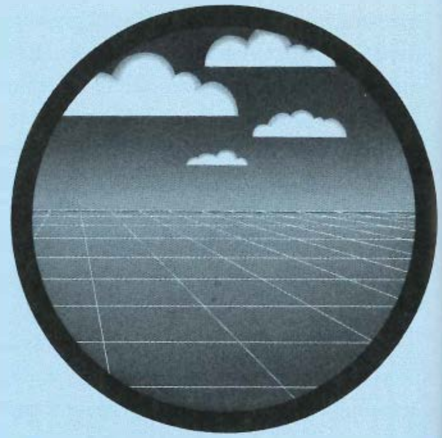
On bases such as these, but especially on the basis of radiation data from TMI and statistical projection, the Kemeny and Rogovin reports both conclude that the accident exposures will produce no discernible direct health effects. When the estimated dose rate at TMI was first aggregated over the 2.3-million population of the area, it amounted to a worst-case estimate of 5300 person-rem; this would imply an average of 0.0023 rem to each person in the TMI area. Later, more detailed analysis suggests a probable value no greater than 2000 person-rem in the TMI area.

There may be a threshold dose of low-level radiation below which it is harmless. Or there may be a linear or some other relationship between dose and effect. Different studies of the past 35 years have not resolved this question. However, conservatively assuming that low-level radiation effects are in linear proportion to dose, the 5300 person-rem figure leads to a 50% chance of one additional cancer case attributable to TMI in the next 20 years. This could never be detected because the total number of cancers ultimately expected in this size population is about 300,000, and the rate will vary unpredictably over time and location.

The wide perception . . . and long view

Undeniably, TMI was a spectacular industrial accident, simply in terms of damage to the large investment in pro-

THE BROADER IMPACT



The aftereffects of TMI remain a major influence on most plans involving nuclear power. While TMI no longer makes daily headlines, there are frequent reminders on the inside pages, and for the nation's utilities, nuclear plant licensing delays continue.

Initially, GPU, the owner of TMI, has been the hardest hit. GPU's net additional cost to purchase or produce electricity to replace the lost output of TMI-1 and TMI-2 climbed to $310 million by the end of March 1980. GPU has borrowed $225 million to meet this burden.

Equally painful has been the $100 million in initial costs (through February of this year) to clean the auxiliary building, to install and operate facilities to process and store contaminated water from the auxiliary building, and to provide general caretaking of the crippled plant.

Still to come are projected cleanup costs of $275 million. Repair might add $125 million. It will not be possible to decide whether TMI-2 can be returned to service until after the damaged core has been removed and the primary system inspected and tested. This is not scheduled until about the fall of 1982. A decision concerning restart would not be likely until mid-1983 or 1984.

Although GPU has been the first to feel the financial impact, all utilities with nuclear plants can feel reverberations in the effect of added regulations, and several are suffering delays approaching a year or more in obtaining operating or construction licenses. NRC's response to the accident has come in two waves of recommendations, and it plans to initiate rule-making hearings on several major issues, including siting and, possibly, new design requirements.

The first wave of recommendations (about three months after the accident) contained 23 changes that could be made most quickly, including changes in operating procedures and in equipment, such as instruments to verify that the water is not boiling in a PWR's core. Most of these changes were implemented during 1979 and will cost a total of about $1 billion by the time they are fully implemented in all plants in operation and under construction.

The second wave of recommendations (about nine months after the accident), which NRC has been considering, includes over 180 additional changes, about 50 of which are considered to be reasonably significant. It is estimated that all these changes may cost as much as $3.5 billion for further plant modifications and up to $32 billion for replacement power while the plants are idled or delayed in startup, as well as requiring 13,000 engineering man-years for the work to be done.

For individual nuclear units in the United States, the costs of second-wave changes are expected to vary between $28 million and $700 million for plant modifications and new safety systems. NRC has started to assign priorities to this very large number of recommendations and requirements. There is real doubt that all the proposed changes have merit. Many, while apparently useful if taken alone, are of no added value in the context of changes already made or committed. The response of the nuclear industry has been that this surge of new requirements is not justified by the added safety to be realized and that the burden of implementation is very great.

All this is only the tip of the iceberg. Since that day in March 1979 when the first alarm went off at TMI-2, 16 nuclear plant projects at various stages of development have been canceled. Only 108 of the 124 plants under construction or on order at the time of the accident still remain. In the last half of 1979 there were 28 new schedule delays, and in January 1980 alone, 9 new delays were announced. By March, the starting dates of 30 plants that had been formally committed were rescheduled to 1988 or beyond. Two-thirds of these 30 now carry completion dates in the 1990s or are listed as indefinitely deferred.

While several reasons have been given for some of the delays and cancellations (such as lower load growth and difficulties in raising capital), the regulatory and financial uncertainty, caused by regulatory vacillation, that has arisen in the post-TMI environment is the dominant factor. On almost every electric utility system, whether or not it already includes a nuclear unit, added nuclear capacity would reduce the overall costs of making electricity by offsetting the high costs of existing oil- and gas-fired units. But utilities and their state commissions are wary of costly startup delays or major changes caused by additional regulation and deferred regulatory decisions.

In this environment of uncertainty and misinformation, state regulatory commissions may be reluctant to allow nuclear plants. In several instances, they are bringing pressure on utilities to cancel nuclear projects, even where a considerable investment has already been made. For instance, in encouraging Wisconsin Electric Power Co. to cancel its Haven nuclear plant project, Commissioner Edward Parsons of the Public Service Commission of Wisconsin said, "We don't know yet what the aftermath of TMI is." Wisconsin Electric Power had already spent $45 million on the Haven project.

Similarly, during consideration of Long Island Lighting Co.'s proposed twin Jamesport units, the chairman of the New York State Siting Board, Charles Zielinski, said that the regulatory uncertainty surrounding nuclear plants since the accident at TMI "leaves us with substantial doubt about the wisdom of relying on a new nuclear plant."

Utilities are wary for reasons other than fundamental issues of safety. They are concerned about the economic risks generated by actual and implied changes in licensing and regulation. They fear delay and retrofit; they feel insecure because they do not know what NRC and FEMA will require. In canceling proposed Erie-1 and -2 and Davis-Besse-2 and -3, in which a total of $60 million had been invested, officials of the Central Area Power Coordinating Group explained in a joint statement, "The political and regulatory uncertainties affecting the future construction of nuclear plants have intensified following the accident at TMI."

Describing the cancellation of the proposed Tyrone unit, Northern States Power Co.'s chairman and president, Don McCarthy, said that TMI was considered by the co-owners when making the decision. "Generally, the accident has increased the uncertainties about the future of nuclear power," he stated. "These uncertainties make it less likely that the Tyrone project could be licensed in a timely fashion."

Frederick Clark, chairman of the New York State Power Authority trustees, recommended canceling the Greene County nuclear power project because of an enormous increase in the estimated cost of the project and recent events that mandate caution and make licensing and construction more difficult. He went on to note, however, that New York must reduce its great dependence on imported oil. Of the electricity produced in New York state during 1978, 44% was generated by burning oil, most of it purchased from foreign countries. At the time of the cancellation, $147 million had been invested in the Greene County nuclear project, and close-out costs were expected to add another $30 million.

The costs that GPU will incur as a result of the accident at TMI-2 are large by any measure. The costs that the utility industry and the nation will bear in reaction and perhaps overreaction to TMI are awesome. But these are dwarfed by the consequences to the United States of 16 nuclear plants canceled and 30 more whose future is uncertain and which, at best, will not operate for a decade or more. These plants would displace the equivalent of approximately 1,250,000 barrels of oil a day.

Since new coal plants to replace this canceled and delayed nuclear capacity now take over 10 years to site, license, and construct, the lost nuclear production will translate into a decade or more of higher oil and gas consumption, higher oil imports, and higher energy prices generally.

duction facilities. Although the health effects are negligible, the accident has contributed to widespread misunderstanding and fear of low-level radiation effects. There continues to be a recurring and exaggerated media theme that any nuclear plant malfunction is a narrowly averted disaster that would produce high-level radiation. Given this message, it is perhaps unexpected that a majority of those polled a year after the accident, both in Pennsylvania and nationally, continue to support nuclear power.

Although a minority view, the perception that nuclear power may not be as safe or economic as once believed has evoked review after review of every facility, operating or planned, and of every investment, regulation, and legislative act touching on them.

Of far-ranging significance, all licensing of U.S. nuclear plants has stopped during the past year, lengthening schedules and resulting in the ultimate loss of an estimated 150,000 MW-years of nuclear electricity-generating capability. This is equivalent to burning 1400 million barrels of oil in conventional fossil-fueled power plants; and if this was done in a single year with imported oil, it would use more than half our present imports and represent a $30 billion negative effect on the U.S. balance of trade.

Further delays that may be ascribed to the TMI-2 accident will be more costly as regulatory reviews slow even more and the costs of investment capital continue to rise. Ten nuclear projects were canceled in the first four months of 1980, and more are likely to be canceled while the combination of regulatory uncertainty and high financing costs prevails. Meanwhile, electricity rates are rising because of sharp increases in the cost of conventional fuels—oil, gas, and coal. The irrevocable loss of nuclear generating capacity for the rest of the century is already equivalent to 2 million barrels of oil per day during that time, regardless of conservation efforts. This represents an additional fuel bill of as much as $500 billion, or $2000 for every person in the United States, and is one measure of the price being paid as a consequence of fear arising out of an accident that according to the most thorough estimates may not have physiologically hurt even one member of the public.

Could it have been worse?

The widespread alarm occasioned by the TMI accident stems not only from what did happen but also from fear of what might have happened, then or afterward.

"What if . . . ?" became the catch phrase of many inquiries a year ago. It also marked expressions of intellectual curiosity from serious safety-minded observers, and it has been a major task for engineers of NSAC. Their second charge, after thoroughly documenting the actual accident sequence (completed last July), was to postulate and analyze other plausible accident sequences that might have happened at TMI if equipment or operator responses had been somewhat different. These studies help to identify the remaining margin of safety and provide a basis for evaluating proposed improvements in reactor design or operation.

One such study treats the extreme circumstance in which water loss through the pressurizer is never stopped and makeup water flow stops altogether. Without emergency cooling, the core would boil entirely dry. One of the most dramatic and widely quoted statements to flow from authoritative investigation of the TMI accident appears to describe the consequence of this eventuality. NRC's Rogovin report, issued in January of this year, considered what might have happened if the TMI operator had not closed the pressurizer block valve some $2\frac{1}{2}$ hours after the accident sequence began and later restored, at least temporarily, the pumped circulation of primary coolant. According to this statement, ". . . Within 30 to 60 minutes, a substantial portion of the fuel in the core —certainly the center of the top half of the core, and perhaps as much as half of all the fuel—would have melted [within the reactor vessel]."

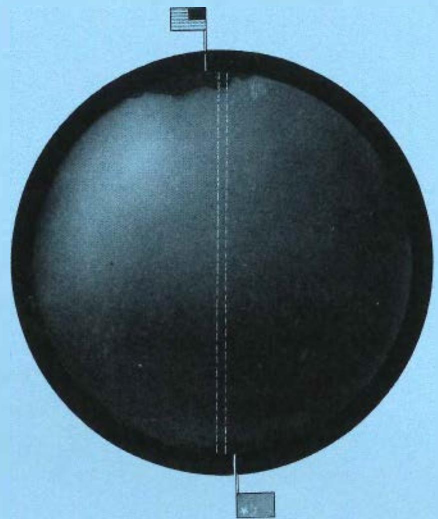
Many people, however, are not familiar with an equally important statement three paragraphs further on: "One thing the analyses do seem to agree on, though, is that even with a core meltdown, there is only a small probability that the consequences of TMI would have been catastrophic to public health and safety. The most likely probability is that the reactor building would have survived this accident scenario, and the vast majority of the radioactivity released from the fuel would have been retained within the building, not released to the surrounding environment." NSAC, the Kemeny commission, and other analyses all support this conclusion.

For the more than 2 hours that the open pressurizer relief valve of TMI-2 remained undetected, the plant experienced the equivalent of a small pipe break. For such an accident, three important points can be made. One is that there is a relatively long time interval in which to observe and analyze the situation and to start emergency water flow into the reactor. Beyond this, even without water, it would take dozens of hours for the core and then the vessel to melt, and then possibly penetrate the thick concrete containment building floor. As far as it went, the actual TMI-2 accident sequence confirmed these delays.

The second important point is that restoration of water at any time during this period, by any means, with or without closure of the relief valve would stop the progress of damage or melting. Injected water takes away the decay heat sufficiently to stabilize the situation at whatever point of damage may have been reached. And there are many paths for water supply to a reactor, both for its normal operation and for emergencies. Others can be improvised rapidly, even when normal power supplies are lost.

The third point is that even if the relief valve stayed open indefinitely and without additional water, large-scale melting (even to the point of total core melt) would not mean there would be a breach of the containment structure. Given

THE CHINA SYNDROME



Perception that TMI could easily have escalated to a much more serious accident or that total catastrophe was only narrowly averted depends on two assumptions. One is that core melting, once begun, cannot be stopped.

The other assumption is that a completely destroyed core, a meltdown, is tantamount to the China syndrome, in which a molten mass of fuel slowly melts its way through the concrete base of the containment and eventually into the earth below, and from here, radioactivity spreads by diffusion or in the flow of groundwater.

Neither of these assumptions is an inevitable consequence of core damage. These worst-case and what-if assumptions do not stand up against the actual situation at TMI, where the reactor's cooling systems were still intact and usable. Operators had many means of stopping the accident. Nor do these assumptions recognize the sturdy nature of a massive reinforced-concrete containment building. Why, then, did they arise?

As recently as 1974 and as a matter of conservatism in its approach, the benchmark *Reactor Safety Study* (Rasmussen report, WASH-1400) seemingly gave credence to the China syndrome in two of its assumptions. One was that given a fuel temperature of 1200°C (2200°F), gross core melting proceeds almost inevitably. (Zircaloy cladding melts at about 1930°C [3500°F]; uranium oxide fuel melts beyond 2760°C [5000°F].) The other assumption was that gross core melting continues. This does not recognize the numerous actions that can be taken to stop an accident sequence. Thus the pressure vessel was hypothetically allowed to rupture, and the containment eventually was allowed to fail without allowing for the possibility of intervention by either automatic systems or operator-initiated responses. The WASH-1400 assumptions were made as a means of arriving at the worst-case disaster so that the consequences could be evaluated.

It is now clear that with realistic assumptions, many means are available to terminate such a sequence before the containment would be threatened. Adding enough water at any time stops fuel melting by draining off the heat on which it feeds. Plant design provides many built-in mechanisms for heat removal, all of which are capable of stopping fuel melting. Also, multiple systems (some intentionally redundant for safety) provide many courses of operator action. To improve the ability of operators to recognize a potentially damaging excursion and to act appropriately, training to deal with "degraded core conditions" is now being emphasized.

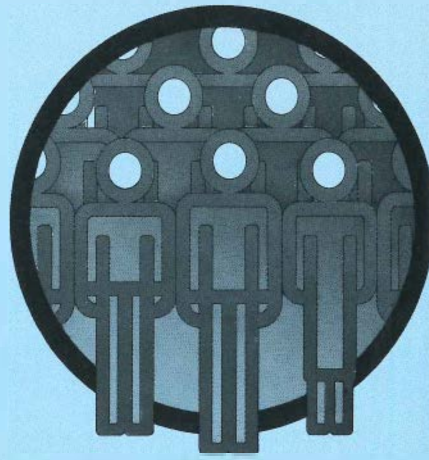
Although the China syndrome seems plausible, it does not accurately take into account the total thermal energy of a reactor core compared with the much larger energy-dissipating capability of the reinforced-concrete mass that is the base of a reactor containment building. At TMI-2 a worst-case melted core would have solidified on and within that concrete mass long before it could start on the path to China.

The quantity of radioactive material released at TMI was small, and all experts agree there is essentially no possibility of finding recognizable physical or genetic damage. But these health issues, together with questions about the psychological well-being of the people living in the vicinity, are now being studied. The Pennsylvania State Health Department and federal agencies (with limited participation by EPRI) are doing epidemiological studies on this population.

Because the measured radiation dose levels were much less than 1% of the lowest levels that have produced biological effects, there is little probability of finding detectable physical effects. This view is the result of extensive tests with both humans and animals over the past 35 years. Current investigation is focused on the fetus, which is more susceptible to radiation effects than is the average adult. Specific areas of investigation include studies of thyroid function and infant mortality among pregnancies in progress in the vicinity of TMI-2 at the time of the accident. So far, there are no physical results beyond what would be expected in an ordinary population, independent of any radiation-induced effects, and none are anticipated.

Psychological impacts are evident. Stress and the related health consequences of real or anticipated accidents have received little study, but various techniques are being used to probe these effects around TMI, including telephone surveys and interviews of people who might be susceptible to stress from the accident, such as utility employees, psychotherapy patients, and mothers of small children. Although neither of these two studies is yet complete, preliminary results of the telephone surveys indicate some psychological symptoms among those living within 15 miles of the plant. These reported symptoms include physical complaints, such as headaches and diarrhea, increased anxiety, restlessness, and increased use of cigarettes and alcohol.

Assessing immediate dollar costs is the target of a third set of studies. Many people left their homes and jobs during the four-to-five-day period following the accident. The utility an-



nounced by radio that it would cover expenses away from home, including personal out-of-pocket expenses for transportation, lodging, and meals, as well as the economic penalties of lost work time. Visits to doctors also multiplied, adding a further cost burden for health care.

Another study already in progress will register everyone within five miles of the plant and assign a carefully researched estimate of the radiation dose to each person. This information could be useful to allow individuals to compare the size of their own dose with the much higher natural background levels. (The background levels of the area have been measured both before and after the accident.)

Cancer studies have been stopped—health authorities recognize that the likelihood of finding any discernible effects is remote because of the vastly larger and normally variable natural background of spontaneous cancers. Similarly, there is no basis to warrant looking for genetic changes.

A danger in any health inquiry where there are many unknowns is the possibility of attributing a condition to a cause that is not the cause at all. The recent discovery of six instances of fetal hypothyroidism in adjoining Lancaster County and the speculation that they could be the result of iodine releases from TMI seem to be a case in point. The incidence of this condition (which can lead to mental retardation if untreated) is indeed higher than in 1978. However, a number of factors make it very unlikely that TMI played a part. The measured iodine release from TMI was extremely small and produced negligible off-site doses, especially when compared with doses from weapon-testing fallout. Further, Lancaster County was not downwind from TMI during the accident. Several of the cases displayed structural abnormalities or family predisposition, features that exclude the possibility of radiation-based causes.

The studies of infant health will continue to pursue the goal of separating fact from speculation in assessing the health effects of the accident at TMI. Pennsylvania Health Secretary Arnold Muller has said that the rate of 15.7 infant deaths per 1000 around TMI in the April to September period of 1979 was only slightly higher than the state average of 13.3. Excluding the city of Harrisburg from the data, the infant mortality rate was about the same as the rest of Pennsylvania. (Harrisburg has a large black population, which has a higher infant mortality rate.) Muller also pointed out that prior to the accident the infant mortality rate around the plant fluctuated greatly. For example, from October 1977 to March 1978, the mortality rate was 16 per 1000, but from April to September 1978, it dropped to 2.3 per 1000.

enough time in this circumstance, a molten mass of fuel would melt through the bottom of the reactor vessel and spill on the containment floor. Still, the heat dissipation capacity of the 12-ft-thick concrete floor and base pad would retain the core for several days, and probably indefinitely. In any event, adding water by any of the means that existed at TMI would have arrested the penetration and maintained containment integrity. Under the most unlikely of circumstances, if radioactive material had reached the ground under the containment building, there is little chance it would have dispersed widely.

Studies since TMI, for the Kemeny and Rogovin commissions and by NSAC, all conclude that such a melted core at TMI would eventually refreeze, even if not permanently water cooled. This is a matter of time. The production of decay heat from core debris continues to decrease. After a few weeks, the concrete slab and its reinforcing steel can conduct the heat away indefinitely.

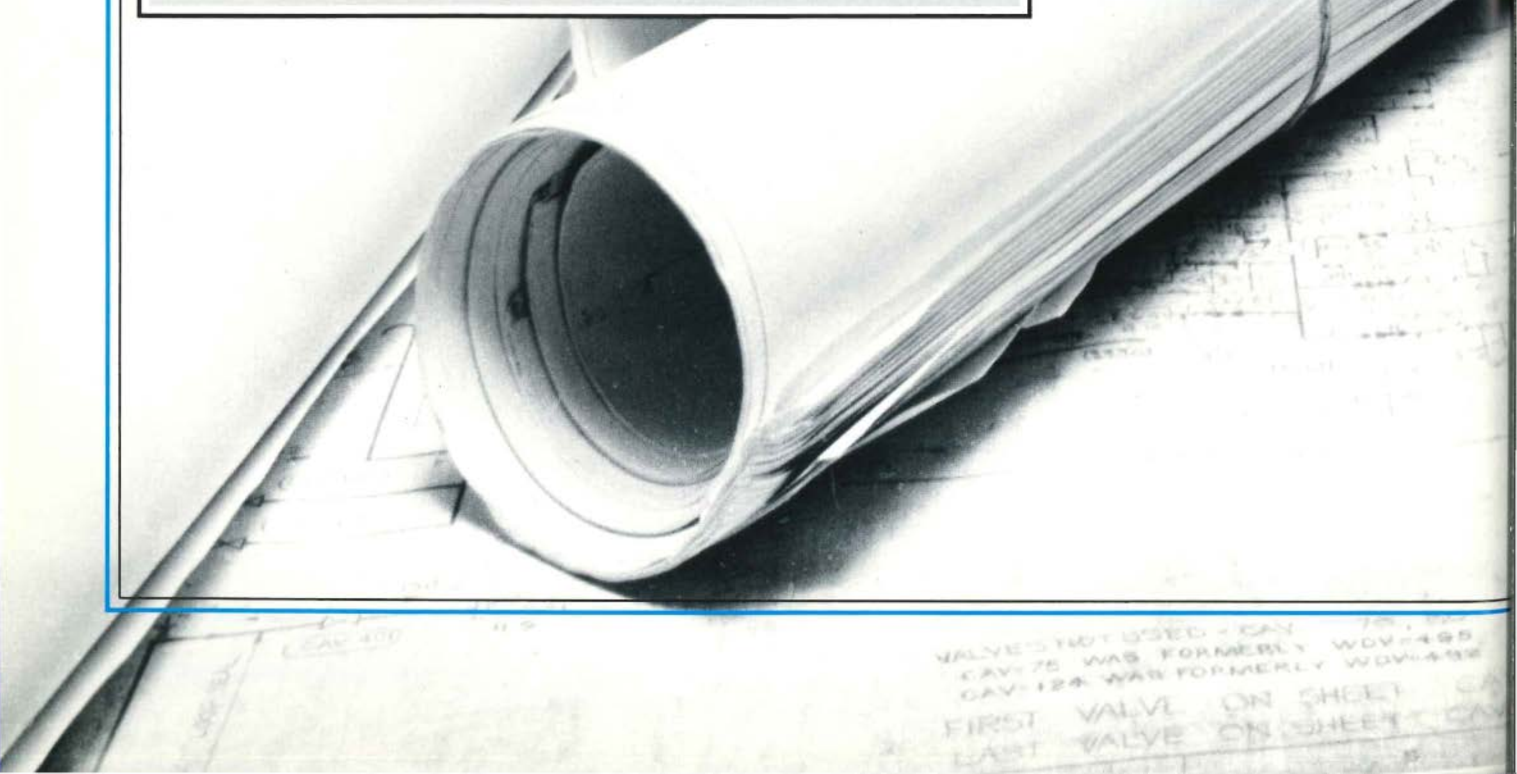
Such an occurrence would constitute a catastrophic accident in terms of damage to plant equipment. It would be costly in money, that is, lost energy production and lost plant investment. But this meltdown would not destroy lives, health, or even nearby property. ■

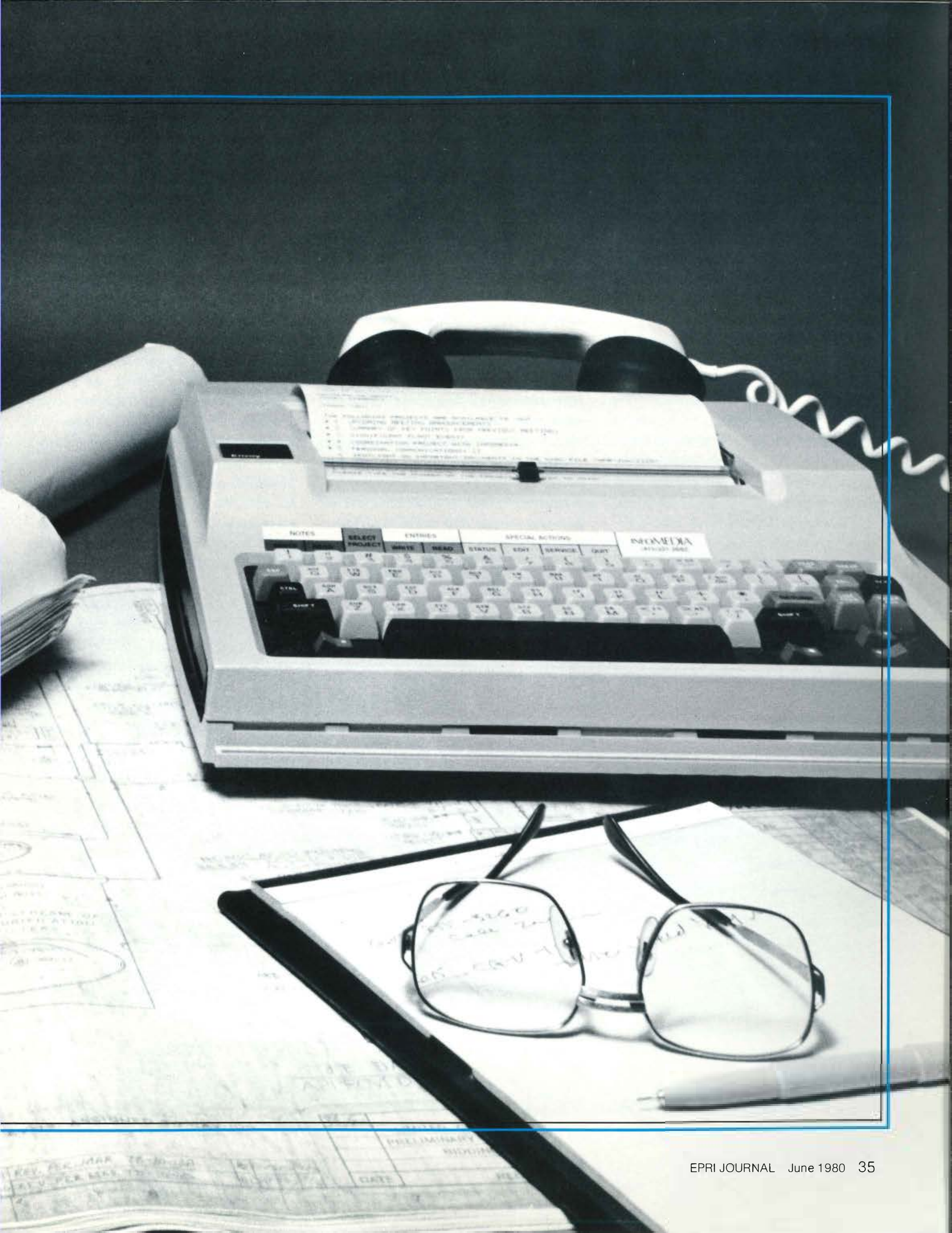
DIRECTIONS:

Making Nuclear Plants Safer

Experience is the best of teachers, and the accident at TMI-2 is no exception. The positive actions that have emerged from over a year of analysis by the electric utilities, the reactor manufacturers, and government agencies have made nuclear power plants safer and have improved the level of preparedness for similar emergencies.

One very important lesson of TMI-2 is that small errors or malfunctions in a nuclear power plant can compound into an accident whose consequences are potentially as serious as those caused by a single, large loss-of-coolant accident, which in the past has been the main focus of licensing requirements. Safety planning must now focus on the accidents and accident sequences where the safety risk is potentially greatest.





What happened at TMI-2 was not a catastrophic rupture of one of the large coolant pipes that carry heat away from the hot reactor core, or any of the other major failures considered in most studies. Such events are routinely assumed for design and licensing analyses, but the probability of their happening is extremely low.

Instead, the accident at TMI-2 was triggered by a sequence of smaller events, including an auxiliary feedwater system that operators failed for a few minutes to realize was shut off; a pressure relief valve that stuck open, allowing water to escape from the core; instrumentation that misled operators into thinking the valve was closed; and the manual throttling back of the automatic emergency cooling water to the core because the primary system was believed to be filled with water.

Preaccident studies, such as the Rasmussen report (WASH-1400), had indicated the significant role that relatively minor events can play in nuclear power plant accidents. Nevertheless, the smaller triggering events, such as happened at TMI-2, had not been emphasized by NRC in the formal regulatory review process. The nuclear industry had concentrated its manpower and money on the topics of most intense regulation: the big loss-of-coolant accidents. And with resources concentrated on improbable events, fewer resources were devoted to the prevention and termination of smaller—but more probable—sequences.

Accident prevention

Since the accident at TMI-2, these smaller and more numerous malfunctions have been receiving the industry's highest priority. The first order of business included corrections that could be made most quickly to prevent future events that could result in core damage. After scoping studies by NSAC, EPRI initiated an effort to test plant safety and relief valves to make sure they will operate properly with water or water-steam mixtures, as well as with steam alone. Instruments are also being installed in each plant to give positive indication of whether relief valves are open or closed, thereby eliminating the ambiguous indications that confused the operators at TMI-2. Meters have been installed at all plants to let operators know at a glance whether there are trends toward a loss of water by any route or toward inadequate core heat removal.

These and other specific remedies should prevent the recurrence of a TMI-2-type event or any of the whole spectrum of events involving a loss of water. The nuclear power industry is now carefully examining its operating experience beyond the accident at TMI-2 for other potential problems.

One of the important efforts involves analyses of individual nuclear power plants. These analyses use fault trees and event trees, which can identify the more probable events that could lead to potential accidents. Once these events are identified, additional safety precautions can be taken through design or through procedures and training.

The nuclear industry has also realized it must make better use of past experiences. Sequences of events similar to those that occurred during the first few minutes of the TMI-2 accident had happened twice before the March 28, 1979, accident at Harrisburg: once in 1974 at a reactor in Beznau, Switzerland, and once in 1977 at The Toledo Edison Co.'s Davis-Besse plant in Ohio. Both incidents included the now-familiar pressurizer relief valve that stuck open and misleading indications to operators that the coolant system was full of water. In both cases the operators recognized the situation early and were able to terminate the incident before damage occurred. However, the significance of these events was not widely recognized at the time.

Today the industry is taking measures to study incidents that in themselves may produce little damage but which may be part of a sequence with more serious consequences. NSAC is now reviewing thousands of operating experience reports from every nuclear plant in the United States, as well as from some foreign plants. NSAC's Significant-Event Evaluation Program has already screened some 1000 Licensee Event Reports (reports of abnormal occurrences that are required to be filed with NRC). Some significant findings are already emerging. These findings are communicated quickly to the affected utilities, often via Notepad, an NSAC-sponsored electronic conferencing system that rapidly transmits safety-related information.

The nuclear power industry has already pinpointed specific areas where improvements may help avert another accident like that at TMI-2. One area is improving the capabilities of plant operating personnel. Since the events at TMI-2, operator training has been expanded to include more thermal hydraulics and other fundamentals pertinent to emergency situations. The basic educational requirements are being stepped up, as well as training. More use of power plant simulators during training is being required so operators can get the feel of many situations that they would not ordinarily encounter in on-the-job training. Operator certification requirements have been stiffened by NRC to require higher grades on examinations.

The electric utility industry's newly formed INPO plans to audit operator training and plant operations. Although INPO will not actually train operators, it plans to review curricula, lesson plans, and training materials; accredit instruction systems; certify instructors and assist in their training and in the development of teaching skills.

Plant personnel, however, can only be as good as the procedures and equipment they have to work with, so efforts are also being made for improvements in both those important areas.

The procedures that guide operators in their work must be reliable. Some of the key operating procedures in use at TMI on March 28, 1979, were not adequate for or applicable to the actual situation. Operating procedures at nuclear power plants are now being reexamined and reworked by the individual nuclear utilities to ensure they are written clearly and accurately for reliable use by operators.

The human engineering aspects of plant controls and control rooms are also being reviewed to improve operator awareness of abnormal circumstances. Investigations after the accident at TMI-2 showed that the control room at TMI was not effectively designed to handle certain kinds of accidents. For example, over 100 alarms sounded or indicators lighted in the early stages of the accident, with no indication of relative importance or priority for operators. Some key indicators relevant to the accident were on the back of a control panel.

An ongoing EPRI R&D program has shown several directions for improvements in the human factors design of nuclear plant control rooms. EPRI's research on human factors and INPO's planned evaluations of human factors should help eliminate deficiencies in this area.

Another program under way in NSAC is to select and recommend to the utilities the key plant parameters that are important to safety. These parameters would be displayed on a control room safety panel, in a near-site emergency operations center, and in an on-site technical support center. In the interest of "helping the operator first," the safety panel is receiving priority attention.

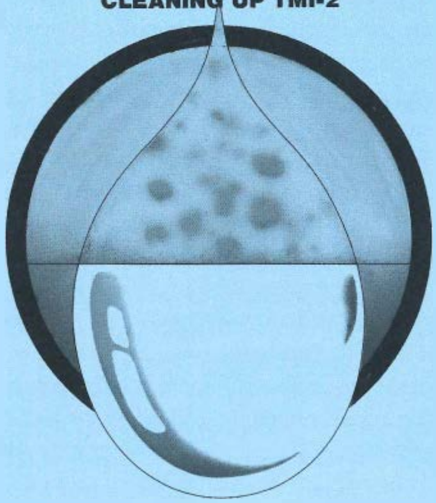
Dealing with emergencies

The accident at TMI-2 also demonstrated that better ways to deal with emergency situations at nuclear power plants are needed.

One initial change in this direction has been the addition of a shift technical adviser at every nuclear plant. Previously, the operators in these plants relied on their operations supervisor for backup advice, but that supervisor may have been carrying out other duties elsewhere in the plant when emergencies arose. The technical adviser is stationed in the control room and backs up the regular operators in evaluating any plant upset or malfunction that may arise.

Another way for utilities to better deal with emergencies is to have direct means of communication with the suppliers that design and manufacture their nuclear systems. The suppliers have extensive knowledge about the nuclear system and the basic engineering science behind it. Because of this, their advice can sometimes be particularly valuable in event of an emergency. Direct communications have been established between most utilities and their reactor suppliers since

CLEANING UP TMI-2



The accident left large volumes of liquid and gaseous radioactive wastes in the TMI buildings, which have to be processed before recycle or disposal.

In the reactor containment building and in the auxiliary building there are approximately a. million gallons of radioactively contaminated water. Also sealed inside the containment is about 1 ft^3 of radioactive krypton gas mixed with 2 million ft^3 of air.

Several systems will be required to clean the contaminated water. Two systems have already been installed and are now processing the water that contains material at low and medium levels of radioactivity. The systems work in much the same way as home water softeners, removing undesirable material to produce purified water. Although all this purified water is being stored, it could reasonably be released to the nearby Susquehanna River, meeting even the most stringent drinking water standards.

All technical evaluations indicate the best course to follow is the gradual, monitored release of the gas from the containment building over a period of several months. Under these circumstances, for the average person the effect of the radioactive gas would be about equal to standing in the sun for a few minutes.

But as of this writing, no cleanup activities have yet begun inside the containment. No one yet knows the extent of damage to the core or the extent of the effort needed to clean it up. It is only possible to estimate the cost of decontaminating the plant and restoring it to operating condition; at this time the estimate is $400 million.

the accident. At many plants, for example, there are now dedicated telephone lines connecting plant and reactor vendor, as well as NRC. Vendor personnel can be summoned to the telephone by radio paging systems.

In the event of an emergency, assistance may also be obtained from experts in many fields, who are available on call. Since the accident at TMI-2, three lists have been issued to utilities owning nuclear power plants. The lists, from NRC, from NSAC, and from INPO, include the names, telephone numbers, and areas of specialty of the experts on call.

Utilities are now providing better plant facilities to deal with emergencies. The control room at TMI-2 was usually manned by a handful of operators. But during the accident it was congested by the presence of many people, including support personnel reporting for their emergency assignments. On-site operations support centers are now available or are being set up at each nuclear power plant. There, auxiliary operators and technicians can report and work without interfering with the control room.

At TMI-2, a greater availability of the plant's technical data at the site would have helped personnel deal with the accident. On-site technical centers are now being set up at each nuclear plant, where support personnel will have access to as-built drawings of the plant and other essential records. This will permit better technical support of recovery activities.

Changes are also being made so that the containment buildings themselves are better prepared for emergencies. For example, several radiation-monitoring instruments designed for normal operating conditions temporarily went off-scale during the course of the TMI-2 accident, thereby depriving operators of information that might have been useful. New instruments are being installed to monitor a wider range of such containment conditions as radiation and water levels. Facilities for extracting samples of reactor coolant and containment atmosphere under high-radioactivity conditions are also being upgraded.

The industry is also taking a closer look at postaccident core heat removal. Although an accident may cause core damage, cooling must continue. While general studies had been done before the accident, specific models of damaged cores had not existed. Industry groups, including EPRI's Nuclear Power Division, Safety and Analysis Department, have prepared models of the TMI-2 core, and the development of models for other reactor designs is under way.

Tasks that lie ahead

The accident at TMI-2 has produced a blizzard of safety recommendations: The final report of NRC's Lessons-Learned Task Force and the NRC Draft Action Plan, for example, tally over 200 recommendations. Yet the nuclear industry has limited resources, particularly in respect to technically qualified manpower. Not all the proposed recommendations can be implemented at once.

Under NSAC sponsorship, a system for setting priorities for these many recommendations has been developed and applied. The system is based on an engineering evaluation of risks, and this should make it possible to identify the really important recommendations and to eliminate any that are ineffective or duplicative.

The question of how safe is safe enough needs answering. To do so will require a determination of the relative risks versus the cost of achieving additional safety. Definite overall safety goals are a continuing objective. NSAC is working with several industry committees and with regulatory authorities to reach consensus on a practical safety goal.

Much of the responsibility for seeing that high standards of operation and management are attained and maintained belongs to INPO. A combination of example, audit, and counseling will be used. INPO plans to have evaluation teams visit nuclear plants once a year to help utilities evaluate changes in operating and maintenance practices that might improve their operations.

Thus the intense reassessment of nuclear safety begun by TMI-2 continues. Much has been learned from the accident. And the massive efforts now under way to improve the technical, institutional, and human systems that govern the safe operation of nuclear power will help to prevent such an event from happening again.

NUCLEAR EMERGENCIES: Coordinating the Federal Response

As recommended by the Kemeny commission and directed by the president, the Federal Emergency Management Agency (FEMA) has assumed primary responsibility for coordinating the federal response to emergencies at nuclear power plants.

In its final report to the president the Kemeny commission criticized the way in which all levels of government handled the accident at Three Mile Island and expressed concern about the general status of preparedness and response for nuclear emergencies. "We are disturbed both by the highly uneven quality of emergency plans and by the problems created by multiple jurisdictions in the case of a radiation emergency," wrote the commissioners in the report issued last October. "At all levels of government, planning for the off-site consequences of radiological emergencies at nuclear power plants has been characterized by a lack of coordination and urgency."

Planning for and responding to emergencies at nuclear power plants is a complex matter that involves several federal agencies, as well as state and local governments and the utilities themselves. In the event of a nuclear emergency the primary responsibility for response within the confines of the plant itself (on-site) belongs to the utility and the Nuclear Regulatory Commission (NRC). The jurisdictional lines become less distinct, however, when considering the off-site consequences of a nuclear emergency—the effect on the community surrounding the plant. In this case such federal agencies as the Environmental Protection Agency (EPA), the Department of Health, Education, and Welfare (HEW), and the Department of Energy (DOE) may become involved, as well as the state and local government agencies that have primary responsibilities for the health and welfare of their citizens.

Because of these multiple jurisdictions, the Kemeny commission recommended that emergency planning and response be centralized in a single agency at the federal level that would coordinate closely with the state and local governments. It recommended that this responsibility be given to the newly constituted Federal Emergency Management Agency (FEMA), an organization that already had responsibility for coordinating the federal response to possible nuclear attacks and other national crises and natural disasters.

Acting on this recommendation President Carter in his December 7, 1979, message on the commission report directed FEMA to take the lead in off-site planning and response for nuclear emergencies and to complete by June 30 a review of state emergency plans in those states having operating reactors.

Logical Choice

The role was a logical one for FEMA, an agency created by President Carter a little over a year ago to consolidate within the federal government such emergency management activities as civil defense

Robert T. Jaske, deputy director of FEMA's Division of Radiological Emergency Preparedness, discusses a map illustrating the emergency planning zones that have been adopted by FEMA and NRC for nuclear power plants. The plume exposure pathway extends 10 mi around the plant and the ingestion exposure pathway is 50 mi.

In the event of a presidentially declared disaster, FEMA establishes disaster assistance centers where victims can seek various forms of federal, state, local, and private aid. Red Cross officials are usually on hand to help.

preparedness, flood and crime insurance, fire prevention training and data collection, and response and recovery activities after presidentially declared disasters or emergencies. Prior to the formation of FEMA, these and other emergency functions were scattered throughout a number of federal agencies, often resulting in confusion within the states and localities who had to deal with one agency for flood insurance, another for civil defense, and still another for natural disasters. FEMA provides one focal point in the federal government for the states and localities, who really carry the major responsibility for planning for, responding to, and recovering from emergencies.

"When you have a major disaster, the front line is local government," notes Russell Clanahan, a FEMA public information officer. "The job of state government is to back up local government and the job of federal government is to assist both when the emergency is too large for either to handle."

In an official publication, FEMA Director John W. Macy, Jr., also points to this key role of providing assistance to the front line. "We believe that emergency management should be implemented where it can be done best—as close as possible to the citizens at the state and local level. FEMA will support these local efforts by providing resources and guidance, and will always be ready to respond when demand exceeds the capacity of local resources and capabilities."

FEMA sees itself in a facilitator role. "This is primarily a coordinating agency," notes Clanahan. "Its fundamental purpose is to try to bring together all the agencies and entities involved in an emergency so they can work together in an effective, coordinated way, rather than duplicating efforts and being counterproductive."

President Carter proposed the formation of FEMA on June 19, 1978. Congress approved the plan that September, and on April 1, 1979, FEMA was created from five existing federal agencies and several other emergency-related programs.

Consolidated into FEMA were the U.S. Fire Administration, formerly under the Department of Commerce; the Federal Insurance Administration, from the Department of Housing and Urban Development (HUD); the Defense Civil Preparedness Agency, from the Department of Defense; the Federal Preparedness Agency, previously under the General Services Administration; and the Federal Disaster Assistance Administration, from HUD. Other federal functions transferred to the agency included earthquake hazards reduction, dam safety, and planning for the consequences of terrorist incidents.

FEMA is currently organized into six main units. FEMA currently has 2000 employees, evenly divided between headquarters in Washington, D.C., and 10 regional offices and training facilities. Its FY80 budget is $441 million.

The U.S. Fire Administration works closely with the nation's fire departments in coordinating fire prevention planning and control activities. FEMA estimates that 8500 deaths are caused by fire each year—about one every hour and 20 times those caused by floods, hurricanes, and tornadoes combined. Property loss is estimated at $5 billion annually. The U.S. Fire Administration works to mobilize federal, state, and local resources to prevent and reduce fire loss. It operates the National Fire Data Center and provides assistance to communities in planning and implementing educational programs. Last December it opened the National Fire Academy in Emmitsburg, Maryland, where some 6000 students (mostly fire department officials) are to be trained each year in fire prevention.

The Federal Insurance Administration administers more than $33 billion in national insurance protection for floods, crimes, and riots. Through the National Flood Insurance Program, property owners are able to purchase reasonably priced flood insurance, in return for which communities agree to carry out floodplain management measures. The Federal Crime Insurance Program offers insurance against burglary and robbery losses to businesses and residents in eligible states. The Federal Riot Reinsurance Program reinsures general property insurance companies in this area of coverage.

The Plans and Preparedness Office coordinates planning to assist governments at all levels to cope with wartime emergencies, such as a nuclear attack, and peacetime emergencies, such as major transportation or industrial accidents, weather-related disasters, and nuclear power plant accidents. This includes planning for succession to office, emergency reorganization of government departments and agencies, shelters and population relocation, and emergency information systems that inform people what to do in a variety of emergency situations. It also includes planning for managing scarce resources, such as stockpiling strategic materials. Through this office, FEMA also designs and conducts tests to measure national, state, and local readiness to respond to an emergency.

The Disaster Response and Recovery Office coordinates federal efforts in the event of a presidentially declared emergency or major disaster. When a life-threatening emergency or a disaster grows beyond the capabilities of local or state governments, the state governor sends a request to the president through FEMA for federal assistance. FEMA evaluates the situation and makes a recommendation to the president. If the president declares a major disaster or an emergency, he will appoint a federal coordinating officer from FEMA to control recovery activities at the site. This person's responsibilities include coordinating federal disaster assistance programs with the efforts of state and local governments and private agencies. Such assistance may include temporary housing, low-interest loans, federally subsidized state grants, disaster unemployment assistance, emergency food stamps, and social security assistance. To aid in this process, FEMA establishes one or more disaster assistance centers where people can apply for aid.

The Mitigation and Research Office seeks new knowledge that will help decrease loss of life and mitigate injury, damage, and social disruption. Among other activities, it coordinates the National Earthquake Hazards Reduction Program and the National Dam Safety Program. It also conducts research on the handling, transportation, and disposal of chemical and toxic materials.

The Training and Education Office administers various emergency management training programs for FEMA. For example, it operates the Staff College in Battle Creek, Michigan, which previously focused primarily on providing civil defense training for state and local officials and for staffs of private organizations engaged in emergency management. The college is currently broadening its focus, however, and will become the Emergency Management Institute when it is relocated later this year to be near the National Fire Academy at Emmitsburg, Maryland. The institute will conduct courses in emergency management for both public and private officials.

Nuclear Emergencies

FEMA's new assignment to manage the federal off-site response to peacetime nuclear emergencies is an appropriate one for the year-old agency, according to Robert T. Jaske, deputy director of FEMA's Division of Radiological Emergency Preparedness. In its new role FEMA "deals primarily with support and coordination of the federal effort in backing up state and local governments," he remarks, "and this will be a good test of the basic FEMA plan put together by the president last June." Jaske believes that in carrying out this role, FEMA officials will be able to draw on the experience

FEMA's regional offices serve as a central communication point during an emergency. The communication room of FEMA's underground Region III headquarters in Olney, Maryland, had a key role in relaying messages between various federal agencies and the Pennsylvania Emergency Management Agency during the TMI accident.

John W. McConnell (left), an official with the Defense Civil Preparedness Agency, which is now part of FEMA, discusses possible evacuation of the counties surrounding TMI with Oran K. Henderson, director of the Pennsylvania Emergency Management Agency. McConnell was sent by the White House to consult with state and county civil defense agencies on measures to meet the nuclear emergency. He is now assistant associate director of FEMA's Population Preparedness Office.

and knowledge gained in other areas of emergency management that fall under the jurisdiction of the agency.

FEMA is working closely with NRC in fulfilling its new mission. After the president directed FEMA to take the lead role in off-site planning activities, FEMA and NRC signed a joint agreement defining each agency's responsibilities in preparing for nuclear emergencies. Although the agreement applied to a broad range of nuclear facilities, the emphasis during the past six months has been on emergency preparedness at commercial nuclear facilities.

The agreement specifies that by June 1980 FEMA will complete a review of state and local emergency plans in states with operating reactors and a determination of the plans' adequacy and capability of being implemented. NRC, on the other hand, will assess the adequacy of the utilities' emergency plans and verify that the plans are being adequately implemented. The agreement specifies that as soon as possible FEMA will complete a review of state and local plans in states with plants scheduled for operation in the near future and will assume responsibility for emergency preparedness training of state and local officials. FEMA will also develop an updated series of interagency assignments for emergency planning and response.

As part of the agreement, NRC loaned 12 employees to FEMA for six months. These loaned employees, one of whom was Jaske, have been working on the evaluation of state and local emergency plans. Jaske notes that some of the loaned officials may elect to stay with FEMA after the assignment ends in June to work as part of the Division of Radiological Emergency Preparedness.

As a tool to aid FEMA and NRC in reviewing emergency plans, in January the two agencies published a criteria document. According to Jaske, this document lists 200 basic elements the agencies have used to evaluate the emergency preparedness status of utilities and state and local governments. The document, "Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants" (NUREG-0654/FEMA-REP-1), formally endorses the emergency planning zone concept and urges its immediate use by state and local governments and by utilities that operate nuclear power plants. This concept defines two areas around the plant for which planning is needed to ensure prompt and effective action can be taken to protect the public in the event of an accident. One of the areas is called the plume exposure pathway. This extends for a radius of 10 miles from the plant and is the area in which a person could receive whole-body exposure to gamma radiation from the plume and deposited material or could inhale such material or gases. The other area is called the ingestion exposure pathway. This extends for 50 miles and is defined as the area where exposure could come from ingestion of contaminated water or foods, such as milk or fresh vegetables.

FEMA has been working through its 10 regional offices in reviewing emergency plans and has had the assistance of regional advisory committees. Each of these committees is headed by a FEMA official and includes representatives from other government agencies involved in emergency response, such as DOE, NRC, EPA, and HEW.

What happens if FEMA finds a state plan inadequate? "We try to deal with that situation through the regional advisory committees," responds Jaske. "We have asked them to work continuously with the states to try to avoid the impasse of a plan coming forward that is not adequate." He adds that FEMA has no statutory authority to force a state to come up with a plan. It must work in cooperation with the states.

Jaske believes that FEMA and NRC will meet the June 30 deadline for completing the review of the emergency response plans. "We expect to report to the president on June 30 with a document that will give our best judgment as to how the state and local governments working with the utilities have arranged their affairs," he says. "We will be judging the whole status of preparedness on the state, local, and utility levels." He adds that neither FEMA nor NRC expects that the ultimate objective of an effective response system can be achieved by June 30. "We don't view the report to the president as reaching ultimate preparedness," he says; "it's a step."

FEMA has also been working on an interagency agreement that will assign roles during a nuclear emergency to the various federal agencies that may be involved. (FEMA expects to publish rules governing these assignments in the *Federal Register*.) Jaske says he expects DOE, for example, will play a major role in coordinating the off-site monitoring of radiological emissions. Through its defense programs, Jaske observes, DOE is well prepared for this role. It owns hundreds of millions of dollars of equipment that could be used for monitoring, such as aircraft, helicopters, and radio systems. It also operates a computerized meteorological advisory system, the atmospheric release advisory capability (ARAC) that was used at Three Mile Island. ARAC can give both a forecast and an inventory of radiological releases. According to Jaske, it allows one to calculate person-rem exposure on a continuing basis for a fairly large area.

FEMA is interested in expanding systems like DOE's ARAC for use by states and utilities. "We are working with DOE and NRC now to put in place a pilot ARAC system in two states, at two nuclear utilities, and at NRC headquarters," Jaske explains. FEMA already has firm agreements for installation of such a system at Consolidated Edison Co.'s Indian Point nuclear plant and in the state of New York. FEMA will be looking to the utilities (and perhaps to EPRI) to provide leadership in providing specifications and criteria for the industry side of such a system, according to Jaske. "We believe this is a good opportunity for utilities to deal with state and local governments in an area of mutual interest," he remarks.

Jaske says that such systems as ARAC are precursors of a new world of electronics-assisted decision making. He expects FEMA will be increasingly involved in computerized, comprehensive emergency management systems that can be used for planning, simulating exercises, and decision making during actual emergencies.

"We would expect ultimately to see very sophisticated programs in every state, which FEMA would contribute toward, standardize, and maybe link together." Thus in the event of a national emergency, the destruction of a major city would not destroy established, well-integrated state systems. ■

H-Coal Pilot Plant Begins Operations

If successful, the two-year pilot operation should allow scale-up to commercial plants.

A milestone was reached in the startup of the H-Coal pilot plant in Catlettsburg, Kentucky, which is designed to convert coal to a clean-burning liquid fuel for boilers. On March 21 the catalyst was added to the reactor while the unit was processing startup oil at near design pressure.

A two-year operation is planned to confirm design scale-up of the H-Coal process from 3 t/d to 250–600 t/d. One subbituminous and two bituminous coals will be processed, and a range of processing severities will be demonstrated to yield product slates of heavy, low-ash, nondistillable fuel oil and all-distillate syncrude. Successful operation of this unit should allow scale-up to commercial or demonstration plants with acceptable technical risk. Extensive mechanical equipment tests and material evaluations are planned to ensure the mechanical viability of future designs.

Fuel oil products from the plant will be stored in 1000-bbl quantities for short-term, EPRI-sponsored combustion tests at utility sites.

Hydrocarbon Research, Inc., which has been involved in developing the H-Coal process since 1963, was responsible for plant engineering. Ashland Synthetic Fuels and Badger Plants, Inc., were responsible for plant construction. Ashland will operate the plant, with technical support and laboratory assistance from Hydrocarbon Research.

DOE is providing about 85% of the funding. Other participants are the Commonwealth of Kentucky, EPRI, Ashland Oil Inc., Conoco Coal Development Co., Mobil Oil Co., Standard Oil of Indiana, and Ruhrkohle (West Germany). EPRI has been involved in the project since 1974, with a current commitment of about $12.5 million, according to Norman Stewart, the project manager. ■

EPRI Hosts EEI

EPRI President Floyd Culler (left) and Jack Young, senior vice president, Edison Electric Institute, at a recent meeting hosted by EPRI for the EEI Corporate Planning Committee. EPRI officials provided EEI's planners with a detailed outline of program strategies to assist utilities during the next 20 years.

Improved Scrubber Under Construction

A $50 million prototype scrubber that removes sulfur dioxide from the stack gases of coal-fired power plants and converts it to elemental sulfur is being funded by EPRI and other agencies.

The new system, which is under construction at Niagara Mohawk Power Corp.'s Huntley steam station in Tonawanda, New York, will be the first full-scale demonstration of a process that uses coal to recover sulfur. Most scrubbers now being used by utilities to prevent harmful emissions produce a sludge that not only is of no value but causes environmental problems in disposal. A few systems have been developed to convert stack gases to elemental sulfur, which can be reused, but these systems generally require natural gas, which utilities may soon be forbidden to use.

EPRI is cosponsoring this five-year project with Empire State Electric Energy Research Corp., the U.S. Environmental Protection Agency, the New York State Energy Research & Development Authority, and Rockwell International Corp.

The complex flue gas desulfurization device, which is being developed by Rockwell, uses a water solution of sodium carbonate that reacts with the sulfur dioxide in the gases and produces solid sulfur compounds. These compounds are then mixed with coal in a molten salt bath, and ultimately sulfur and regenerate sodium carbonate are produced. The sulfur can be sold commercially. By comparison, scrubbers based on a lime or limestone cycle generally produce a sludge whose disposal poses problems.

In addition to this new process, EPRI is also funding development of another experimental system that uses limestone to convert stack gas residues into commercially useful gypsum.

"The ultimate economic advantage of these new scrubber systems is not yet clear," commented Richard Rhudy, EPRI project manager, "but EPRI is concerned that utilities have a wide range of options among which to choose.

"One potential advantage of the sodium carbonate system," he added, "is that it can use the very high sulfur coal abundant in the eastern United States. Coal containing at least 2.3% sulfur will be used in the initial tests." ■

Nuclear Surveillance System Studied

Two parallel short-term projects have been started by EPRI and DOE to independently assess the scope and feasibility of disturbance analysis and surveillance systems (DASS).

Conceptually, DASS provides nuclear plant personnel with integrated plant process and subsystem information to continuously evaluate system configuration as a function of the mode of operation, promptly recognize and terminate disturbances, and assist the operator in bringing the plant to a safe shutdown following an accident.

A technical advisory group has been formed that will provide EPRI and DOE with technical guidance on the scope and direction of the DASS projects. The group will also study priorities, the technical merit of specific capabilities, relevance of other industry activities, and the applicability of the concepts in the near- and mid-terms. J. Turnage, manager of nuclear engineering and development at Yankee Atomic Electric Co., is chairman of the group, which includes 17 representatives of utilities, nuclear steam supply system vendors, NRC, national laboratories, and selected organizations outside the industry and the United States.

The group has held two meetings and expects to complete its work in August after receiving final reports prepared by the two contract teams: Babcock & Wilcox Co., Duke Power Co., Burns & Roe, Inc., and General Physics Corp.; Westinghouse Electric Corp., Commonwealth Edison Co., Sargent & Lundy Engineers, and Systems Control, Inc. ■

CALENDAR

For additional information on the EPRI-sponsored/cosponsored meetings listed below, please contact the person indicated.

AUGUST

26–28
EPRI Solar Energy Program Review Meeting and Workshop
Rockport, Maine
Contact: Edgar DeMeo (415) 855-2159

OCTOBER

6–7
Third NO_x Control Technology Seminar
Denver, Colorado
Contact: Edward Cichanowicz
(415) 855-2374

13–16
Coal Conversion Technology Conference
San Francisco, California
Contact: Seymour Alpert (415) 855-2512

21–22
Turbine-Generator Nondestructive Evaluation Workshop
Washington, D.C.
Contact: Anthony Armor (415) 855-2961

27–29
Coal and Ash Handling Systems Reliability Workshop
St. Louis, Missouri
Contact: I. Diaz-Tous (415) 855-2826

R&D Status Report
ADVANCED POWER SYSTEMS DIVISION

Dwain Spencer, Director

TURBINE SYSTEMS FIELD TESTING

In support of its effort to develop reliable, fuel-flexible, and environmentally acceptable combined-cycle power plants, the Power Generation Program of EPRI's Advanced Power Systems Division is performing field tests to study alternative-fuel combustion techniques and hot corrosion. In addition, a comprehensive data base is being developed from the operating experience of a group of utilities as a means to improve the operation of existing gas turbine generating systems.

Alternative-fuel field testing

The aim of this group of projects is to field-test alternative combustion turbine fuels and associate component hardware systems. The fuels of current interest are petroleum residuals, methanol, shale oil, and coal-derived liquids and gases. Testing of hardware systems focuses on the identification of the operation, maintenance, and equipment design factors that must be considered when burning these fuels.

A test program to compare the operation and maintenance costs of firing heavy fuel with those of firing distillate fuel has recently been completed (RP1079). Testing was performed at the Putnam station of Florida Power & Light Co. (FPL) on two identical 260-MW Westinghouse Electric Corp. combined-cycle units (Figure 1). Testing was completed in July 1979 after about 2500 h of operating time. Very useful field test data were obtained that compare the firing of a blended, low-sulfur residual fuel with firing light distillate fuel in terms of operation and maintenance costs, reliability, and availability. The data have been entered into an FPL data-handling system called GEMS (Generating-Equipment Maintenance System), which is capable of sorting and retrieving information in various formats to determine costs, so that cause-effect relationships related to the maintenance and operating characteristics studied in the field tests can be identified. The GEMS data will be included in the final report for the project, scheduled to be published in late 1980.

Preliminary project results indicate that the firing of blended residual oil accelerates the rate of combustor and turbine deposition, particularly if the fuel has a high vanadium content. This increased deposition rate affects performance and also appears to affect combustor life. In test engines firing distillate oil, combustor life has been observed to be 4000–5000 h, whereas in engines firing residual oil, it is 2500–3500 h. Turbine washing partially restores performance lost because of deposition, but it adversely affects system availability and net plant heat rate because of the long (24-h) motor-driven cooldown required before water washing. Characteristics of both the residual fuel and the light distillate fuel used for starting have an effect on fuel system stability. A tendency for insoluble asphaltenes to precipitate from the fuel was observed and is suspected to be caused by the mixing of incompatible light and heavy fuels; these precipitates cause rapid fuel filter plugging. Early evidence of hot corrosion on turbine parts was noted. More detailed metallurgical data will be issued by Westinghouse for inclusion in the final report.

The most significant finding of this project is that firing heavy blended residual fuel is technically feasible and, given high distillate-residual fuel cost differentials, is economically advantageous. For example, the preliminary figures show the increased maintenance cost from heavy oil firing was

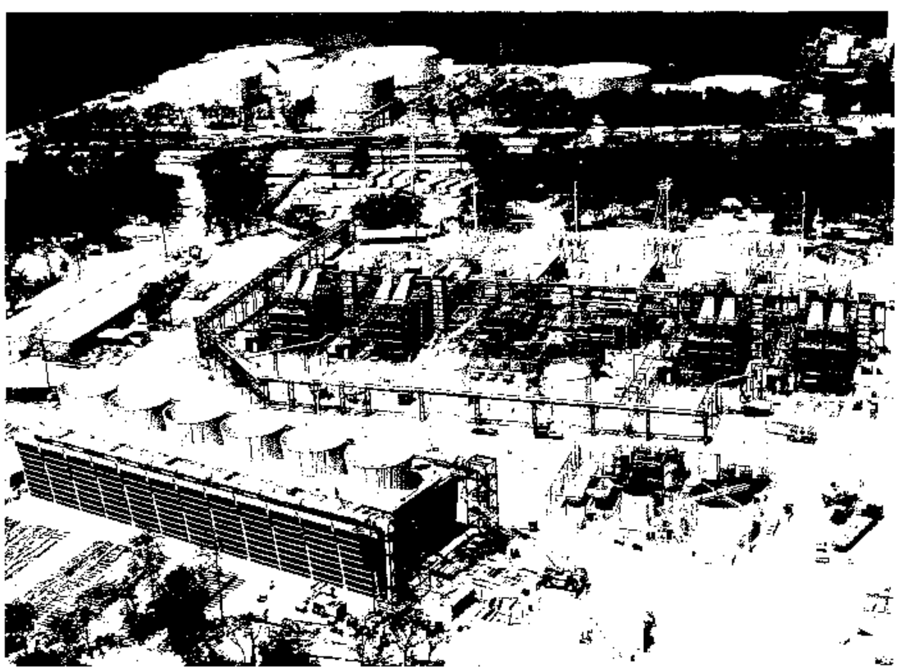


Figure 1 Tests were conducted at Florida Power & Light Co.'s Putnam station to determine the operating cost differential between light and heavy oil.

about 0.7 mill/kWh, while the fuel cost differential (distillate cost over heavy fuel cost) averaged about 6.5 mills/kWh during the testing period (August 1978–July 1979). It is anticipated that residual oil emissions tests will be run later this year.

Another fuel scheduled to be tested in 1980 is a severely hydrotreated shale oil residual. This work should give some insight into the performance of future commercial shale-derived fuels. It will be carried out at Long Island Lighting Co. on a United Technologies Corp. (UTC) FT-4 engine in a simple-cycle twin-pack configuration. The main purpose of this short (50-h) test will be to monitor emissions (especially NO_x and particulates) generated by this liquid, which has a high fuel-bound-nitrogen content. Additionally, an instrumented combustor can will be used to determine metal combustor temperatures during operation. Metallographic inspections of turbine components will be carried out to explore the possibility of any unusual corrosion or deposition problems. This test will be followed by rig tests, using an instrumented combustor can; data on shale oil and No. 2 oil from these tests will be compared with rig test data obtained in RP989, which is investigating the problems associated with burning various coal- and shale-derived liquid fuels in a standard gas turbine combustor.

In a related effort, current worldwide experience with burning residual and crude oils in gas turbines was surveyed. The results, which are reported in AF-1243, indicate that many users of heavy oil have equipment needs and operation and maintenance problems similar to those experienced at FPL. Fuel-related problems involve storage, desalting, effluent wash water quality, fuel additives, fuel pumps, filters, flow dividers, starting and stopping, turbine deposition, corrosion (due to vanadium and alkali metals in the fuel), combustor deposition, and liner burnout. One survey respondent indicated that when fuel was carefully washed and vanadium inhibited, long runs were achieved without corrosion failures (up to 20,000 h at 1650°F [899°C] turbine inlet temperature without air-cooled blades). This again points to the viability of firing heavy fuel if proper equipment and proper operation and maintenance techniques are used.

Another alternative turbine fuel that has been tested is methanol (RP988). A 500-h test (operating 5 h/d, 5 d/wk) was performed at Southern California Edison Co.'s Ellwood station (Figure 2). Petroleum distillate fuel was fired in one engine of a UTC twin-pack FT-4C1 gas turbine-generator set, and methanol was fired in the other. Preliminary results show that methanol caused minimal deposition on hot-gas-path components and fuel nozzles. When burned without water injection, it produced almost 75% less NO_x emissions than distillate oil without water injection. It was not necessary to add lubricants to the methanol; fuel system components operated successfully without them. A final project report will be published in mid-1980.

Operation and maintenance studies

Field testing is being conducted to develop technology to automatically monitor the operating factors thought to cause hot corrosion in turbine systems (RP643). The site is Long Island Lighting Co.'s Holbrook plant, where the air has a high salt content. During Phase 1 of the testing, one engine of a twin-pack FT-4 turbine-generator set was water-washed at every opportunity; the other was washed only when the alkali metal integrators that monitor both air and fuel to the engine indicated that a sufficient cumulative amount of contaminants warranted washing. The fuel in each case was No. 2 oil.

The preliminary conclusion is that airborne sodium salt is the chief corrosive agent. There appears to be a cyclic buildup and spall-off (or shedding) of sodium salt deposits on compressor blading, and a buildup of salt clinkers in the combustor. When spall-off occurs, molten salt deposits on turbine blading and, after a short "incubation" period, causes rapid corrosion. It appears that massive water washing before the incubation limit is reached can sharply reduce corrosion from this source.

In Phase 2 of this project, begun in October 1979, the system is being calibrated by removing and metallographically inspecting eight initially clean turbine vanes after 50, 100, 500, and 1000 h of operation. The 50-h and 100-h inspections have already been completed; no corrosion was visible to the naked eye.

Field data on the operation and maintenance of gas turbines have been gathered from the experience of an operational development group of around 20 users of peaking and combined-cycle gas turbines (RP990-2). This group (now an EEI task force) presents its data at semiannual meetings. The information is then computer-processed and made available to utilities that contribute data. A guidebook is being prepared on the basis of these data to inform the utility industry of operation and maintenance practices employed by these users

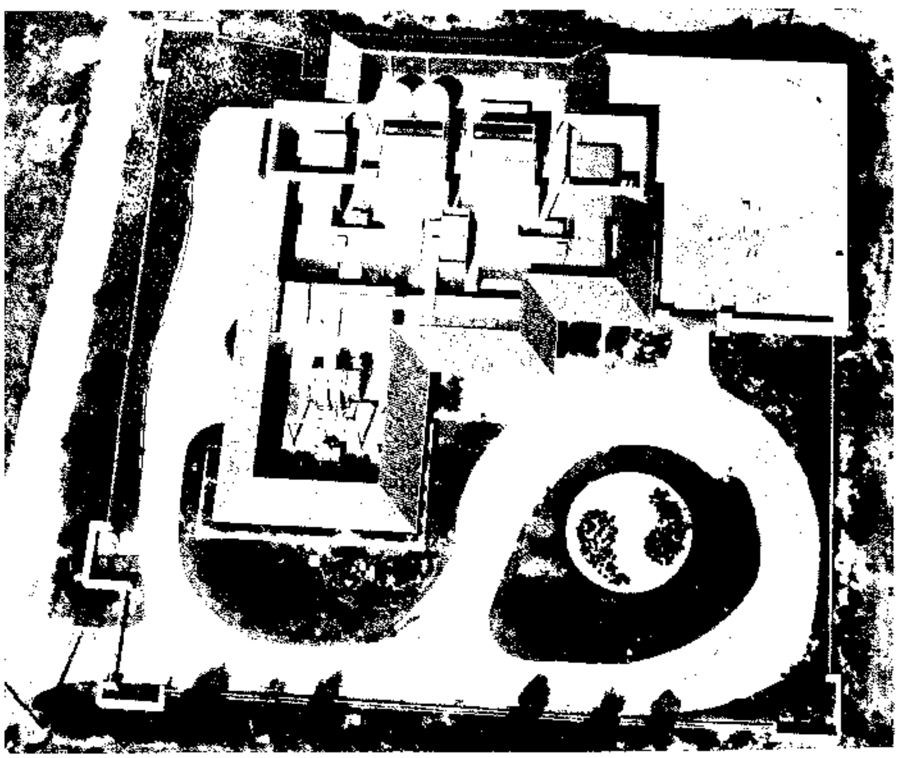


Figure 2 Methanol combustion tests were carried out on twin gas turbines at Southern California Edison's Ellwood energy support facility.

to overcome operating problems and improve combustion turbine performance. Data from this group are also useful to utilities in evaluating the product information disseminated by equipment manufacturers. *Project Manager: Henry Schreiber*

GEOTHERMAL POWER SYSTEMS

EPRI's Geothermal Power Systems Program places primary emphasis on the near-term development of hydrothermal resources—natural deposits of water (or brine) at temperatures high enough to have the potential for economic production of electricity. Based on results from previous EPRI geothermal research, the development of binary-cycle power conversion technology has been the largest single effort of the program. Components critical to flashed-steam and binary-cycle power generation are being developed and tested at geothermal field sites. These include a brine-to-isobutane heat exchanger, a combined steam separator–hydraulic turbine, and a heat exchanger for the removal of hydrogen sulfide (H_2S) gas from geothermal steam.

Binary-cycle development

On the basis of assessments of available geothermal resources and alternative conversion processes for using these resources, EPRI has selected binary-cycle technology as the major focus of the geothermal program. The objective of this effort is to establish the commercial viability of power generation from moderate-temperature (150–205°C; 300–400°F) resources. Such resources constitute about half of the identified resource base capable of supporting electric power generation (Figure 3).

The binary-cycle energy conversion process involves two closed loops: (1) the geothermal fluid loop, in which fluid flows from the geothermal reservoir through a heat exchanger and back to the reservoir, and (2) the working fluid loop, in which a liquid (such as isobutane) is heated in the heat exchanger to a vapor state and then expanded in a turbine to drive a generator. A third loop, an open cooling-water loop, is also needed to condense the working fluid but is not a distinctive feature.

The critical components of this power cycle are the heat exchanger and the turbine. In previously reported projects EPRI contractors tested heat exchangers in the geothermal field at Heber, California (EPRI 376, ER-572) and developed conceptual designs for turbines employing Rankine-cycle expansion of hydrocarbon working fluids (ER-513). Results indicate that adequate performance can be obtained from standard tube-in-shell heat exchangers constructed from either mild carbon steel or titanium, and a turbine with a gross capacity of 35 or 65 MW (e), although substantially larger than hydrocarbon expansion turbines currently in operation, can be purchased with only minor development risk.

Field tests of a binary-cycle test loop were completed in January 1980 (RP1094). The test unit consisted of a heat exchanger that transferred heat from geothermal fluid to a hydrocarbon working fluid, a throttling valve that simulated the turbine in the hydrocarbon loop, a cooling system that condensed and cooled the hydrocarbon fluid, and a cooling tower that supplied water for the condenser. The heat exchanger was large enough to be readily scaled up to commercial size. Lawrence Berkeley Laboratory supplied the equipment for this project, which was cofunded by EPRI and DOE.

The loop operated for over 200 hours of test runs at East Mesa, California, receiving geothermal fluid from Magma Power Co.'s geothermal field. The geothermal fluid flow rate of about 85,000 lb/h (11 kg/s), or 195 gal/min (0.012 m^3/s), was achieved. The heat transfer rate was about 5 MW (th) (16×10^6 Btu/h), a rate that would be equivalent to about 500 kW (e). Both pure isobutane and an isobutane-isopentane mixture were tested as the working fluid. Operation was very stable with each fluid and under all test conditions, including both supercritical and subcritical hydrocarbon pressures. Heat transfer coefficients measured for the pure isobutane case were within ±10% of those calculated by stream analysis methods. The contractor is Colley Engineers & Constructors, Inc. The report is being prepared with support by PFR Engineering Systems, Inc. and J. R. Schilling.

The latest results will be used, together with previous heat exchanger test results and turbine design studies, to provide guidance for the design of a commercial-size binary-cycle power plant. DOE has selected Heber, California, as the site for a federally supported demonstration plant of this type, and EPRI plans to cofund this demonstration power plant project, now expected to begin in mid-1980.

PFR Engineering is assessing the performance of an 11.2-MW (e) binary-cycle power plant at East Mesa (RP1195). Owned

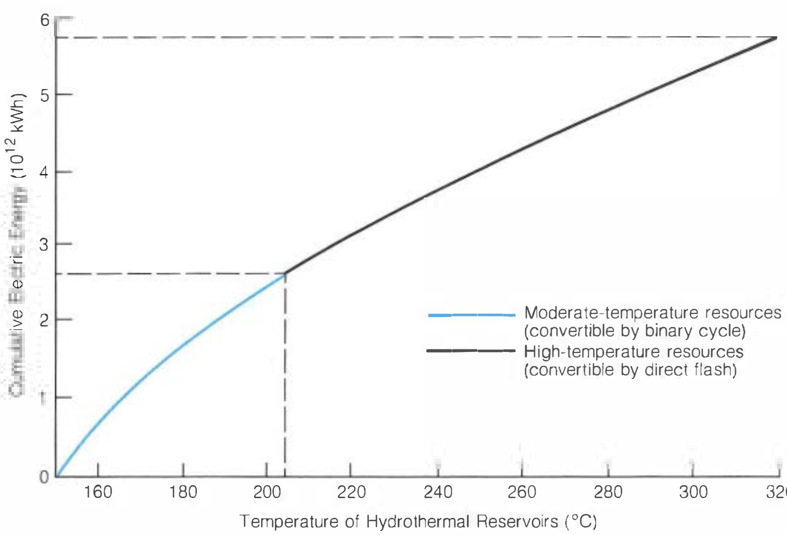


Figure 3 A point on the curve indicates the total amount of electric energy that can be produced from identified hydrothermal resources of or below a specified temperature. EPRI studies indicate the binary cycle is the most economic conversion technology for the moderate temperature range, from 150°C (the lower limit for practical power generation) to 205°C. About half the estimated total falls in the moderate temperature range.

and operated by Magma Power Co., the plant uses a dual binary cycle, consisting of a 10-MW (e) isobutane primary cycle and a 1.2-MW (e) propane bottoming cycle. Magma first delivered power to the Imperial Irrigation District in February 1980, when the plant was operating at about one-third its full capacity. The assessment being prepared for EPRI is to be based on data independently analyzed by the EPRI contractor. It will cover system heat rate, performance of the isobutane and propane power turbines and the isobutane feed pump turbine, heat exchanger performance, and operating characteristics.

Flashed-steam cycles

EPRI contracted with Arizona Public Service Co. (APS) for a study of operating experience at the Cerro Prieto flashed-steam power plant in Mexico (RP1195). On the basis of available recorded data, APS concluded that the Cerro Prieto plant has performed at a very high level of reliability, with an improving trend in annual capacity factor from 0.74 in 1974 to 0.91 in 1978.

Three projects involve field evaluation of components and processes critical to power systems that use hot water geothermal resources: steam separators (RP1672), the rotary separator–turbine (RP1196), and upstream H_2S removal techniques (RP1197). The latter two involve the development of new technology or the adaptation of existing technology to geothermal service.

Steam separator evaluation is being performed by Bechtel National, Inc. In this project, different steam separators are placed in a test loop, and critical operating parameters (e.g., output steam purity, pressure drop, and susceptibility to fouling) are measured during a systematic series of test runs. The objective is to evaluate separators that are leading candidates for the flashed-steam power plants that will be in the design stage between 1981 and 1984. Development and testing of improved steam separators may follow the initial field evaluation effort.

The rotary separator–turbine (RST) is a single unit that performs steam separation, auxiliary power generation, and pumping. A large unit could process the total two-phase flow from a geothermal well or set of wells. The auxiliary power generated by the RST could be added to that generated by a steam turbine driven by the steam output of the RST (Figure 4). By generating power from the kinetic energy of the liquid droplets accelerated during the flashing of geothermal fluid into steam, the RST captures energy that would be lost in throttling in a conventional flash cycle.

Under RP1196 Biphase Energy Systems, Inc., has built a 20-kW (e) prototype RST and tested it at three geothermal sites: East Mesa, Raft River (Idaho), and Roosevelt Hot Springs (Utah). Under the design conditions at Roosevelt, the prototype RST achieved 30% more power output per unit flow of geothermal fluid than would have been achieved by a single-stage flash cycle. The project has now advanced to the stage of final design and construction of a larger RST (~1 MW [e]) capable of handling the full flow of a single geothermal well. EPRI has sponsored the preliminary design of this wellhead unit; Biphase is supporting final design and construction. EPRI plans to sponsor a field test of the large unit in 1981.

The emission of H_2S gas from geothermal steam during power production has become the most significant environmental problem associated with development of the dry steam geothermal field at The Geysers in California. It has also emerged as a significant issue in licensing the flashed-steam power plant being designed for Baca (Valles Caldera) in New Mexico. The problem exists because humans are especially sensitive to the unpleasant odor of H_2S, which is frequently present among the noncondensable gases associated with hydrothermal deposits. The ambient air quality standard is set at 30 ppb in California, and a standard of 10 ppb will be applied in New Mexico.

Methods to control H_2S emissions downstream of the turbine have been developed and are in use at The Geysers. These methods are less effective and more expensive than upstream methods, but upstream methods of H_2S removal are not yet commercially available. Through small-scale testing in the field, EPRI and its contractor, Coury and Associates, Inc., have developed an upstream method that uses a heat exchanger to condense and reevaporate steam (RP1197-2). EPRI has also sponsored an evaluation of the extent to which another method, copper sulfate scrubbing, can be applied over a wide range of geothermal steam conditions; this work was performed by the developer of the method, EIC Corp. (RP1197-3).

The condensation-reevaporation process has been tested at Pacific Gas and Electric Co.'s geothermal site at The Geysers in a 50-kW (e) test unit designed, built, and operated by Coury. The geothermal steam is condensed and reevaporated in a heat exchanger—specifically, a falling-film evaporator—upstream of the turbine. Two output streams emerge from the heat exchanger: (1) clean steam, free of at least 95% of the noncondensable gases that were present in the incoming steam from geothermal wells; and (2) vent gas discharge, consisting of a greatly concentrated flow of noncondensable gases and some of the input steam (3–10%, depending on trade-off and optimization considerations). The vent gas stream is treated to dispose of the H_2S gas. Good performance requires adequate removal of H_2S from the input steam and a rate of heat transfer that is high enough to minimize loss of steam and steam quality (temperature and pressure) in the heat exchanger. The unit tested at The Geysers was successful in both major performance categories, achieving an average H_2S removal level of 94% and a heat transfer coefficient high enough to in-

Figure 4 Rotary separator turbine being tested at Phillips Petroleum's field at Roosevelt Hot Springs, Utah, in September 1979. The bank of tungsten halide lamps mounted on the door dissipates the 20 kW (e) generated by the hydraulic turbine in this test. The steam being discharged to the atmosphere could be used to drive a steam turbine and would produce about 55 kW (e) additional power.

dicate attractive economics at full-scale application (55 MW [e]).

Chemical analysis and scaling control

Geothermal fluids contain dissolved minerals and gases. The chemical and physical changes that take place in these fluids during the power production process can lead to problems of scaling and corrosion. EPRI has developed the capabilities to perform computer simulations of brine chemistry, fluid flow, and scale formation in geothermal power systems (RP653) and to support field operations with on-site chemical analysis (RP741).

Computer codes to simulate scale formation in geothermal power systems were developed during 1978 and have been applied to specific cases during 1979 and 1980. Battelle, Pacific Northwest Laboratories performed both efforts and has used the case study results to improve the codes. The following cases were analyzed: 2000-h heat exchanger tests at Heber; flashing flow in wells at Cerro Prieto; flashing flow experiments performed in a test loop and in a porous plug by Republic Geothermal Co. at its East Mesa field; flashing flow in a surface pipeline at Kizildere, Turkey; the binary-cycle test loop at East Mesa; and Southern California Edison Co.'s two-stage flash power plant being designed for Heber. Reports on these cases, plus other documents describing the codes and how to use them, are being prepared.

A workshop on computer simulation of scaling was held late in 1979 at Battelle's facilities in Richland, Washington, and the proceedings are being prepared for publication. Work to date indicates that the computer codes for analyzing equilibrium chemistry (EQUILIB), scaling and corrosion deposition rates in a flowstream (FLOSCAL), and thermodynamic and hydrodynamic conditions in a well bore (WELL) are ready for use.

Instruments for a full range of chemical analyses of solid, liquid, and gaseous samples are now installed in a 40-ft trailer that is fully equipped for operation at geothermal sites (RP741). This trailer will provide immediate, on-site chemical analysis in support of field tests conducted by EPRI, utilities, and others. The initial field operation is being conducted at the DOE test facility at East Mesa. After these tests, the mobile laboratory will be available for measurements in the field. The contractor is Rockwell International Corp.

Geopressured resources

High pressure, geothermal heat, trapped water, and organic matter have combined at depths of 1500–7600 m (5000–25,000 ft) in large sedimentary basins to form geopressured resources. Prospects of producing both natural gas and electric power from geopressured resources along the U.S. Gulf Coast motivated the addition of a geopressure subprogram to the Geothermal Power Systems Program. An initial assessment of the potential of these resources (RP1272) has been performed by Southwest Research Institute (SWRI), and a follow-up project is being planned (RP1671).

EPRI contracted with SWRI for the initial assessment to determine the potential for recovering and converting geopressured geothermal energy to electricity. The scope of the project included only the Texas and Louisiana Gulf Coast geopressured region and addressed the issues of energy-in-place, recoverable energy, electricity generation, waste brine disposal, and economics. The study relied primarily on the existing body of data in the geotechnical areas and used statistical analyses to estimate likely production potentials. It concluded that the combined resource potential of some 20 sites in Texas and Louisiana is about 7×10^{12} ft^3 of methane and 13 quadrillion (10^{15}) Btu. A net economic gain is projected if the methane can be sold for \$7.50/1000 ft^3, the hot water can be sold for 5¢/bbl, and the waste brine can be disposed of for 5¢/bbl. The three most critical physical parameters of geopressured resources are the amount of methane dissolved in each unit of brine, the thickness of the rock formations containing the brines, and the extent of the volume surrounding a well bore that can be produced (drained) by that single well. *Program Manager: Vasel Roberts; Project Manager: Evan Hughes*

R&D Status Report
COAL COMBUSTION SYSTEMS DIVISION

Kurt Yeager, Director

COAL CLEANING

Coal is one of the country's most abundant energy resources, and its substantial role in the total national energy mix is likely to increase. About 45% of the U.S. electricity supply is generated in coal-fired boilers. The use of such large quantities of coal causes environmental problems in the form of sulfur and particulate emissions. Coal cleaning is one of the ways in which these problems can be minimized in a cost-effective manner. The increasing importance of coal as an energy resource and the need to minimize its environmental impact are major factors guiding the research of EPRI's Coal Cleaning Program.

The objectives of this program are to improve present cleaning technology and broaden its application to coal-fired steam power plants; develop new technologies to improve liberation and rejection of pyrite and ash-forming minerals at high-Btu recoveries; and develop the capability to produce super-clean coals that can reduce or eliminate utility dependence on oil. Several projects are under way to achieve these objectives and help the utility industry realize the benefits of coal cleaning: clean, cost-effective utilization of a large indigenous energy resource and improved boiler performance. Valuable assistance in developing these projects has come from the representatives of utilities and coal-producing companies and the coal-preparation consultants who serve on the program's advisory committees.

Development of pyrite liberation models

Run-of-mine coal contains a significant amount of ash-forming and sulfur-bearing minerals. Part of these contaminants are in a free state in the run-of-mine coal and can be easily removed by cleaning, but large quantities are distributed throughout the coal's mass and cannot be readily removed. The progressive reduction of particle size tends to liberate more of these impurities. For some coals an ultimate particle size has been postulated at around 400 mesh, at which a large portion of the impurities exist as discrete particles. If it is possible to make a separation at this size, relatively pure coal could be produced.

A project (RP1338-2) is under way to investigate size reduction by the following means: rotary breakers (reduction to 1½ in), roll crushers (¼ in), and rod and ball mills (200 mesh or finer). The basic objective of this project is to describe in mathematical terms the degree of liberation achieved by each of these methods and to validate the results experimentally. The models have been developed, and the prospect of successful validation is excellent.

This work is important because future coal-cleaning technologies will depend on advanced liberation techniques, including the controlled liberation of pyrite and ash-forming minerals to preselected levels and the differential grinding of impurities and coal particles to facilitate separation.

The Otisca process

The Otisca heavy-media coal-cleaning process uses Freon in separating coal from refuse particles. Freon has a specific gravity of 1.5, a low boiling point, and low viscosity. These properties make it an ideal fluid for this purpose. One advantage of the Otisca process is that it can be applied to unsized feeds. Also, because of Freon's low viscosity, much finer particles (down to 200 mesh) can be effectively cleaned. The high volatility of Freon and the use of surface-conditioning reagents before the cleaning step make the drying of coal easier. Because these reagents render the surface of coal particles hydrophobic, surface moisture tends to be transported to the refuse particles. As a result, the clean coal from this process is much dryer than the reject or the feed. For example, if the feed contains 6% surface moisture, the moisture of the clean coal and the reject could be 3% and 12%, respectively.

The Otisca process has been under pilot plant testing for about five years, and a 125-t/h production plant was started up in December 1979 by American Electric Power Service Corp.; however, a comprehensive analysis of its efficiency has not been made. Thus EPRI undertook to develop data for use in evaluating the merits of this process (RP1030-15).

About 40 tons of ⅜ in × 0 coal were processed in the Otisca pilot plant in a continuous operation at 5 t/h. Feed, clean coal, and reject samples were collected throughout the pilot run and analyzed to determine the variation in product quality from hour to hour. Washability tests were performed on four size fractions (⅜ in × ¼ in, ¼ in × 28 mesh, 28 mesh × 100 mesh, and 100 mesh × 325 mesh) of composite samples of the feed, the clean coal, and the reject. Data from these tests were used to plot distribution curves for each individual size fraction, as well as for the ⅜ in × 325 mesh composite. Preliminary results indicate that the separations were made with very low probable error and high efficiency. The final report will be published after data analysis to determine other efficiency parameters is completed.

Upgrading low-rank western coals

The low-rank coals of the western United States represent a significant energy reserve. These coals are generally found in thick seams, are amenable to large-scale mining operations, and are low in ash-forming minerals and sulfur. These advantages are somewhat offset by the coals' high moisture content and ash-fouling characteristics in boiler applications. Improvement of these undesirable qualities would increase the use of western coals.

EPRI is sponsoring a project to gather information on the reserves, characteristics, use, and production trends of the low-rank western coals (RP1030-11). Although the project will identify available and potential technologies for exploiting this resource, the main emphasis will be to determine whether direct use or upgrading is the better option for low-rank coals; it is hoped that the answer to this question will be definitive. In the event that the results favor upgrading, future projects in the following areas are considered likely: moisture reduction in lignites, economics of storing and transporting dry low-rank coals, size agglomeration, and modification of ash characteristics.

Coal-cleaning test facility

The United States has long been a leading producer and user of coal. Current production stands at 700–800 million tons a year. However, the R&D effort in coal cleaning and utilization has not kept pace with production. Historically, the approach to coal cleaning has been empirical. It has been viewed and practiced as an art rather than a science, especially for the coals used in power production. This attitude developed as a result of the abundant supply of cheap oil and gas before 1970 and the status of coal as a second-rate energy source. As oil becomes more costly and less available and as the quality of run-of-mine coal deteriorates, R&D to improve coal processing and promote rational coal use is becoming imperative. EPRI's coal-cleaning test facility is a response to these changing circumstances (RP1400).

Some of the ways the facility will help the industry improve the economics of coal cleaning are by developing superior flow sheets for steam coal; verifying flow sheet design before installation; verifying and developing new processes; and testing various unit operations. The test facility is capable of processing 20 t/h of ¾ in × 0 coal through a number of flow sheets. Its unit processes include heavy-media cyclones, water-only cyclones, tables, and flotation cells. Auxiliary equipment includes classifying cyclones, centrifuges, and thickeners. The design of this facility is so flexible that almost any commonly used flow sheet can be set up by reconnecting various units.

The test facility has been designed to enable easy sampling, and it will be instrumented and automated to allow continuous monitoring of various process parameters. These features will ensure data reliability and will permit a better understanding of the effects of process variables on product quality. It is expected that during the first four or five years of operation, a large coal-cleaning data base will be developed to assist the industry in designing plants on a more scientific basis.

A large amount of plant space will be left vacant to accommodate future developments and expansion. This, coupled with the facility's flexibility of concept and design, will allow many other systems and processes to be set up on a temporary basis and tested exhaustively. Construction of the facility is under way, and it should be ready to receive coal by October 1981. *Program Manager: Kenneth Clifford; Project Manager: Randhir Sehgal*

SO_2 CONTROL BY DRY SORBENT INJECTION

Utilities face the costly task of removing both fly ash and SO_2 from the flue gas of coal-fired boilers in order to meet clean air regulations. Therefore, integrated emission control processes designed to remove two or more pollutants are of considerable interest both economically and operationally. As part of its effort to assess and characterize current and future technologies for cleaning flue gas, EPRI's Air Quality Control Program is conducting research on the technical aspects of removing SO_2 by injecting a dry sorbent into the flue gas ahead of the fabric filter (baghouse) typically used for fly ash removal. If effective, this dry sorbent injection process would enable integrated, continuous removal of particulate matter and SO_2 from the flue gas stream. Compounds of interest for use as dry sorbents are nahcolite (naturally occurring sodium bicarbonate, $NaHCO_3$) and trona (a naturally occurring mixture of sodium bicarbonate and sodium carbonate).

EPRI has completed a laboratory-scale project that measured the sensitivity of SO_2 removal by dry sorbent injection to important process parameters (RP982-8) and is participating in a full-scale project to demonstrate the technical and energy requirements of achieving 70% SO_2 removal by dry nahcolite injection ahead of a fabric filter (RP1682).

The primary advantages of SO_2 control by dry sorbent injection are the lower capital costs associated with removing particulate matter and SO_2 in a single system and the higher availability levels and reduced maintenance requirements resulting from system simplicity. Also, energy and water consumption are lower than in a conventional wet scrubbing system. Disadvantages include limited levels of SO_2 removal, potentially limited availability and high cost of dry sorbents, lack of operating experience, and disposal of the spent sodium sorbent.

Previous investigations have confirmed that calcium- and magnesium-based sorbents are relatively ineffective in removing SO_2, while alkaline materials containing sodium are attractive as dry sorbents. Also, injection of sorbent into higher-temperature flue gas generally results in better SO_2 removal, although detailed information on the kinetics of the heterogeneous reaction is not available. Most dry scrubbing studies have focused on nahcolite as the sodium-based dry sorbent. Only limited data are available on the effectiveness of trona as a dry scrubbing agent.

A recent EPA study reviewed the economics of using a sodium-based reagent for SO_2 removal in conjunction with a baghouse. It concluded that the dry sorbent–baghouse system appears to have an economic advantage over currently available flue gas desulfurization technology for western power plants that burn low-sulfur coal. However, the study recognized the lack of basic process data and recommended a pilot project to provide meaningful technical and economic data for utility application.

Laboratory-scale results

A laboratory-scale study was conducted by KVB, Inc., to characterize the dry removal of SO_2 with nahcolite and trona in conjunction with a baghouse (RP982-8). The experimental system, which fired a western coal with a sulfur content of 0.45%, had a flue gas flow rate of 800 standard ft^3/min (0.38 m^3/s) at the baghouse inlet. The experiments investigated the effects of the following parameters on the dry removal process: sorbent type (nahcolite, trona, commercial sodium bicarbonate), sorbent utilization, sorbent particle size, baghouse temperature, air-to-cloth ratio, cleaning cycle time, sorbent injection schedule (continuous, batch), flue gas temperature at injection point (up to 800°F; 427°C), predecomposition of the nahcolite, and inlet SO_2 level.

With the nahcolite sorbent, the reaction time required to achieve maximum steady-state SO_2 removal at a baghouse inlet temperature of 270°F (132°C) was about 40 minutes. A stoichiometric quantity of nahcolite yielded an average SO_2 removal level of 50% for a 90-minute test period; the maximum SO_2 removal was 67%. A sorbent ratio, SR (actual sodium-to-sulfur ratio normalized by the sodium-to-sulfur ratio required to form sodium sulfate), of 1.5 was required for an average SO_2 removal level of

70%. The average removal level at an SR of 0.9 was increased from 42% to 66% by precoating the bags with the nahcolite sorbent.

Injecting the nahcolite into high-temperature (up to 800°F; 427°C) combustion products increased the level of SO_2 removal; maximum removal occurred at 550°F (288°C). Using stoichiometric amounts (SR = 1), the SO_2 removal with injection into the duct at 550°F was 80% compared with 67% with injection at the baghouse inlet (270°F; 132°C). SO_2 removal decreased to 60% as the duct temperature was increased to 800°F. Varying the baghouse air-to-cloth ratio from 2 to 4 ft/min (0.6 to 1.2 m/min) had no effect on SO_2 removal.

Trona was also effective in removing SO_2 from the combustion products, although the level of removal was not as great—40% at an SR of 1, with an SR of 3 required for 70% removal. The trona reacted rapidly with the SO_2 on injection; thus SO_2 removal was essentially independent of cleaning cycle time. At an SR of 2, injecting the trona at elevated flue gas temperatures enhanced SO_2 removal to a level of 70–78%, compared with 50–62% removal when the sorbent was injected at the baghouse inlet.

Both of these dry sorbents also showed some removal of NO; at an SR of 1, nahcolite removed 12% of the NO and trona 5%.

In other tests, commercial sodium bicarbonate (soda ash) was generally found to behave like nahcolite in terms of SO_2 removal. However, the absolute removal level was somewhat less than with nahcolite.

Full-scale demonstration

To complement this laboratory work, EPRI is cofunding a project with Public Service Co. of Colorado to demonstrate the injection of alkaline material into the fabric filter at the 22-MW Unit 1 of the utility's coal-fired Cameo station near Grand Junction, Colorado (RP1682). The objective of this demonstration is to determine the amount of nahcolite (and the associate costs and energy consumption) required to achieve a continuous removal of 70% SO_2. The dry injection process for the Cameo facility was designed by Stearns-Roger, Inc.

After mining and crushing, the nahcolite will be trucked to the plant site, where it will be stored on a prepared surface and covered with plastic to prevent contamination and material loss from weathering. A front-end loader will transport the material from the storage piles to the reagent preparation area. It will be pulverized and then injected into the flue gas stream in the ductwork between the mechanical dust collector and the fabric filter. Initial reagent injection will be in the direction of the gas flow.

Hardware changes in the fabric filter are not planned. However, the maximum anticipated sorbent injection rate will approximately triple the present solids loading on the baghouse, which may necessitate such operating changes as increasing the number of baghouse cleaning cycles, operating the reverse air fan, staggering compartment cleaning, and increasing ash removal rate.

Before nahcolite is injected into the baghouse, emissions will be characterized in terms of SO_2 and SO_3 levels and baghouse inlet and outlet particulate loadings and size distribution. A familiarization test series will then be conducted to define the system capability. Next, a comprehensive series of tests will be conducted to determine the effect that variations in system and process parameters have on dry SO_2 removal. When these tests have been completed, the recommended operating parameters will be selected and used in a continuous one-week test (24 h/d) to establish the operability of the system under normal plant conditions.

The SO_2 removal efficiency of the Cameo system will be evaluated as a function of the following variables: nahcolite utilization, nahcolite particle size, baghouse cleaning cycle and mode (within operating pressure drop limits), and boiler load. Testing will be performed by KVB, Inc., and is scheduled to start in July 1980. *Project Manager: Richard Hooper*

R&D Status Report
ELECTRICAL SYSTEMS DIVISION

John J. Dougherty, Director

TRANSMISSION SUBSTATIONS

High-power vacuum interrupter

The state of the art for transmission-class power circuit breakers has changed greatly in the past 20 years. Requirements for very high current-interrupting and voltage ratings, together with the need for shorter interrupting times, resulted in the development of power circuit breakers that use either compressed air or SF_6 gas. The SF_6 gas breaker has been established as the more acceptable of the two. Today, the oil circuit breaker is used predominantly below 242 kV, and the SF_6 gas circuit breaker serves for higher voltages.

During this period of development, the vacuum interrupter gained wide acceptance for application at the lower distribution system voltages; the application of vacuum interrupters to transmission-class power circuit breakers would seem to promise units characterized by lighter weight, reduced operating effort, lower auxiliary power requirements, and less-demanding maintenance needs. However, the available vacuum interrupters have been so limited in current- and voltage-handling capability that their use as high-voltage breakers has not been practical. These ratings must be improved if vacuum interrupters are to be used in transmission-class circuit breakers.

In response to this need, EPRI initiated a project (RP754) with General Electric Co. about three years ago to develop a vacuum interrupter with a maximum interrupting rating of 63 kA at 72 kV and a continuous current rating of 3 kA; this goal represents a large increase over previous ratings. The design concept for the new interrupter is based on a novel electrode arrangement that keeps the arc in a diffuse mode up to very high current values, thus reducing electrode erosion and promising improved interrupter dielectric performance. Rods, fixed in position, are used as electrodes to maintain the arc in a diffuse mode. The current is interrupted by separating the current-carrying butt contacts and transferring the resulting arc to the rod electrodes, where it is carried until interruption occurs at the first current zero.

The ability to maintain the desired high magnitudes of arc current in a diffuse mode was demonstrated with a triggered gap interrupter, using the rod-type electrodes. The electrode erosion on this duty was slight, indicating a long operating life for the interrupter. Tests proved the interrupter's ability to handle the desired high-magnitude fault currents at a voltage in excess of 90 kV. However, satisfactory transfer of the arc from the butt contacts to the rod electrodes was not achieved.

When considerable work on the arc transfer problem showed no promise of success, a decision was made to stop the effort. Nevertheless, work done as a part of this project did provide new and valuable information on contact popping and the holding forces required to control it. The research also provided useful information on the effects of contact material erosion and splatter products on the dielectric performance of vacuum interrupters.

Although EPRI's work on the high-power vacuum interrupter has concluded with its demonstration of the advantages of maintaining the arc in a diffuse mode, other researchers are continuing this work. Further development of the interrupter could lead to a new generation of transmission-class power circuit breakers. *Program Manager: Narain Hingorani*

Gas detector

The presence of combustible gases in the insulating oil of transformers is an indication of an incipient transformer fault. A one-year field evaluation of the operation of an incipient fault detector (also known as the gas-in-oil detector) has just been completed, and two prototype instruments have been produced (RP748-1).

The fault detector consists of two modules: One extracts the gas from the oil and the other performs a chromatographic analysis of the extracted gas. The extraction function is accomplished by a permeation cell, which, through the action of a rubber membrane, extracts gas from transformer oil circulated through the device. The analysis module is automatically activated once a day to analyze a measured sample of the gases collected during the previous 24-hour period. Although five of the gases commonly present in transformer oil can be detected, the device is specifically designed to sound an alarm when levels of carbon dioxide and hydrogen exceed preset levels.

The two prototype detectors, developed by Westinghouse Electric Corp., monitored transformers at two utility sites: an 880-MVA step-up transformer at the Pennsylvania Power Co. Shippingport generation station and a 572-MVA autotransformer located at Consolidated Edison Co. of New York, Inc., Goethals substation on Staten Island.

The units were very successful in performing the basic functions for which they were designed. It was noted, however, that the performance could be improved by several minor design changes. One improvement involved the addition of a perforated plate to reinforce the rubber membrane on the oil side of the permeation cell. The second design modification provided a fail-safe feature that automatically deactivated the detector to prevent contamination of the analysis module in the unlikely event of rupture of the rubber membrane. These two changes were incorporated about midway in the year's field trial. A third improvement involving more precise control of the automatic timing sequence was not installed in the prototype units but is being included in two new detectors that are currently being manufactured for service on transformers of Niagara Mohawk Power Corp. and American Electric Power Co., Inc.

Although the two prototype units are presently performing properly, an insufficient number of trial detectors have been evaluated to justify sale of warranted instruments. Westinghouse would like to obtain field experience from a larger number of detectors before approving the design for full-scale production. A final report will be issued in late 1980. *Project Manager: Edward Norton*

Ice release coating for air-break switches

It has long been recognized that under certain atmospheric conditions, ice buildup on air-disconnect switches can lead to difficult or incomplete switch operation. This obviously hampers remote operation of air-break switches. As reported previously (*EPRI Journal*, September 1978, p. 49), RP931 was undertaken to determine if inexpensive, commercially available coatings can be applied on standard air-disconnect switches to reduce ice buildup and/or facilitate ice removal during the switch operation.

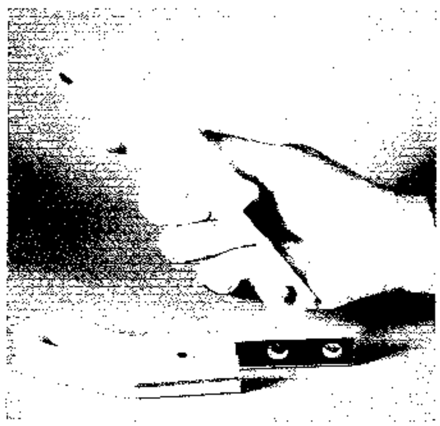
This two-year project with Siemens-Allis Corp. sought to select a coating material from those commercially available to either reduce the ice buildup or facilitate removal of ice from the coated material with less force; and to apply this coating material on key components of standard disconnect switches and conduct ice-release tests to evaluate its effectiveness (Figure 1).

This recently concluded project has verified that by selectively coating key switch parts, the torque requirements for switch operation under ice-loading conditions can be reduced substantially. During this work, it was concluded that switches coated with commercially available, Teflon-filled urethane material required less than half the force necessary to open uncoated switches under comparable ice loading. There was no noticeable improvement during the closing operation of a coated switch. One of the goals of this project, to minimize ice buildup, did not materialize.

The successful demonstration of the coating's ice-release characteristics is especially encouraging because the switch contacts involved (particularly those manufactured by Siemens-Allis) can easily be replaced with coated units in a minimum of outage time.

The actual task of coating the switch parts was carried out by an independent coating company, Color Tech, Inc., located in Seattle, Washington. Switch manufacturers may eventually want to develop their own coating capability or contract with other coating vendors located closer to their switch-manufacturing operation.

Figure 1 If key switch components are coated with commercially available Teflon-filled urethane material (as shown by these reverse loop contacts), the torque requirements for switch operation under iced conditions can be reduced to less than half that needed to operate uncoated switches.



If the coating method developed under this project is routinely applied to all vertical-break disconnect switches, both suppliers and utilities will have an excellent opportunity to reevaluate and reduce the cost of switch drive components, which are now designed to operate with high torques under severe ice-loading conditions.

Several switches treated with this newly developed coating technique will be tried out on utility equipment to see if the improvement in the switch performance is as marked as that observed in the laboratory tests. Since the coating would account for only a small increment (2–5%) of the total switch cost, utilities with icing problems may want to specify ice-release coating in future purchases. *Project Manager: Vasu Tahiliani*

DISTRIBUTION

Improved methods for distribution loss evaluation

Every electric utility planning engineer has had to deal with the problem of assigning a value to distribution losses. Although there is a great deal of published material on the subject, there is no consistent and easy-to-use method available to determine the cost of distribution losses. Therefore, arriving at such a number is a time-consuming and difficult task.

With the cost of a generation plant up tenfold in the past 20 years and the cost of fuel increasing at an annual rate of 25% during the past 7 years, the proper evaluation of loss costs has never been more important. Correct economic treatment of losses can result in large savings in fuel costs and reduced plant investment.

In a two-year project begun in October 1979, Westinghouse Electric Corp. is developing improved methods for distribution loss evaluation (RP1522-1). The project consists of three basic objectives.

- Search the literature to determine the state-of-the-art methods for loss evaluation and typical ranges of parameters used in these methods
- Improve present loss evaluation methods and develop new methods where possible; perform field tests to verify these methods; and perform a sensitivity analysis on the key parameters (load growth, inflation, and load factor)
- Implement and demonstrate the methods and software on a host utility system

To aid in the development and testing of the models and software, Westinghouse will be joined by Salt River Project (Arizona) and Public Service Electric and Gas Co. (New Jersey) in the second and third steps of the project.

The results of this project will include a distribution planner's application manual that describes the common methods of loss evaluation (with numerous examples to assist the user) and a simplified computer program with a fully documented user's manual. *Project Manager: Richard Lambeth*

Estimation of cable life

Loss of cable life caused by water (electrochemical) treeing has been a source of increasing concern in recent years. This subject is of high interest because of the large volume of polyolefin-insulated high-voltage distribution cable installed in the United States and a belief that the anticipated 30–40-year life expectancy of these cables may be shortened by this water-induced phenomenon.

Current EPRI projects dealing with this problem area focus on cables insulated with high-molecular-weight polyethylene (HMWPE). By comparing the tree growth on full-size, newly prepared 15-kV cables subjected to accelerated testing with real-world tree growth on cables recovered from the field, Phelps Dodge Cable & Wire Co. and the University of Connecticut's Institute of Material Science (IMS) are attempting to estimate the remaining life of installed cables. This approach will also be employed to estimate the life of newly manufactured cables.

The Phelps Dodge project (RP1357-1),

which is concerned exclusively with HMWPE insulation, is a follow-on to an earlier EPRI-sponsored project employing insulated wires (EL-647). The approach assumes that the growth of such trees is the limiting factor in cable life and an assessment of their influence can be accurately portrayed.

Newly manufactured 15-kV cables are presently being subjected to accelerated testing both at conventional operating stresses and frequencies and at high stresses and frequencies. Testing has been in progress up to one year; all cables that have been examined exhibit significant visible water-induced tree growth, which is evident after only several months of testing under all conditions. These trees are primarily of the bow-tie type.

In addition to the testing of the newly prepared cables, older cables that had been prepared years ago, buried, and energized have been recovered from the field and submitted by various utilities for testing, together with cables that have been in utility storerooms for several years (never energized).

Preliminary electric test data have been developed on the newly manufactured 15-kV cables. Ac breakdown tests performed after 5-, 10-, and 30-minute steps exhibit similar slopes for the probability of breakdown, but breakdown strength is reduced with increased step times. (In this respect, results are similar to those of mechanical strength tests.) From these results, it was concluded that all future tests could be performed after the 10-minute step.

Comparison of these dielectric strength results with data provided by Pacific Gas and Electric Co. (PG&E) revealed overlapping results: The PG&E data for 29 tests indicated ac breakdown strengths of 440–760 V/mil; results on this project showed 550–800 V/mil for 10-minute steps, and 440–645 V/mil for 30-minute steps.

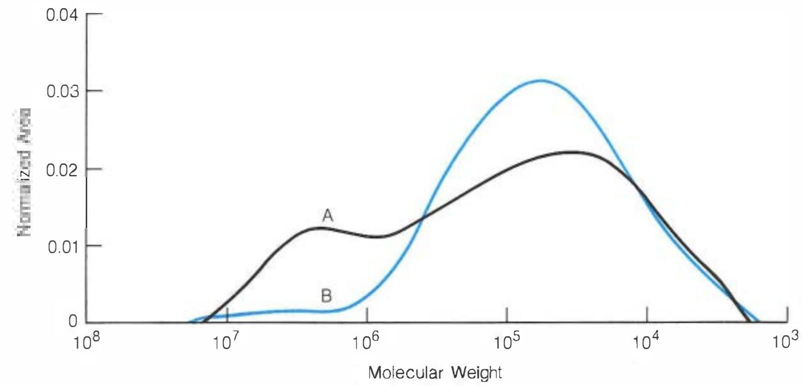
Test results to date generally indicate a trend toward reduced dielectric strength with aging (this supports the scattered test results reported in the literature). A quantitative correlation between laboratory- and field-aged cables will be attempted in the future as more data are developed.

Because a key objective of the project is to predict the remaining life of both unused and installed cables, it will be necessary to correlate the response of field-aged cables with the response of cables manufactured during the same period but aged in utility storerooms rather than energized in the field. To achieve this, accelerated tests will be performed in the laboratory on the storeroom cables and the tree growth compared with that of the field-aged cables. This will correlate the laboratory testing with the real-world aging for both sets of older cables. The accelerated aging of the newly manufactured cables will provide a further correlation of tree growth with the older cables and therefore enable an estimate of life for all the cables, at least for the particular environment from which they were obtained.

It is clear that the potential success of this project depends on obtaining unequivocally matched pairs of field-aged and storeroom-aged cables. However, utilities do not always have the records necessary to match the location of installed cables with warehouse samples. To overcome this problem, EPRI has entered into a separate contract with IMS to perform sophisticated characterization tests (RP1357-3). IMS will employ gel permeation chromatography (GPC) techniques in an effort to characterize the molecular weight distribution (MWD) of field-aged and storeroom-aged cables. The GPC method works by providing a "fingerprint" of the MWD characteristics of an insulation.

All polyethylenes are composed of polymeric chains of various molecular weights; these chains, normally entangled, can be separated by the GPC methodology. In essence, the HMWPE is dissolved in a hot solvent and passed along a column that separates the molecular chains on the basis of their lengths—shorter chains take a longer time to pass along this column than longer chains. Hence, a curve can be obtained that shows the chain length distribution (i.e., molecular weight) as a function of time required for the passage.

Figure 2 Gel permeation chromatography can characterize HMWPE insulation by determining its molecular weight distribution. Curve A represents the MWD of samples obtained from Pacific Gas and Electric Co.; Curve B, Florida Power and Light Co.

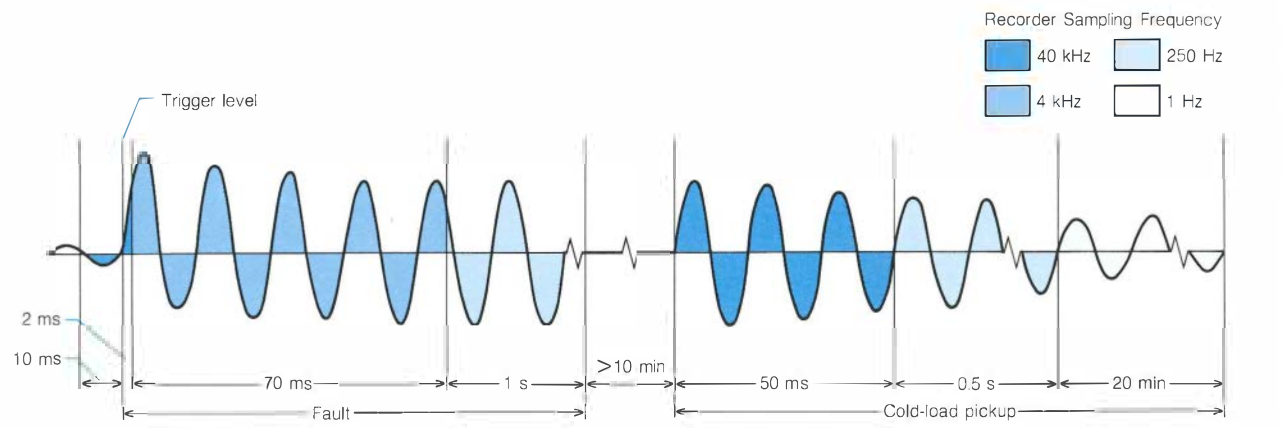


The significance of this technique for this project is the fact that a matched pair of cables will have the same MWD and different grades of HMWPE will have different distributions. As an example, GPC curves for two different HMWPE grades are shown in Figure 2. The differences in MWD between the two insulation materials are apparent. The equipment required to perform this work is quite expensive and not available within the cable industry.

Work to date has concentrated on evaluating newly manufactured cables, checking reproducibility, and developing confidence in the test method. Samples of storeroom-aged cables provided by Navajo Tribal Utilities have also been tested (the only case where, because of purchasing practices, a matched pair can be verified independently), and the MWDs of the older cables have been demonstrated to match; however, the MWDs of the older and the newly manufactured cables were observed to differ markedly. During the testing of cable segments in this manner, the sensitivity of the approach was demonstrated by the fact that the GPC method was able to pick out a splice region (because of its different MWD) in the installed cable.

As an adjunct to this work, IMS will ultimately evaluate newly manufactured samples that have been subjected to acceler-

Figure 3 A complete fault–cold-load pickup event. Sampling rate is high during times when the transient is expected to be rich in high frequencies. The medium (4-kHz) sampling rate will capture the low-order harmonic wave shape. The once-a-second (1-Hz) sampling will yield the decay rate of the cold-load pickup current.



ated aging and compare them with 60-Hz-aged samples. *Project Manager: Bruce Bernstein*

Fault current analysis

To give engineers a better understanding of the electrical characteristics of faults, EPRI has initiated a project on distribution fault current analysis (RP1209). The first objective of this three-year project with Power Technologies, Inc., is to compile data on the electrical characteristics of faults experienced on primary distribution systems.

Since each permanent fault is necessarily followed by reenergization of the load, a second objective is to investigate the characteristics of cold-load pickup. This is a subject that is frequently discussed but for which data are scattered and incomplete.

Results of this project will give distribution engineers a comprehensive knowledge of how voltages and currents change during faults and what to expect of currents during the reenergization of the interrupted load. Engineers will then be able to make more efficient use of properly rated equipment, specify relay settings with greater confidence, and restore load more rapidly.

To provide a statistically valid data base of fault characteristics, fault events will be recorded on 50 utility feeders for periods up to two years. Following interruptions greater than 10 minutes, the cold-load pickup currents and voltages will be recorded and sampled long enough to provide the needed data on magnitude and decay characteristics.

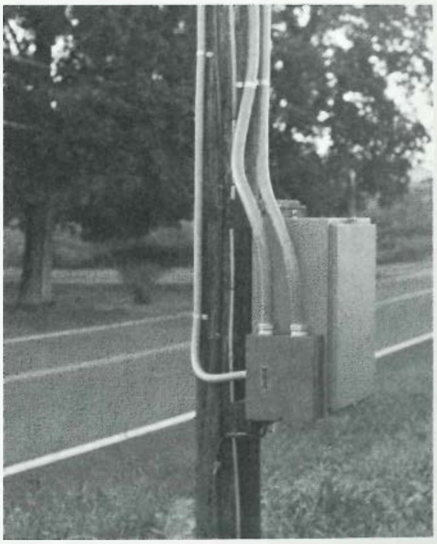
In preparation for the data-gathering phase of this project, it was necessary to design and build a suitable recording instrument, arrange with participating utilities for the installation of the recorders, and prepare digital computer programs to process the recorded data.

The recorder, designed and built by Macrodyne, Inc., has seven channels for recording the phase-to-ground voltages, the three-phase currents, and the residual current for each fault and cold-load pickup event. An additional channel is provided for recording up to eight digital information inputs.

Voltage and current data are stored in computer-compatible digital form on a cassette tape. With a frequency response of up to 10 kHz, the overall error of the recorder is less than ±3% of full scale.

Figure 3 shows the timing sequence of fault and cold-load pickup events. A complete fault event is composed of the initial fault followed by three unsuccessful reclosures and a subsequent cold-load pickup. The storage capacity of the cassette tape is four such complete events. For the case where all faults are temporary (requiring only a tripping followed by a successful reclosure) 32 events can be stored on the tape. Thus when removed at the specified monthly interval, a tape may contain a combination of records of permanent faults, cold-load pickups, and temporary faults.

Figure 4 Field testing of the Macrodyne fault data recorder resulted in several minor but important design modifications. Voltage and current from the poletop transformers and the 120-V power source enter the terminal box on the side of the recorder cabinet.



The recorders are now being installed at the participating utilities. Figure 4 shows the recorder installed by New York State Electric & Gas Corp.

Thirteen utilities will install a total of 50 recorders. In selecting the feeders to be monitored, attention was given to obtaining diversity of operation and environmental conditions, such as climate, geography, and isokeraunic level; load type and density; and feeder design and construction. The variety of the selected feeders is reflected in the following characteristics.

- Circuit voltage: 4–34 kV, with 15 kV predominating
- Historical fault rate: 2–74 faults per feeder per year
- Substation size: 2–429 MVA
- Maximum fault currents: 1.3–17 kA

The utilities have supplied all the background data needed to perform the analysis of fault records, and as faults occur, they will document pertinent data for submission with the cassette tape. *Project Manager: Herbert Songster*

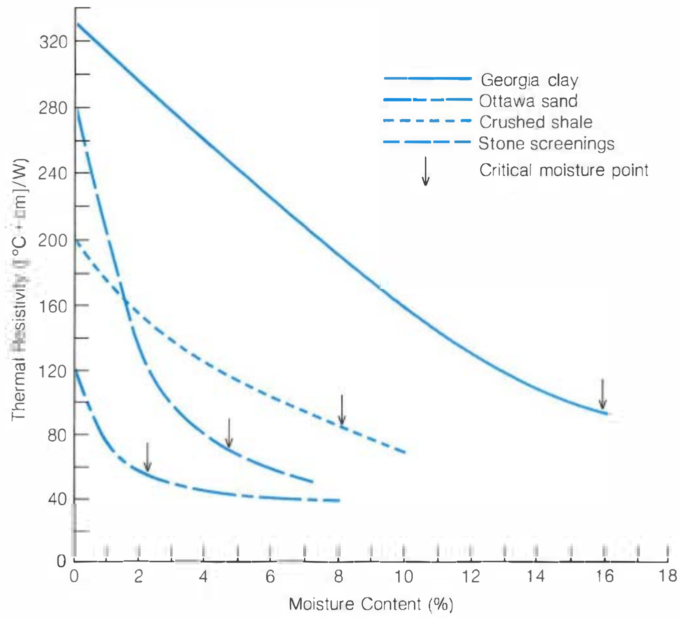
UNDERGROUND TRANSMISSION

Measurement of soil thermal resistivity and stability

The uncertainties associated with the soil environment for underground transmission and distribution cables have been a major restraint in the economical design, installation, and service rating of electric cables. As part of an EPRI project on soil thermal characteristics, nearing completion, a portable prototype instrument has been produced for field or laboratory analysis of soil thermal properties (RP7861). As a result of this research, engineers should gain a better understanding of, and therefore greater confidence in predicting, native and thermal soil backfill characteristics. This, in turn, means the nature of soils will become a far more important factor in the economic rating and operation of extensive underground cable facilities.

Three basic soil characteristics have always been a factor in underground system planning. Soil thermal resistivity is a critical parameter in the design rating of underground cables by the classic Neher-McGrath formulas or by CIGRE procedures. Soil thermal diffusivity, indicating the heat capacity of the soil, is another essential parameter in determining the maximum safe transient and emergency operating levels for underground cables. Soil thermal stability, the ability of the soil to transfer high heat flux without increase in thermal resistivity and without exceeding the critical moisture balance, is the third parameter.

Figure 5 Classification of soils and thermal backfills by moisture relationship. Desirable thermally stable backfills, such as stone screenings, have a very low thermal resistivity before the critical moisture level (50 [°C·cm]/W, or under, at 2% moisture), and a relatively low thermal resistivity (<130 [°C·cm]/W) even at 0% moisture. Georgia clay, on the other hand, is unstable at moisture contents below 16%.



In the past, the measurement and analysis of these soil parameters was cumbersome, time-consuming, and unreliable. Measurement was somewhat empirical, because the mechanics of heat flow, flux density, and moisture transfer dynamics of the soil were not fully understood. With the instrumentation developed under this project, it is now possible to determine all three soil parameters reliably in the laboratory or in the field.

Consequently, the scope of this project has bridged the many gaps between theoretical cable design, economic installation, and effective operating practices. With the results achieved on soil measurement, it will be possible not only to confidently determine optimal cable sizes and ratings but to accurately assess installed costs related to in situ soil characteristics and locally available backfills. It is also anticipated that it will now be practical, during construction, to make trench-side judgments on the economically optimal balance between native trench soil and selected backfill replacement as trenching proceeds.

The contractor, Ontario Hydro, has provided classifications of the most familiar soils and backfills, such as those in Figure 5, relating soil thermal resistivity to percent moisture content. With established physical and mechanical characteristics (e.g., particle grading and compaction densities), all the necessary soil parameters have now been identified and referenced for useful application.

In addition to characterizing important native soils and backfills, the contractor has compiled the theoretical studies and data needed to relate soil characteristics to underground cable design rating and emergency operation. Valuable correlation between computerized weather data and statistical prediction of seasonal thermal resistivity has been provided to aid in anticipating thermal resistivity changes during recurring soil drought periods; this information will enable utilities to safely load cables during and after droughts.

Another practical, mathematical application of this project's parametric soil studies concerns thermal backfill. A correlation between thermal diffusivity and heat flux can confirm the effectiveness of good thermal backfill for increased cable rating. For example, it has been determined that the heat capacity is dependent on heat flux and heat

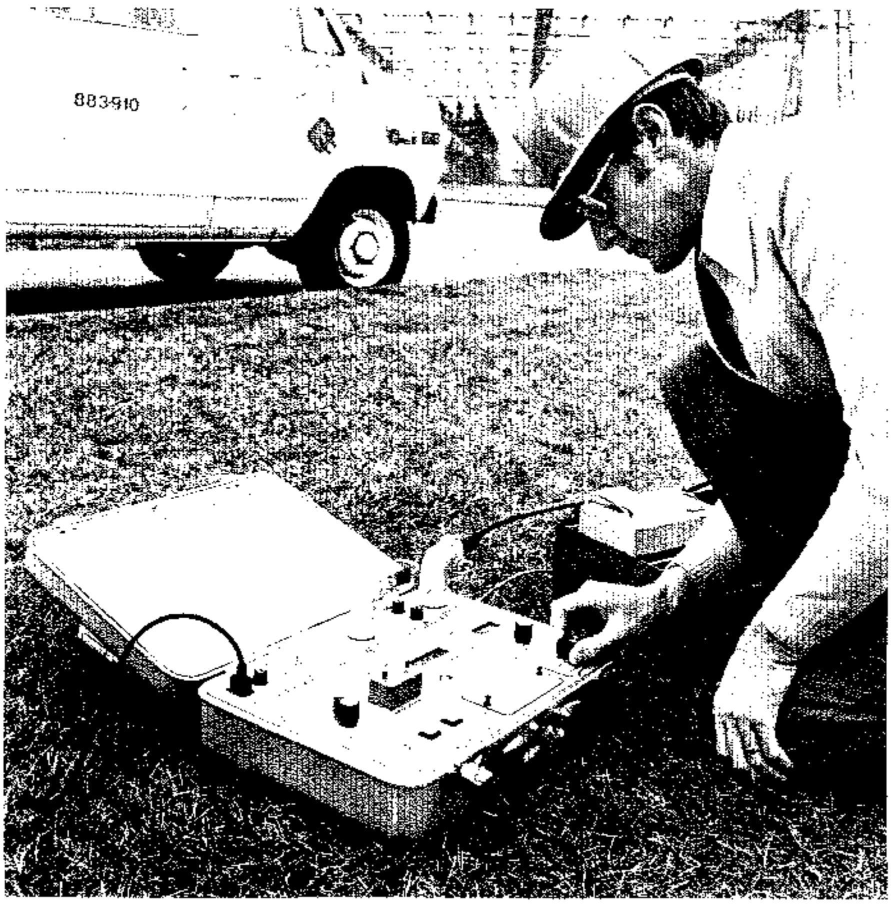


Figure 6 The thermal property analyzer is a modern, highly versatile, microprocessor-controlled compact instrument weighing less than 25 lb (11 kg). It measures up to six thermocouple probes and calculates thermal resistivity values continuously by least-squares fit of the temperature–ℓn data.

source diameter. Thus, although a planned small cable with poor backfill might be vulnerable to soil-drying surface temperatures, the addition of a large cross section of stable thermal backfill can increase its capacity for higher heat flux considerably (by a factor equal to the square of the diameters). Usually, critical moisture conditions at the backfill–native soil interface either are not reached because of relatively slow diffusion, or are alleviated by seasonal moisture.

Portable, compact thermal property analyzers (TPAs) designed, built, and tested by Ontario Hydro have been delivered to two utilities for immediate field evaluation. The TPA, weighing less than 25 lb. (11 kg), is a highly versatile instrument package, combining modern microprocessor technology with advanced designs of transient needle thermal probes (Figure 6). The main components are a microprocessor-controlled current source, programmed in 256 steps; a six-station multiplexed thermocouple reader with 0.1 °C resolution; and a programmable control/memory microprocessor. Selection controls include choice of a high, medium, or low thermal resistivity setting (for correct power level), calibration for probe heater resistance, and choice of a single or a double heat run.

The microprocessor is programmed to check and respond to probe-soil contact, automatically store data, and calculate thermal resistivity continuously on a weighted least-squares fit of the slope of the temperature–ℓn time data. An LED display selector gives real-time thermocouple temperature, thermal resistivity, thermal diffusivity, curve fit, and power level. Keyboard access to programmable memory is provided to temporarily change parameters and limits. This gives exceptional versatility for laboratory investigation or field use. As many as six soil samples can be analyzed simultaneously for thermal resistivity, thermal diffusivity, and thermal stability.

For measurement of soil thermal stability, two heat runs are made. In the single mode, a temperature–ℓn heat run is made on the probe temperatures at a relatively low power input. In the double mode, a second heat run is automatically programmed at 8–10 times the power output. Soil thermal instability, or drying out, at the higher heat flux can be recognized from a significantly higher second-run thermal resistivity value.

The versatility and reliability of the TPA in providing instant values of soil thermal resistivity in the field or the laboratory and its capability for positive determination of soil thermal diffusivity and stability are expected to fill a long-standing need. Confident determination of soil characteristics and more economic thermal design rating will lead to more beneficial use of cable systems.

Response is invited from utilities interested in purchase of TPA instruments or in participation in the evaluation of the prototype TPAs. Because the source and quantity for manufacture will largely depend on inquiries, interested parties are encouraged to respond as early as possible. The final report for this project should be published in late 1980. *Project Manager: Stephen Kozak*

R&D Status Report
ENERGY ANALYSIS AND ENVIRONMENT DIVISION

René Malès, Director

ELECTRIC UTILITY RATE DESIGN STUDY

The Electric Utility Rate Design Study has completed five years of research and published some 80 technical reports relating to rate design and the direct control of customer loads. Undertaken at the request of the National Association of Regulatory Utility Commissioners (NARUC) for an examination of ways to control the growth in peak demand and their impact on electricity prices, the study has entailed a nationwide research effort by EPRI, the Edison Electric Institute, the American Public Power Association, and the National Rural Electric Cooperative Association. Now a program is under way to communicate the results of this research to those responsible for determining and implementing policy on rate design and load control—regulatory commissions and electric utilities.

Literally hundreds of researchers have participated in the Rate Design Study, and an equal number of utility and regulatory professionals have provided direction, advice, and review as members of project committees and task forces. Although the study has benefited greatly from the direct participation of the industry, the wealth of information that has been produced will not be readily assimilated or fully applied by regulatory commissions and utilities without a specific plan of transfer. Additional effort is required to facilitate the application of research findings and insights to the general problem of implementing practical, cost-effective load management programs and to the more specific problem of utility rate design. The development of effective mechanisms for disseminating information from the study is particularly important because of the requirements placed on the industry by the Public Utility Regulatory Policies Act of 1978 (PURPA). Both NARUC and the project committee asked EPRI to give this effort high priority.

The transfer program was inaugurated in May with three regional conferences for regulatory commissioners and electric utility executives. These conferences provided an integrated overview of the findings of the Rate Design Study for industry decision makers. Follow-up technical workshops in the fall of 1980 will provide a more in-depth treatment of specific research topics. These meetings and other proposed transfer mechanisms are discussed more fully below.

Background of the Rate Design Study

In December 1974 NARUC passed a resolution to study (1) the technology and cost of time-of-use metering and electronic methods of controlling peak period electricity use, and (2) the feasibility and cost of shifting various types of electricity use from peak to off-peak periods. In 1975 the NARUC resolution was translated into a detailed research plan that emphasized the development of time-of-use rates based on alternative costing methodologies and the evaluation of alternative direct load control techniques. In 1976, before the results of the research phase had been disseminated to the industry, NARUC requested additional work.

The technical substance of the Rate Design Study is organized into four major areas that incorporate a number of specific research topics.

- Costing, rate design, and elasticity: pricing approaches, electricity demand elasticity, rate experiments involving small customers, costing for peak load pricing, and ratemaking

- Load controls and equipment for using off-peak energy: metering, mechanical controls, and other instrumentation technology

- Customer understanding and acceptance

- Cost-benefit analysis to determine the potential cost advantages of peak load pricing and load control

In December 1978 the president of NARUC requested help for state regulatory commissions in carrying out their responsibilities under PURPA. In response, a reference manual was prepared that links the requirements of PURPA to pertinent Rate Design Study information (*EPRI Journal*, September 1979, p. 53). Finally, in July 1979, the oversight project committee asked EPRI to expedite the technical research and to appropriate funds for activities to communicate the study's results to regulators and utility load management professionals. These activities—including regional overview conferences, technical workshops, and the publication of load management manuals and case studies of specific applications—are planned for 1980 and 1981.

Application of research results to industry problems

The Rate Design Study focuses on the pricing of electricity, a particularly sensitive area of regulation and a subject of great concern both to utility management and to regulators. Pricing decisions affect electricity use, determine the costs various customers must bear, and influence the revenues a utility collects to cover its expenses and provide a fair return to its investors. Rate design and load control decisions will affect the growth in peak demand and, consequently, requirements for new generating capacity (i.e., how much and what kind). Capacity expansion plans, in turn, largely determine a utility's financial requirements and thus have an important impact on customers' bills. With total annual industry revenues at over $70 billion and total annual investment at $25 billion, the pricing of electricity is of utmost concern. Also, because about one-third of the primary energy used in the United States is converted to electricity, the pricing of electricity is particularly important in terms of allocating society's scarce resources.

Since the passage of PURPA, state commissions and utilities have a legal mandate to consider the appropriateness of several ratemaking standards. Fortunately, much of the technical information developed by the Rate Design Study over the past five years is relevant to this task. Some of the information has already been disseminated to the utilities to help them comply with the analytic requirements of PURPA. However, it is important that the study's findings be made available to all segments of the industry quickly and in forms that will facilitate their application. The technical transfer plan is designed to accomplish this critical task.

Objectives and basis of technical transfer plan

The objectives of the technical transfer plan are to

- Integrate the concepts, data, and analytic tools developed during all phases of the Rate Design Study
- Assist regulators and utilities in applying this integrated knowledge to current industry problems
- Broaden and develop the regulators' and utility analysts' knowledge of rate design and load control
- Gather, disseminate, and update load management information resulting from industry compliance with PURPA and combine this practical experience with the Rate Design Study research findings
- Bring together representatives with diverse professional backgrounds from all segments of the industry to exchange information and experiences

The basis of the transfer program will be seven papers that consolidate and summarize the Rate Design Study material—an overview of the entire study and six topic papers on the major areas of research. Most of the topic papers will present research results in two main categories: methodology improvement and data development. These topic papers will have a common conceptual approach and will be designed for use with a five-step procedure to evaluate load management strategies (Figure 1). The topic papers represent the culmination of the Rate Design Study research effort.

Mechanisms of technical transfer

Several forms of communication will be used to transfer the findings and insights of the Rate Design Study to the industry. In May three regional conferences were held in San Francisco, Kansas City, and Washington, D.C., for utility executives, regulatory commissioners, and senior staff. These conferences provided decision makers with an overview of issues and findings in the areas of costs and rates, load research, load control, customer response and acceptance, and the cost-benefit evaluation of load management alternatives. In addition, the conferences featured discussions by regulatory and utility personnel of actual load management applications. A series of follow-up regional technical workshops will be held in fall 1980 and spring 1981 to provide an in-depth treatment of specific topics for utility and commission technical staff. Tentative topics include alternative costing methodologies, cost-benefit analysis, and direct load control techniques and equipment.

Load management manuals, intended to parallel the topic papers being written by the staff of the Rate Design Study, constitute another means of technical transfer. The manuals will serve as textbooks of principles, integrating research findings from the study's 80 reports with relevant information from other sources. Thus, in addition to filling the need for reference tools, the manuals can be used to teach load management concepts.

Another aspect of the technical transfer plan will involve the analysis of two kinds of case studies. Load management case studies will provide a guide for organizing the institutional processes critical to the successful implementation of any load management program. They will examine what happened and why at every step through the internal company structure and the external regulatory process. Case studies in cost-effectiveness analysis will present actual applications of analytic methods to the determination of practical load management programs. Examples of cost-benefit calculations leading to real-world load management decisions can provide valuable insight into the handling of uncertainty about future events, lack of data, and the limitations of analytic tools. *Project Manager: Eugene Oatman*

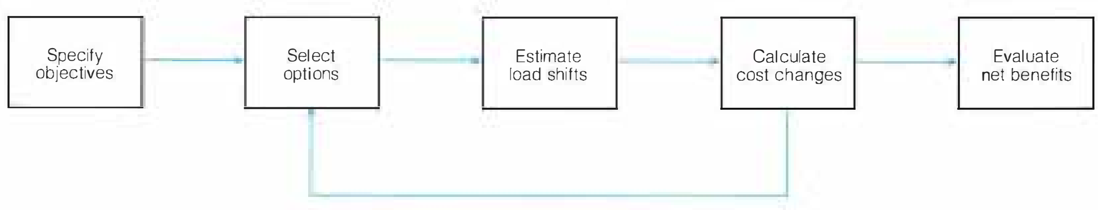


Figure 1 A five-step procedure is used to evaluate load management strategies. Input to the procedure will be provided by topic papers on the major areas of rate design research: cost and rates, load research, load controls, customer attitudes, customer response, and cost-benefit evaluation.

R&D Status Report
ENERGY MANAGEMENT AND UTILIZATION DIVISION

Fritz Kalhammer, Director

FIRST-GENERATION FUEL CELLS

The major objectives of EPRI's fuel cell research are to expedite the commercial introduction of first-generation phosphoric acid fuel cells capable of heat rates of 8300–9300 Btu/kWh when using petroleum and coal-derived fuels in an environmentally acceptable manner for dispersed power plant applications; to develop the fuel cell components required to improve power plant heat rates to 7500 Btu/kWh; and to develop fuel cell systems for use with coal gasifiers in combined-cycle power plants. This report focuses on first-generation fuel cell activities. Program and project background has been discussed in previous EPRI Journal *articles (November 1978, p. 6; November 1979, p. 40).*

The largest first-generation fuel cell effort, with an EPRI appropriation of over $13 million, involves the installation and operational test of a 4.5-MW net ac (4.8-MW dc) fuel cell module on the system of Consolidated Edison Co. of New York, Inc. (RP842). During the past year, progress was made in several key areas. The site in downtown New York City has been prepared, and all the ancillary equipment needed to support, monitor, and evaluate the power plant has been installed, including systems for liquid and gaseous fuel supply, purge gas supply, control air, auxiliary power, and data acquisition. Many of the power plant modules (power conditioner, cooling towers, water treatment system, and plant control system) have been delivered by the manufacturer, United Technologies Corp. (UTC) and installed at the site by Consolidated Edison (Figure 1).

The project is about two years behind schedule at this time. As reported earlier, problems in fabricating the advanced formed-plate heat exchangers used in the power plant delayed production by approximately one year. Since then, fabrication of the power plant modules has been slowed by extraordinary quality assurance procedures mandated by the New York City Fire Department, which was given complete responsibility for the safety of the power plant by the City Board of Standards and Appeals when siting was approved. The department has taken a very conservative approach, establishing requirements that go well beyond national standards and even New York City codes for similar equipment. Module assembly is virtually complete, but the possibility of further delays of installation and testing as a result of new fire department mandates should not be precluded. Three of these modules, which incorporate the fuel-processing and thermal control subsystems of the power plant, have been delivered to the site. These will be installed first and checked out to calibrate the plant's control system. When this has been completed, the two power section modules, containing 10 fuel cell stacks each, will be installed. If check-out activities proceed smoothly, the power plant could be on-line early in 1981 and ready to begin its planned 6700-h test.

The objective of this project is to demonstrate that utilities can economically install, operate, and maintain fuel cell power plants on their systems. Because the 4.5-MW demonstrator is not yet a commercially optimal configuration, parallel technology efforts have been defined and initiated under the sponsorship of EPRI, DOE, Northeast Utilities, and UTC. The route to a commercially viable first-generation power plant involves increasing the system's operating pressure from 35 lb/in² (241 kPa) to around 100 lb/in² (690 kPa) to make more effective use of fuel-processing and thermal management equipment; incorporating a more durable fuel cell stack configuration; and generally reducing the complexity of the system.

These objectives are being pursued in a 42-month, $50 million program that builds on existing stack technology. (EPRI's share, under RP1777, is $7.7 million.) The program is expected to complete the design, specification, and technical verification of an economically attractive power plant configuration and to result in an initial offering of approximately 500 MW of power plants for delivery beginning in 1985.

A specification committee that includes representatives of 14 utilities will help define the preferred characteristics for these initial units. At present the committee is conducting trade-off studies to assess variations in these characteristics from both a utility's perspective (to determine their value to the utility) and the manufacturer's perspective (to determine their cost). The major parameters to be considered include power plant ratings of 5–13 MW, heat rates of 9300–8300 Btu/kWh, fuel selection, minimum power point, and part-power heat rate. While the relative values of these parameters will be somewhat application- and utility-specific, requirements are probably sufficiently alike from one utility to another to enable the definition of a single power plant configuration that can serve a broad utility market. The specification targets for the commercial power plant will be set by the end of 1980. Table 1 compares the likely characteristics of initial commercial units with those of the 4.5-MW demonstrator.

A fuel cell users group, composed of 37 electric utilities as charter members, has recently been formed to work with manufacturers and federal funding and regulatory agencies in building a bridge between demonstration and full commercial service. The specification committee now serves under this group, and additional committees are being formed to address such issues as market potential and commercialization strategies. EPRI is providing technical and administrative support to the group (RP1677).

Other efforts in support of the first-generation fuel cell power plant include a series of projects to improve key power plant subsystems (RP1041). Specifically, the feasibility of processing certain coal-derived liquid fuels (solvent-refined coal and H-Coal derivatives) under fuel cell power plant conditions was demonstrated in the past year.

Figure 1 The 4.5-MW (ac) fuel cell installation in midtown Manhattan is nearing completion. All the power plant equipment is delivered to the site in truck-transportable modules.

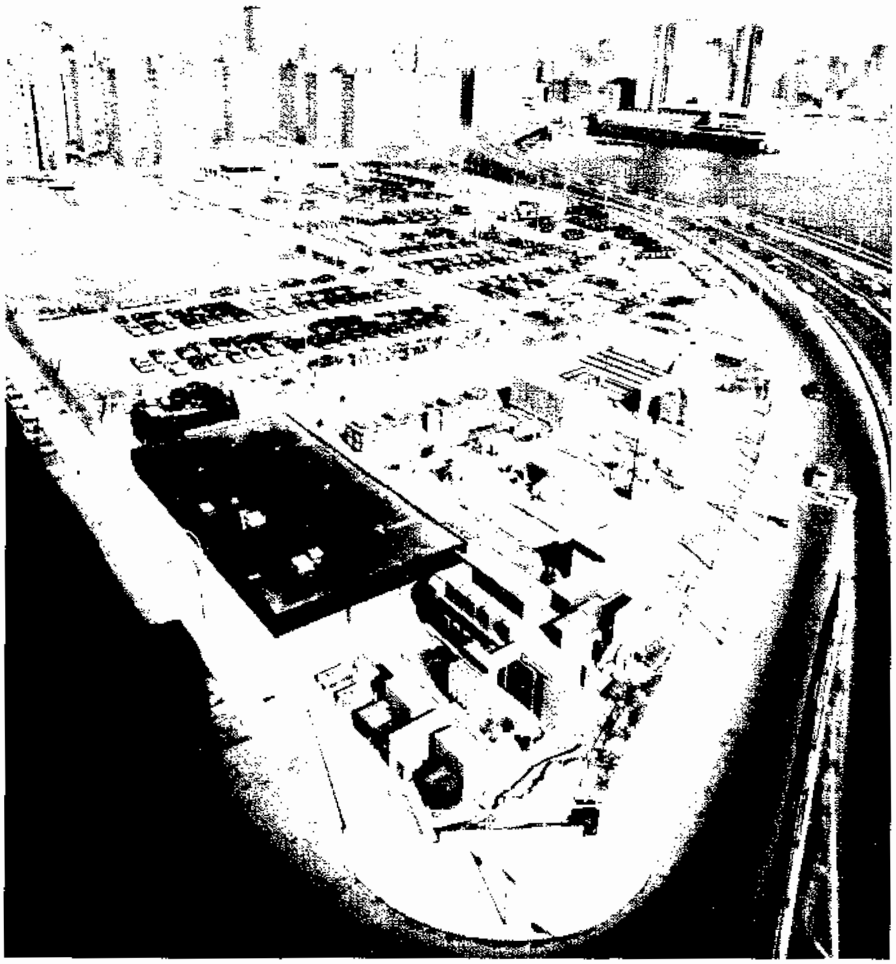


Table 1
FIRST-GENERATION FUEL CELL CHARACTERISTICS

	Demonstrator	Commercial Configuration
Module size (MW)	4.5	10
Heat rate (Btu/kWh)		
Full load	9300	8300
Half load	9000	9000
Fuel	Naphtha, natural gas, synthetic natural gas	Light petroleum and coal distillates, natural gas, synthetic natural gas, medium-Btu gas, alcohols
Projected life (yr)*	20	20
Projected cost ($/kW)†	~750	~400
Projected operating and maintenance cost (mills/kWh)	4–5	5–6

*Book life, with cell stack replacement every 40,000 hours.
†In 1979 dollars, not including interest during construction and installation; assumes a production rate of 500 MW/yr.

Improved fuel-processing catalysts that are tolerant of the high aromatic content of coal liquids and the sulfur content of middle distillate petroleum fuels were successfully tested at conditions meeting the heat rate targets for the first-generation power plant. The feasibility of modifying or retrofitting the fuel-processing subsystem of initial commercial units to enable use of coal-derived fuels as they become available is now being assessed by the specification committee.

Alternative methods of transporting liquid fuels to dispersed metropolitan sites and of storing them there were assessed for 12 cities across the country (RP1349). The study concluded that all cities would require underground fuel storage, surface transport by tank truck would be acceptable, and contract truck service was most economical, except for some sites that could be served by barges at even lower costs. Under the study's assumptions (5-day fuel supply stored on site, 15-mile transportation distance, 3000-h/yr power plant operation), fuel delivery and storage costs (in January 1979 dollars) added about 2 mills/kWh to the cost of power for multiple-plant installations and about 3 mills/kWh for a single 10-MW power plant.

During the coming year EPRI's role in two other important first-generation fuel cell efforts will be defined. One involves a proposal by Westinghouse Electric Corp. and Energy Research Corp. to further develop a phosphoric acid fuel cell that would compete directly with units from UTC. A unique feature of the Westinghouse design is a potentially more reliable gas-cooled fuel cell stack. An EPRI assessment of the gas-cooling concept concluded that it could be integrated into a power plant to yield a 9000-Btu/kWh heat rate, the projected cost of the cooling subsystem ($40/kW) was acceptable, but the option to use reject heat from the power plant in a dual energy use system would be lost with the specific configuration analyzed (TPS79-725). Cooling system modifications to regain this option are being evaluated under DOE-sponsored projects.

The other new effort to be addressed involves a plan by DOE, the Gas Research Institute, and UTC to field-test up to fifty 40-kW phosphoric acid power plants as on-site generators of electric and thermal energy in residential and commercial applications. A number of electric and gas-electric utilities have expressed an interest in participating in these field tests. Also, an assessment of the role of small, on-site power plants in electric utility service may be undertaken in conjunction with EPRI's Energy Utilization and Conservation Technology Program. *Project Manager: E. A. Gillis*

R&D Status Report NUCLEAR POWER DIVISION

Milton Levenson, Director

TWO-PHASE FLOW SIMULATION METHODS

Detailed simulation of two-phase flow is essential for the accurate prediction of both steady-state and transient performance of nuclear steam supply system components, particularly in reactor cores and steam generators. Existing computer codes that simulate two-phase flow require solution times that are often much longer than the real-time systems events. Also, the ability of some codes to accurately simulate the phenomena of interest is strongly dependent on various physical system parameters used as code input. These shortcomings have prompted a search for new and better methods of simulating the time-dependent behavior of two-phase flow. EPRI RP963 is part of this effort.

Recent interest in the field of multiphase thermal-hydraulic flow has resulted in the formulation of a variety of mathematical descriptions and equation sets for modeling complex time-dependent flow behavior. However, the complexity of some of these models and the simplicity of some of the solution methods have led to prohibitive computation costs and, in extreme cases, divergent, unstable, and nonphysical results.

The principal objective of RP963 is the development, implementation, and testing of advanced mathematical models and numerical solution methods that can be used to efficiently and accurately model the thermal-hydraulic behavior of two-phase fluid flow. The research is presently being conducted under contracts with the Department of Mathematics and Statistics and the Department of Mechanical Engineering at the University of Pittsburgh (RP963-1, RP963-3). In this work an original solution method called the dual-variable method has been developed and applied to the equations describing two-dimensional two-phase flow. A computer code, DUVAL, has been written to incorporate this method and has been used to compare results with those of existing methods.

Results show that the dual-variable method is stable, is much more computationally efficient than many of the specialized techniques used today, and is directly applicable to a broader class of flow problems. To date, work has focused on thermally expandable, locally compressible flow in rectangular and cylindrical two-dimensional geometry, although the method can be extended conceptually to three-dimensional multifluid models. Two-phase air-and-water experiments in vertical unblocked and blocked channels and unheated rod bundles are also being conducted to provide data for code validation. An interim EPRI report describing the method and preliminary results is available (NP-1416), and project final reports are expected early in 1981.

System model

The basic conservation equations for mass, momentum, and energy are used to describe the homogeneous behavior of a two-phase mixture, and a drift flux model accounts for slip between the phases. To begin testing the solution method, the fluid was first assumed to be thermally expandable. This assumption (i.e., that the local density depends only on local temperature and a reference system pressure) has been shown to be quite accurate for steam generator simulations. The constitutive models used for friction effects and heat transfer are equivalent to those incorporated in the RETRAN system simulation code (RP342, RP889).

The dual-variable solution method

For a thermal-hydraulic problem composed of N total flow regions (or nodes) and M flow paths (or links) between the nodes, explicit numerical methods typically require the numerical solution of an $N \times N$ matrix problem for the pressures at each time step and require that the time step be sufficiently small to ensure numerical stability.

In contrast, the dual-variable solution scheme allows a linearized implicit numerical solution of the conservation equations. The difference equations that result normally require the solution of an $(N + M) \times (N + M)$ matrix problem for the pressures and mass velocities and an $N \times N$ problem for the enthalpies at each time step. Experience has shown that these equations allow time steps that are much larger (up to orders of magnitude) than those in the explicit methods for equivalent solution accuracy.

The essence of the dual-variable method lies in the recasting of these finite difference equations as vector equations that involve particular network-related matrices. Through the use of these matrices, the unknown pressures are eliminated from the calculations, and the unknown mass velocities along each link of the flow network are replaced by dual variables in each topological cycle of the network. (The technique is similar to the use of loop current analysis in the solution of electric network problems.) This replacement results in a linear system approximately one-third the size of the former system, and the solution of a matrix problem approximately $(M - N) \times (M - N)$ in size is then required for the dual variables at each time step. Original problem variables are recovered by back-substitution. Thus greater computation efficiency and economy are achieved by the application of the dual-variable method.

DUVAL code development

The DUVAL computer program has been developed to demonstrate the validity, accuracy, and efficiency of the dual-variable method. The code presently features rectangular and cylindrical geometry, variable mesh spacing, impervious or open boundaries, various boundary condition options, user-oriented input, restart capability, graphic output, execution diagnostics, and portable coding. The code is being developed on the University of Pittsburgh DEC10 computer and is compatible with other large conventional computer systems. The code incorporates a frontal method solution technique for matrix inversion that decreases small-core memory requirements and allows very large problems to be simulated.

Steam generator applications

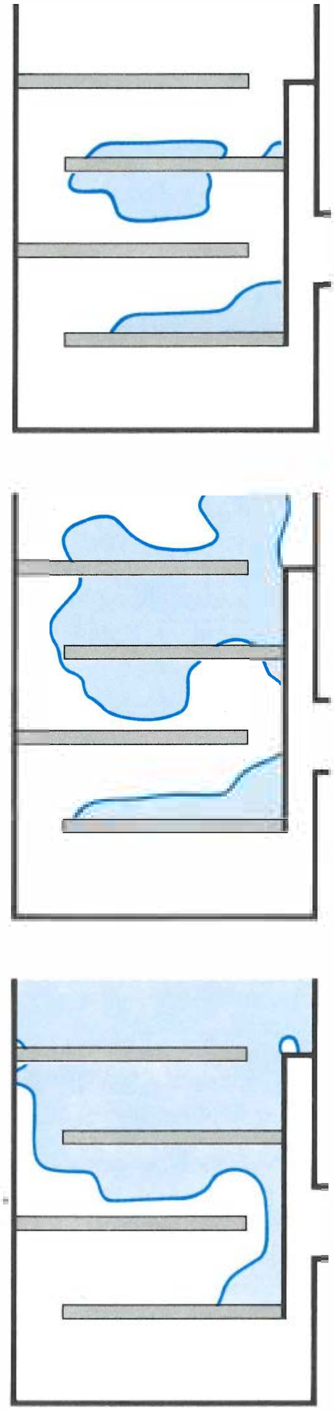
A representative preheater section of a steam generator has been used to illustrate the capabilities and advantages of the dual-variable method (Figure 1). The preheater is composed of a 5.62-ft-wide (1.71-m) vertical channel with a closed bottom, four porous horizontal baffles spaced 1.49 ft (0.45 m) apart, and a tube support plate spaced 1.24 ft (0.38 m) above the uppermost baffle. Inlet feedwater flows into the 1.24-ft (0.38-m) feedwater nozzle, down the 0.51-ft (0.16-m) deflection channel, around and through the baffles, and out the top of the section.

The section includes rigid (free-slip) side walls and deflection walls, and form losses are used to model the baffles and tube support plates. Representative initial steady-state operating conditions used for this problem are a system pressure of 1000 psi (6.9 MPa), a fluid enthalpy of 483 Btu/lb (1.12 kJ/g), no heat addition, and no feedwater flow. The transient is begun by imposing 189 lb/(ft^3·s), or 3.03 Mg/(m^3·s), feedwater flow with 425 Btu/lb (0.99 kJ/g) feedwater nozzle inlet enthalpy and a nonuniform heat profile of 264 Btu/(ft^3·s), or 9.83 MJ/(m^3·s), at the top of the preheater, increasing to 1020 Btu/(ft^3·s), or 38.0 MJ/(m^3·s), at the bottom.

Results have been calculated with the DUVAL code by using a 400-node model representation with a 20 × 20 rectangular grid (Figure 1). As a result of the thermal-hydraulic flow, regions of saturated two-phase liquid (above 544 Btu/lb; 1.26 kJ/g) are calculated to occur first above the lower baffle at 4.5 s into the transient. This region is then seen to expand and proceed upward with the flow until, at 10 s, the entire upper portion is two-phase.

These results and other calculations indicate that the dual-variable method can be successfully implemented for the solution of two-dimensional, thermally expandable two-phase flow phenomena, and the DUVAL code can calculate results accurately in approximately one-twentieth of the time required by similar codes presently employed by the power plant industry. *Project Manager: Patrick Bailey*

Figure 1 DUVAL results of a steam generator preheater problem. The colored areas are regions of two-phase saturated flow at (**a**) 5 s, (**b**) 6 s, and (**c**) 8.5 s into the transient. At 10 s, the entire upper portion is two-phase.



CHEMICAL CLEANING OF NUCLEAR STEAM GENERATORS

The presence of corrosion products is known to be a factor in corrosion damage mechanisms on the secondary side of PWR steam generators. Corrosion products formed in the steam, feed, and condensate systems and transported by the feed train result in a yearly deposit of several hundred pounds of sludge—a mixture of magnetite (Fe_3O_4) and copper—on a steam generator's tubesheets and in the tube–support plate crevices. Aggressive impurities (such as chlorides and hydroxides) concentrate in this sludge and corrosively attack the Inconel tubes and carbon steel support plates. The corrosion of the support plates, in turn, causes the growth of nonprotective magnetite in the crevices between the plates and the tubes. The growth of these deposits leads to the phenomenon known as denting, which causes both tube and support plate damage. Denting and its effects have led one utility to replace steam geneators in a nuclear unit and other utilities to make serious plans for replacement. The chemical removal of corrosion products, both those transported by the feed train and those formed as a result of support plate corrosion, has the potential to significantly increase steam generator, and therefore nuclear plant, reliability.

Chemical cleaning to remove corrosion-product deposits from heat transfer surfaces in fossil-fired boilers is a common practice. However, processes developed for fossil units cannot be directly transferred to nuclear units because of differences in design, configuration, and materials of construction, as well as the need to ensure the integrity of the radioactive primary coolant pressure boundary formed by the tubes in PWR steam generators. Therefore, the utility industry has undertaken several efforts to develop and qualify processes that can be safely and effectively used in nuclear plant steam generators. These efforts have resulted in a process for preoperational cleaning to remove rust and other corrosion products formed during the long construction storage and layup period; this process was used by the Tennessee Valley Authority to clean the Sequoyah Unit 1 steam generators. However, industry efforts to develop a process to remove the magnetite-copper sludge and nonprotective crevice magnetite produced during operation have, for various reasons not associated with the process, yet to reach the field application stage.

Chemical cleaning process development is one program area of the EPRI Steam

Generator Project Office, which was formed in the spring of 1977 to manage research projects aimed at solving steam generator problems (*EPRI Journal,* April 1978, p. 53). The goal of this program area is to build on industry experience and complete the development of a process that uses nonproprietary chemicals and application techniques to remove operationally formed corrosion products. Toward this goal, candidate processes are being demonstrated in test vehicles that simulate the geometry, materials of construction, and thermal-hydraulic characteristics of operating steam generators, and the processes tested will be ranked by their effectiveness and corrosivity. Guidelines will then be prepared to help utilities make management decisions on the feasibility and desirability of applying these cleaning processes or of undertaking further development, testing, and optimization.

Three specific problems are being considered: sludge removal, crevice deposit removal, and solvent replenishment during crevice cleaning.

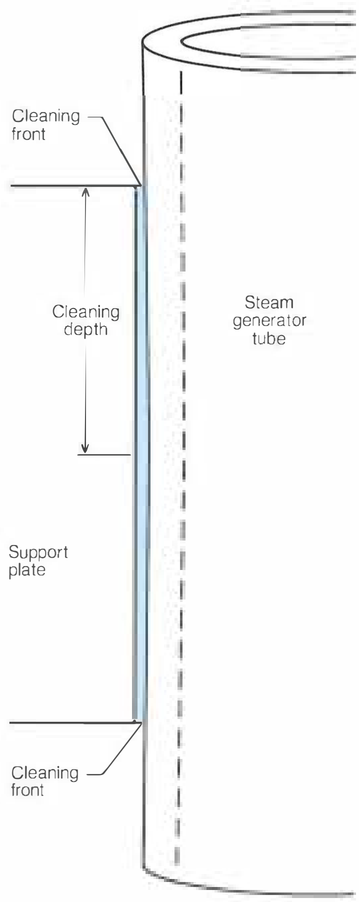
Sludge removal

Sludge removal is required to reduce or eliminate the sludge pile that causes corrosion problems and to prevent sludge interference with the crevice cleaning cycle. The sludge is a mixture of magnetite and copper. The proportion of copper varies from less than 10% to as high as 60%, depending on the copper content of a plant's feed and condensate system. The chemical conditions required for dissolution of magnetite are significantly different from those required for dissolution of copper. This necessitates either the alternate application of different solvent systems or the cyclic adjustment of parameters and chemicals within a single system. Problems arise in preventing one system or cycle from interfering with succeeding cycles. The magnitude of the difficulty increases as the copper content of the sludge increases. Testing to date indicates that processes now available adequately remove sludge with a low copper content (<10%), but further testing is needed to determine their ability to treat high-copper sludge.

Crevice deposit removal and solvent replenishment

Crevice deposit removal involves applying a solvent to dissolve the densely packed magnetite that has formed in the narrow tube–support plate crevice. As shown in Figure 2, the geometry of the crevice is such that the solvent must penetrate a deposit that is 0.75–1 in (19–25 mm) deep by way of

Figure 2 A magnetite-filled tube–support plate crevice, shown here at four times actual size, illustrates a typical relationship between cleaning front (0.014 in) and cleaning depth (0.375 in from each front). In this case, the ratio of cleaning depth to cleaning front is about 27:1. However, the cleaning front is often so small that the ratio is 50:1 or 100:1



a cleaning front that varies in width from virtually zero to only about 30 mils (0.76 mm). Cleaning proceeds from both the top and the bottom of the support plate. However, the ratio of the depth that must be penetrated to the front on which penetration is proceeding is at best 12 to 1 and more likely much greater (50 or 100 to 1).

The objective of work in this area is to develop a solvent system that if adequately replenished, will remove the packed magnetite in a reasonable period of time with acceptably low corrosion to the structural materials of the steam generator. Acceptable corrosivity is plant-specific and depends on a number of factors, including the condition of the support plate at the time of cleaning, tube vibration limits in the cleaned crevices, and the number of anticipated cleanings over the plant lifetime. The definition of reasonable time is also plant-specific to the extent that it is based on outage duration considerations; however, another important consideration is the relationship of time to corrosivity (i.e., as cleaning time is increased, for a given solvent system total corrosion of the steam generator materials is increased).

Solvent systems are available today that satisfactorily clean the crevices between dented tubes and support plates in test vessels. However, the performance of these systems is a function of solvent replenishment, and it is yet to be determined whether the replenishment achieved in test vessels can be obtained in an actual steam generator.

A number of methods of solvent agitation and replenishment at the cleaning front have been considered, including pumped circulation, pumped level oscillation, pressure cycling, ultrasonics, fill and drain, and nitrogen sparging. Pumped circulation and pumped level oscillation show the most promise in the near term. They can be used with virtually any solvent system under most application conditions and do not require any major development effort. One disadvantage, however, is the significant amount of temporary piping and hardware they require. Another is that because of steam generator geometry, realistically achievable flow velocities are quite low, even with extremely large pumping capacities; thus there would be large areas of stagnation with no effective replenishment.

Pressure cycling to promote boiling should provide uniform replenishment but would require a solvent system that could operate at elevated temperatures. Also, these temperatures may interfere with plant outage requirements for containment integrity. This method will require considerable development work and is being incorporated into EPRI's nonconventional process research effort. The laboratory use of ultrasonics to promote cavitation at and in the crevice has indicated feasibility, significantly reducing the time required to clean dented tube–support plate intersections. This method will also require considerable technology and hardware development, but if successful, could be of great benefit. The fill and drain and the nitrogen sparging processes are not currently being pursued because their disadvantages outweigh their advantages.

The cleaning processes developed to date rely on pumped circulation or level oscillation for replenishment. At velocities approaching 2–6 in/s (5–15 cm/s) through the tube bundle (4–12 in/s [10–30 cm/s] across the support plate), crevice cleaning in test vessels has been accomplished with acceptable corrosion in about two weeks. However, presently achievable velocities in a full-size unit are only about 1–2 in/s (2.5–5 cm/s) across the support plate; tests at these velocities are being conducted.

Chemical cleaning projects

The steam generator chemical cleaning research consists of five projects grouped into three areas: conventional process development, nonconventional process development, and process support. (The term *process* encompasses solvent, corrosion inhibitor, application methods and sequence, and control parameters.) Project results through February 1980 are discussed below.

Conventional Process Development Earlier industry efforts focused on the development of a low-temperature (<250°F; 121°C), multistep (sludge copper removal, sludge magnetite removal, crevice magnetite removal, and passivation) process, using organic acids and chelating agents as solvents and pumped circulation or level oscillation for solvent replenishment. In Project S127, Babcock & Wilcox Co. is refining and optimizing one such process jointly developed by Consolidated Edison Co. of New York, Inc., and DOE for cleaning Indian Point Unit 2. The capabilities and limitations of the process are being determined by a sequence of increasingly representative process demonstration tests. The process has been modified to incorporate nonproprietary corrosion inhibitors and, where possible, will be further modified to reduce the effects of identified limitations.

To help bridge the gap between the laboratory and field application, Combustion Engineering, Inc. (C–E) is performing process demonstration tests under conditions that simulate those of actual steam generators (Project S128). The approach is to chemically clean fouled and dented pot and model boilers with processes that meet the laboratory testing criteria. These tests will evaluate effectiveness, corrosivity, and post-cleaning side effects.

Demonstration tests of the Consolidated Edison–DOE process in two of the three applicable test vehicles were conducted between October 1979 and February 1980. In these tests the process was successful in removing a low-copper (<10%), real-plant sludge and in cleaning the crevices between representative dented tubes and support plates. The time required for crevice cleaning was two weeks, and total corrosion of steam generator materials was acceptable. This success is qualified by the following factors, however: Only low-copper, preloaded sludge was present, as opposed to the high-copper sludge found in most field units; a high-sulfur corrosion inhibitor was used, which may interfere with copper removal; and a uniform replenishment flow velocity of no less than 4 in/s (10 cm/s) was maintained across the tube support plate (by level oscillation), which is unrealistic for a real steam generator. Work is under way to modify the process to treat high-copper (>50%) sludge, to incorporate a low-sulfur corrosion inhibitor, and to operate effectively under realistic flow conditions (velocities of 1–2 in/s across the support plate).

Nonconventional Process Development A parallel effort toward achieving a field-applicable chemical cleaning process is considering solvent systems, process parameters, and application techniques that have not been explored in depth by the nuclear industry. In Project S150, UNC Nuclear Industries, Inc., is pursuing development of a nonconventional process that involves a high-temperature (up to 350°F; 177°C) crevice cleaning method with pressure cycling (or boiling) to achieve solvent replenishment. The process uses solvent systems similar to those in conventional processes but applied under different pH and temperature conditions. As development proceeds, a different class of solvent systems may be investigated.

A high-temperature test facility is under construction, and basic laboratory testing to define solvent chemical concentrations and application parameters has been completed. A feasibility demonstration test of the complete process was performed in May 1980 in a pot boiler at C–E (Project S128). Results are being evaluated. After feasibility is shown, modification, optimization, and further demonstration testing will be conducted through April 1981.

Process Support Two projects are providing support to the process development efforts. In Project S148 the Tretolite Division of Petrolite Corp. is identifying, screening, and ranking nonproprietary corrosion inhibitors. Replacement of the proprietary inhibitors is necessary to ensure quality control and prevent dependence on a particular vendor for chemicals and services. Further, it is desirable to provide an inhibitor that does not contain sulfur (as many inhibitors do) to avoid the potential for stress corrosion cracking of Inconel 600. Several candidate inhibitors have been identified, and one (tetraimidazoline) is currently being incorporated into both process development programs.

Project S185 involves the development and field testing of a system that enhances solvent replenishment by using ultrasonic transmission to agitate the solution at and in the tube–support plate crevices. Such a system has shown feasibility under laboratory conditions and may prove effective in enhancing replenishment in the periphery of the tube bundle, where pumped circulation is likely to leave large areas of stagnation.

Outlook

Prospects are good that by March 1981 demonstration testing will be completed, and the capabilities, limitations, and application methods of at least two processes—the basic Consolidated Edison–DOE process and a modified version of that process as discussed above—will be fully documented and reported. This information will provide a basis for utilities to make management decisions about steam generator cleaning. As utilities begin to apply chemical cleaning in field units, work required to optimize these processes will be undertaken. *Project Manager: Charles Welty*

New Contracts

Number	Title	Duration	Funding ($000)	Contractor/ EPRI Project Manager
RP475-8	Technical Evaluation of Ceramic Tube Solar Receiver	4 months	22.6	Cummings Solar Corp. *J. Bigger*
RP734-3	Acoustic Emission Characterization of Turbine Rotor Steels	2 years	502.8	Science Applications, Inc. *J. Parkes and R. Viswanathan*
RP772-4	Dosimetry Measurements of Neutron and Gamma-Ray Fluxes in LWR Cavities	2 years	237.1	University of Arkansas *H. Till*
RP827-4	Analysis of Dosimetry Measurements in LWR Cavities	2 years	79.8	University of Missouri *H. Till*
RP982-19	Screening Study of Corrosion Inhibitors in Sulfur Dioxide Removal Systems	8 months	43.7	SUMX Corp. *D. Stewart*
RP1117-3	Study of Recent Reactivity-Initiated Accident Test Results	5 months	22.6	Intermountain Technologies Inc. *R. Oehlberg*
RP1117-4	Transient Failure of Zircaloy	17 months	25.0	Anatech International Corp. *R. Oehlberg*
RP1260-18	Environmental Impediments to Synthetic Fuels	5 months	19.6	Leland D. Attaway & Associates *R. Komai*
RP1266-17	Pitting Susceptibility of 17-4 PH Stainless Steel	5 months	5.5	SRI International *R. Viswanathan and B. Syrett*
RP1324-4	Theoretical Analysis of Pipe Break Phenomena	22 months	418.0	Department of Energy *J. Carey*
RP1377-4	BWR Refill-Reflood Project Support	33 months	180.0	Jaycor *M. Merilo*
RP1395-5	Nondestructive Evaluation Techniques for Residual Stress Measurement	10 months	17.4	Pennsylvania State University *J. R. Quinn*
RP1412-9	Study of the Combustion Characteristics of SRC-I	10 months	183.0	C–E Power Systems *W. Rovesti*
RP1412-10	Characterization of Synthetic Fuels	10 months	20.0	Babcock & Wilcox Co. *W. Rovesti*
RP1441-1	Sensitivity Theory for LWR Thermal-Hydraulic Analyses	1 year	90.0	Union Carbide Corp. *J. Naser*
RP1444-1	Analysis of Foreign Experimental Structural Data	7 months	59.9	Intermountain Technologies Inc. *R. Oehlberg*
RP1485-1	Application of Energy Analysis and Environment Research to Industry Decisions	18 months	221.9	Decision Focus, Inc. *E. Oatman*
RP1524-2	Introduction of Electric Vehicles Into the Utility System: Analysis of Research Needs	3 months	42.6	Systems Control, Inc. *J. Mader*
RP1532	Surge Characteristics and Protection of Distribution Transformers	1 year	648.8	General Electric Co. *H. Songster*
RP1548-1	Study of Fission Product Behavior in LWR Systems Following Abnormal Occurrences	22 months	150.0	University at Buffalo Foundation, Inc. *H. Till*
RP1551-1	Analytic Method for Nuclear Plant Availability Improvement	1 year	59.1	Westinghouse Electric Corp. *B. Chu*
RP1570-3	Definition of Section XI Ultrasonic Test Techniques	25 months	289.4	Combustion Engineering, Inc. *G. Dau*
RP1570-7	Construction Management Services for EPRI Nondestructive Evaluation Center	15 months	3690.5	J. A. Jones Applied Research Co. *G. Dau*
RP1603-2	Eastern Extension of EPRI's Water Supply Data Base System	2 years	320.0	University of Arizona *E. Altouney*
RP1636-2	Avian Interactions With Transmission Lines	18 months	89.4	Dames & Moore *J. Huckabee*
RP1654-2	On-Line Monitor of Solid Concentration in Coal-Water Slurries	1 year	72.5	Rockwell International Corp. *J. Yerushalmi*
RP1678-1	Technical, Economic, and Utility Systems Analysis Support for R&D Planning and Evaluation	15 months	250.0	Bechtel National, Inc. *R. Loth*
RP1678-4	Technical, Economic, and Utility Systems Analysis Support for R&D Planning and Evaluation	14 months	35.0	Systems Control, Inc. *O. Gildersleeve*
RP1685-2	Manual for Upgrading Existing Waste Disposal Facilities	1 year	210.9	SCS Engineers *D. Golden*
RP1704-8	LMFBR Design Assessment: Consultation to Contractors	10 months	124.9	Rockwell International Corp. *J. Matte*
RP1734-5	Performance of PWR Overpressure Protection System	6 months	38.2	S. Levy, Inc. *C. Sullivan*
RP1734-6	PWR Relief and Safety Valve Test Program	16 months	180.0	MPR Associates, Inc. *W. Bilanen*
RP7883-1	Thermal Stability of Soils Adjacent to Underground Transmission Power Cables	19 months	277.5	Georgia Institute of Technology *R. Samm*

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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ADVANCED POWER SYSTEMS

Economic Evaluation of GCC Power Plants Based on the Steag Combined-Cycle Design

AF-1288 Final Report (RP239-2); $12.00

Preliminary process design and economic screening studies of four integrated gasification–combined-cycle (GCC) power plant systems are presented. Three of the systems are based on the pressurized-boiler combined-cycle design of the West German firm Steag Ag; the fourth, provided for comparison, is based on a typical U.S. combined-cycle configuration. The gasification processes used in the three Steag GCC systems are the air-blown Lurgi dry ash process, the oxygen-blown Texaco entrained-bed process, and the air-blown Texaco entrained-bed process. The contractor is Fluor Engineers and Constructors, Inc. *EPRI Project Manager: E. L. Force*

Liquid-Phase Methanol

AF-1291 Final Report (RP317-2); $9.50

The project involved bench-scale and process-development-unit testing of a new liquid-phase reactor for producing methanol from synthesis gas. In the first part of the project, the basic process concept was demonstrated; in the second part, an attempt was made to develop a suitable process catalyst. Problems with catalyst attrition and deactivation encountered in this research will be addressed in future projects. The contractor is Chem Systems Inc. *EPRI Project Managers: H. E. Lebowitz and C. J. Kulik*

Engineering Evaluation of a Conceptual Coal Conversion Plant Using the H-Coal Liquefaction Process

AF-1297 Final Report (RP411-4); $8.25

The results of a technical and economic evaluation of the H-Coal process for coal liquefaction are given. Work included the development of overall plant configurations for two large commercial liquefaction facilities, each capable of processing 14,448 t/d of coal. One case is based on a feedstock of Illinois No. 6 bituminous coal, the other on Wyodak subbituminous coal. The design assumes operation in the high-conversion syncrude mode and employs the latest yield data from Hydrocarbon Research, Inc. The contractor is Fluor Engineers and Constructors, Inc. *EPRI Project Manager: Nandor Herskovits*

Nature and Origin of Asphaltenes in Processed Coals

AF-1298 Final Report (RP410); Vol. 1, $5.25; Vol. 2, $18.00; Vol. 3, $5.75

This is the final report of a four-year study of the solvent refining of coal. Volume 1 presents a critical review of the chemistry and basic limitations of today's developing coal liquefaction processes, with emphasis on the initial process phases and products. It also summarizes the project results and their significance and reviews the last 18 months' work. Volume 2 describes the experimental work of the last phase of the project in more detail. It covers new experimental techniques; critical factors in the formation of solids (char) during liquefaction; the chemistry of liquefaction solvents; the effects of changes in process variables on liquefaction; and the effects of coal rank and mineral content. Volume 3 contains six appendixes of data. The contractor is Mobil Research and Development Corp. *EPRI Project Manager: W. C. Rovesti*

Electric Utility Solar Energy Activities: 1979 Survey

ER-1299-SR Special Report; $8.25

This survey to determine the scope of solar energy projects sponsored by U.S. electric utilities contains brief descriptions of 735 projects being conducted by 180 utilities. Also included are an index of projects by category; a statistical summary; a list of participating utilities, contacts, and addresses; a list of utilities with projects designated by category; and a list of available reports on utility-sponsored projects. *EPRI Project Manager: Gary Purcell*

Description of Efficient, Fuel-Flexible Combustion Turbine Plants for Small Electric Utilities

AF-1308 Summary and Final Report (TPS78-802-2); $5.25

This report describes the design concept for two small combustion turbine combined-cycle power plants and presents anticipated performance and operating economics. One concept is based on an open-cycle, direct-fired (No. 2 oil) gas turbine with a steam bottoming cycle; for this plant a net (combined-cycle) efficiency of 39.7% is predicted at an output of 11.56 MW (e) with a turbine rotor inlet temperature of 1935°F. The second concept is based on an open-cycle, indirect-fired (coal or oil) gas turbine with a steam bottoming cycle; it is rated at 3.78 MW (e), with a net plant efficiency of 25% when burning Illinois No. 6 coal. Both systems have cogeneration potential, and both appear capable of technical development by 1985. The contractor is Solar Turbines International. *EPRI Project Manager: A. C. Dolbec*

Open-Cycle MHD Systems Analysis

AP-1316 Final Report (RP640-1); $17.25

Five configurations of a coal-burning open-cycle magnetohydrodynamic (MHD) electric power generating facility were evaluated as candidate first-generation plants. Material balance and energy balance analyses were performed along with cycle analyses to provide information for the conceptual design and costing of all major MHD-related components and subsystems. An economic comparison of the plants was made by developing cost-of-electricity figures on the basis of component costs. Estimates of operating and maintenance requirements and plant performance were also made. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: Andrew Lowenstein and Paul Zygielbaum*

Design Properties of Steels for Coal Conversion Vessels: Rising-Load Tests

AP-1337 Interim Report (RP627-1); $3.50

This report describes the results of rising-load fracture toughness tests on two grades of $2\frac{1}{4}$Cr–1Mo Steel (ASTM A387 Class 2, Grade 22, and ASTM A542 Class 3) and type-347 stainless steel overlay material. The tests were conducted in a standard environment of 6% H_2S–H_2 with pressures in the range of 5.5–24.1 MPa and temperatures in the range of 298–727 K. Material conditions were investigated for base metal, weld metal, heat-affected zone, and temper-embrittled steel. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: Ramaswany Viswanathan and Roger Richman*

Design Properties of Steels for Coal Conversion Vessels: Mechanical Properties of Materials

AP-1338 Interim Report (RP627-1); $4.50

Baseline data are given on two grades of $2\frac{1}{4}$Cr–1Mo steel (fabricated as submerged-arc weldments) and type-347 stainless steel overlay material. The $2\frac{1}{4}$Cr–1Mo steels studied were ASTM A387 Class 2, Grade 22, and ASTM A542 Class 3. Material conditions were investigated for base metal, weld metal, heat-affected zone, and temper-embrittled steel; fracture toughness and other baseline mechanical properties and microstructures were also evaluated. The contractor is Westinghouse Electric Corp. *EPRI Project Managers: Ramaswany Viswanathan and Roger Richman*

COAL COMBUSTION SYSTEMS

Validation of Cooling Tower Analyzer
FP-1279 Final Report (RP1262-1); Vol. 1, $12.00; Vol. 2, $9.50

Volume 1 demonstrates the predictive capabilities of the computer program TACT (Thermal Analyzer for Cooling Towers) and describes how it was validated against performance data from U.S. and European towers. On the basis of physical design information, TACT solves the steady-state, elliptical differential equations for radial and axial components of the air velocity, the air mass continuity, and the enthalpies of the two fluid streams (air and water) in both cross- and counter-flow natural-draft cooling towers. Volume 2 is a user's manual for TACT. It describes its mathematical foundation and its structure, including the necessary FORTRAN input variables. A listing of the validated code and a typical printout of input and output data are included. The contractor is Cham of North America, Inc. *EPRI Project Manager: John Bartz*

Materials Problems in Fluidized-Bed Combustion Systems: Corrosion Chemistry in Low-Oxygen-Activity Atmospheres
FP-1280 Interim Report (RP979-6); $8.75

This project investigated the corrosion of iron-, nickel-, and cobalt-base high-temperature alloys in atmospheres with low oxygen activity and high sulfur activity. These conditions may be present in local regions of fluidized-bed combustion boilers and are also encountered in coal gasification systems. Among the major factors studied were alloy composition and surface condition, exposure time and temperature, and variable exposure parameters. The contractor is Lockheed Missiles & Space Co., Inc., Palo Alto Research Laboratory. *EPRI Project Manager: John Stringer*

Criteria for the Selection of SO_2 Sorbents for Atmospheric Pressure Fluidized-Bed Combustors
FP-1307 Final Report (RP721-1); Vol. 1, $4.50; Vol. 2, $5.75

Volume 1 reports on Task 1 of this project, a review of relevant published work through mid-1976. It discusses requirements for establishing sorbent selection criteria and makes recommendations for future work. Volume 2 presents the results of laboratory studies performed under Tasks 2 and 3. Five limestones were tested to evaluate their suitability as sulfur sorbents in atmospheric pressure fluidized-bed combustors. Physical characterization of the sorbents (grain size and pore volume distribution) and chemical analyses were followed by reactivity tests in a thermogravimetric apparatus and by batch sulfation in a fluidized-bed unit. Reactivity studies covered a range of particle sizes, temperatures, and precalcination treatments. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: T. E. Lund.*

Electric Utility Use of Fireside Additives
CS-1318 Final Report (RP1035-1); $11.25

On the basis of a state-of-the-art literature review and a survey of 38 utilities, this study identifies generic classes of additives found to be effective in combating problems associated with boiler performance and reliability (e.g., corrosion, fouling, and superheat temperature control). Information was obtained on 445 trials involving different combinations of units, additives, and fuels. Additives are classified in terms of their principal chemical constituents. The report includes guidelines for utility use in selecting additives and conducting field trials. The contractor is Battelle, Columbus Laboratories. *EPRI Project Manager: John Dimmer*

Power Plant Waste Heat Rejection, Using Dry-Cooling Towers
CS-1324-Y Summary Report (RP422-2); $2.75

This report summarizes the activities, results, and status of a project to develop dry and dry-wet cooling system technology for steam-electric power plants. A phase-change dry cooling system of increased thermal performance was investigated and demonstrated with an 0.3-MW (e) pilot plant. Ammonia was used as the heat rejection fluid, and improved heat transfer technologies were applied. The contractor is Union Carbide Corp. *EPRI Project Manager: John Bartz*

ELECTRICAL SYSTEMS

Evaluation of Alternative Insulating Oils for Transformers and Other Electric Apparatus
EL-809-SY Summary Report (RP562-1); $5.25

Paraffinic oils and synthesized fluids (alkylbenzenes, polyolefins, and silicones) are evaluated as possible alternatives to naphthenic oils for transformer insulating fluids. Estimates were made of future requirements for transformer oils and of existing and expected production. Paraffinic oils were compared with naphthenic oils under conditions closely simulating actual service. The low-temperature behavior of paraffinic oils was also evaluated. The contractor is General Electric Co. *EPRI Project Manager: E. T. Norton*

Characteristics of Insulating Oil for Electrical Application
EL-1300 Final Report (RP577-1); $11.25

This project analyzed the behavior of a paraffinic insulating oil in representative production-size equipment (e.g., tap changers and power circuit breakers). One objective was to determine if the equipment would operate if exposed to temperatures as low as $-40°C$. Other factors studied included material compatibility, lubricity of the new oil, arc-formed gas, response to dielectric breakdown levels representative of large power transformers, and accelerated aging in distribution transformers. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: E. T. Norton*

High-Voltage Oil Gap Tests Using Parallel-Plane Electrodes
EL-1301 Milestone Report (RP577-1); $4.50

Dielectric tests to compare a naphthenic oil and a paraffinic oil are described. The tests were conducted with two different electrode configurations—uniform-field electrodes and rod-to-plane electrodes. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: E. T. Norton*

Oil Tests in Tap Changers
EL-1302 Milestone Report (RP577-1); $5.25

Two Westinghouse load tap changers were operated in a naphthenic oil and a paraffinic oil, and their performance evaluated. No appreciable differences were noted in the operation of the tap changers in the two oils. The evaluation was based on tests of mechanical performance at low temperatures, load interruption capability, and mechanical life. The contractor is Westinghouse Electric Corp. *EPRI Project Manager: E. T. Norton*

Bundled-Circuit Design for 115–138-kV Compact Transmission Lines
EL-1314 Final Report (RP260-2); Vol. 1, $10.50; Vol. 2, $14.25

This two-volume report is a supplement to the *Transmission Line Reference Book: 115–138-kV Compact Line Design.* Volume 1, which serves as a design manual, presents specific methods and recommendations for bundled-circuit design, reference information, tables and curves, and design examples. Volume 2 documents the results of the experiments and background studies required for development of the design manual. It describes work on supporting insulators and midspan spacers, switching-surge systems, conductor motion, and radio noise. The contractor is Power Technologies, Inc. *EPRI Project Managers: J. P. Piscioneri and R. E. Kennon*

Study of Drifting Charged Aerosols From HVDC Lines
EL-1327 Final Report (TPS78-62); $4.50

A study was made of the mechanism by which atmospheric aerosol particles are charged in the vicinity of a unipolar high-voltage direct-current line. The report includes a numerical analysis that predicts the magnitude of the current carried by wind-driven particulates. The contractor is William A. Hoppel. *EPRI Project Manager: R. E. Kennon*

Ice-Release Coating for Disconnect Switches
EL-1330 Final Report (RP931-1); $3.50

This report describes tests to determine if inexpensive, commercially available coatings can be applied to standard air disconnect switches to reduce ice buildup and/or facilitate ice removal during switch operation. A cost forecast for coated contacts on vertical break switches and recommendations for further development are included. The contractor is Siemens-Allis Corp. *EPRI Project Manager: V. H. Tahiliani*

ENERGY ANALYSIS AND ENVIRONMENT

Cost Models for Coal Transportation by Common Carrier: Appendix 1, User's Manual
EA-675 Final Report (RP866); $8.25

This manual provides technical information on using the three computerized coal transportation cost models (for railroads, waterways, and intermodal transfers) developed in this project. The models calculate the cost of owning, maintaining, and operating transportation and related equipment. The contractor is Manalytics, Inc. *EPRI Project Manager: E. G. Altouney*

Evaluation of a Cooling-Lake Fishery: Fish Population Studies
EA-1148 Final Report, Vol. 3 (RP573); $12.50

Surveys were conducted in Lake Sangchris, a cooling lake, and Lake Shelbyville, a nearby flood control reservoir, to compare the size and composition of the fish populations and to determine the effects, if any, of the thermal discharge from the power plant on the fish community. Quantitative samples of fishes were collected (by electrofishing, gillnetting, and seining) bimonthly from Lake Sangchris and quarterly from Lake Shelbyville. Preferred temperatures and movements of fishes were studied by radiotelemetry. The contractor is the Illinois Natural History Survey. *EPRI Project Manager: J. Z. Reynolds*

Coal Supply Alternatives for Rural Electric G&T Cooperatives

EA-1270 Final Report (RP868-2); $12.50

This report provides an analytic framework that generation and transmission cooperatives can use to evaluate their coal procurement options. It identifies promising coal supply regions and key procurement issues and evaluates alternative procurement strategies. Topics discussed include economic considerations in the choice of coal type and supply region, economies of scale, relationships with coal suppliers, financing coal development, coal purchase contract terms, federal coal leasing, coal transport, and impacts of air quality regulations. The contractor is ICF Incorporated. *EPRI Project Manager: T. E. Browne*

Fly Ash Structural Fill Handbook

EA-1281 Final Report (RP1156-1); $8.25

This handbook is on the design of structural fills and embankments that use fly ash as a substitute for conventional materials. It covers the collection and handling of fly ash, ash properties affecting its behavior as a construction material, laboratory test procedures for determining ash properties, design analysis, and construction methods. The contractor is GAI Consultants, Inc. *EPRI Project Manager: Robert Kawaratani*

Electricity Demand and Consumption by Time of Use: A Survey

EA-1294 Final Report (SOA78-413); $5.25

The theoretical and econometric methodologies available for use in estimating the response of residential customers to time-of-day and seasonally varying electricity prices are summarized. Certain DOE-sponsored pricing experiments and their analyses are evaluated. An annotated bibliography is included. The contractors are Dennis J. Aigner and Dale J. Poirier. *EPRI Project Manager: Anthony Lawrence*

Modeling and Analysis of Electricity Demand by Time of Day

EA-1304 Workshop Proceedings (RP1050); $17.25

This report includes several papers on modeling and forecasting electricity demand by time of day that were presented at a June 1978 EPRI-sponsored workshop in San Diego. The papers and the accompanying comments by participants represent a cross section of the state of the art in this research. Also included are overviews with recommendations on future research. The contractor is the University of Arizona. *EPRI Project Manager: Anthony Lawrence*

Forecasting Residential Electric Loads With Time-of-Day Rates

EA-1321 Final Report (RP943-2); $5.75

A model to predict daily and hourly residential electricity demand under time-of-day rates was developed on the basis of data from the Connecticut Peak Load Pricing Experiment. It was evaluated by comparing forecasts for 20 households with the actual demand measured for those households. The contractor is Charles River Associates, Inc. *EPRI Project Manager: Anthony Lawrence*

ENERGY MANAGEMENT AND UTILIZATION

AC/DC Power Converter for Batteries and Fuel Cells

EM-1286 Annual Report (RP841-1); $8.25

The leading commutation circuit options were tested and analyzed by computer simulation. The report describes an analytic and experimental evaluation of advanced commutation circuits, an evaluation of alternative advanced bridge designs, selection of the most desirable conceptual design, and development of a mathematical model describing the response of self-commutated converters. Experimental data are contained in the appendixes. The contractor is United Technologies Corp. *EPRI Project Manager: R. J. Ferraro*

Technical and Economic Assessment of Advanced Compressed-Air Storage Concepts

EM-1289 Final Report (RP1083-1); $18.00

This report describes a study of advanced compressed-air storage (CAS) concepts in which oil consumption is reduced or eliminated by thermal energy storage (TES) or by coal substitution. A large number of possible cycles were screened, and the most promising examples were ranked by cost and economic benefit to utilities. A near-term hybrid system using TES was identified that is capable of reducing CAS turbine fuel consumption by at least 30% with equipment very closely related to state-of-the-art design. The contractor is the Central Electricity Generating Board (England). *EPRI Project Manager: W. A. Stevens*

Development of the Sodium–Antimony Trichloride Battery for Utility Application

EM-1323 Final Report (RP109-3); $6.50

An overview is presented of the development of a sodium–antimony trichloride battery for load-leveling and peaking applications. ESB and EPRI concluded that this system cannot compete economically or in electrochemical performance with the sodium-sulfur system in the years after 1985. As a result, development of this technology was discontinued in 1978. The contractor is ESB Incorporated. *EPRI Project Manager: J. R. Birk*

Electric Vehicles—How Do They Compare With Synthetic Liquid Fuels?

EM-1326 Final Report (TSA79-285); $2.75

This report presents a framework for comparing electric vehicles with other oil substitution options, namely, synthetic fuels derived from coal and oil shale. The options are compared in terms of resource utilization; capital investment; fuel costs; energy efficiency; and impact on the energy supply industry, the environment, and mobility. The contractor is Purdue University. *EPRI Project Manager: G. H. Mader*

Advanced-Technology Fuel Cell Program

EM-1328 Annual Report (RP114); $5.25

To establish a basis for the engineering development of an improved fuel cell power plant, molten carbonate and advanced phosphoric acid fuel cells, advanced reformers, and the use of coal products are being investigated. In the work reported here, molten carbonate cell configurations capable of enduring thermal cycles were developed and demonstrated in 1-ft^2 stacks of 8 and 20 cells. Subscale cells were tested at pressures of up to 5 atm with little, if any, carbon or methane formation in the fuel cell. In addition, adiabatic, hybrid, and cyclic reformers were evaluated. The contractor is United Technologies Corp. *EPRI Project Manager: A. P. Fickett*

Assessment of Sulfur Removal Processes for Advanced Fuel Cell Systems

EM-1333 Final Report (RP1041-5); $6.50

A technical evaluation and an economic comparison of sulfur removal processes for integration into a coal gasification–molten carbonate fuel cell power plant are given. The plant was assumed to incorporate an oxygen- or air-blown Texaco gasifier fired with 10,000 t/d of Illinois No. 6 coal. Four bulk desulfurization processes were considered: Sulfinol, Benfield, Rectisol, and Selexsol. Capital and cost estimates were developed, and the impact on overall plant performance was determined. The contractor is C F Braun & Co. *EPRI Project Manager: B. R. Mehta*

Development of Advanced Batteries for Utility Application

EM-1341 Final Report (RP128-4, RP128-5); $12.50

This report presents the interim results of a program to develop sodium-sulfur batteries for utility load-leveling applications. Efforts at scaling up the basic cell from 30 Wh to 300 Wh are described. Two concepts for a 100-kWh battery module were investigated. A model was developed and experiments conducted to describe the performance of the resistive mat between the polysulfides and the ceramic electrolyte. New measurements of the entropy change associated with the sodium-sulfur reaction are presented. The contractor is General Electric Co. *EPRI Project Manager: J. R. Birk*

Proceedings of the DOE–EPRI Workshop on Molten Carbonate Fuel Cells

WS-78-135 Workshop Proceedings; $8.25

A workshop on molten carbonate fuel cell technology was sponsored by DOE and EPRI at Oak Ridge National Laboratory, October 31–November 2, 1978. This report includes the papers presented, which represent the state of the art as of fall 1978. Workshop topics were electrochemistry, modeling of electrochemical processes, cell packaging and design, cell materials, and contaminants and cleanup. *EPRI Project Manager: A. J. Appleby*

NUCLEAR POWER

Measurements of ^{235}U and ^{239}Pu Fission-Product Decay Spectra

NP-999 Final Report (RP957-1); $5.75

High-resolution gamma-ray and medium-resolution beta fission-product spectra were measured at various cooling times after 1000-s irradiations of ^{235}U and ^{239}Pu. The results are compared with calculations based on the evaluated nuclear data library, ENDF/B, Version IV. The contractor is IRT Corporation. *EPRI Project Manager: Walter Eich*

Investigation of Interaction Between Heat Transfer and Cladding Swelling in LWR LOCA Analysis

NP-1210 Final Report (RP494-3); $7.25

This report presents the results of an initial assessment of the interaction between coolant heat transfer and Zircaloy cladding deformation in LWR fuel rods under hypothetical loss-of-coolant accident (LOCA) conditions. Current computer-based technology was used as the analytic tool. A parametric evaluation was made to determine the sensitivity of factors that could affect cladding deformation. The contractor is Rowe & Associates. *EPRI Project Manager: R. N. Oehlberg*

On-Line Nuclear Power Distribution

NP-1278 Final Report (RP1120-1); $8.75

The conservatisms and uncertainties associated with the on-line inference of core power distributions from in-core detector measurements were investigated for two PWRs and two BWRs. Detector measurement asymmetries and trends throughout one cycle of data for each plant were evaluated, and inferred power distributions were compared with independent gamma-scan measurements. The contractor is Nuclear Associates International, Inc. *EPRI Project Manager: A. B. Long*

Flooding in Two-Phase Countercurrent Flows

NP-1283 Topical Report (RP1160-1); $4.50

This report describes an experimental and analytic study of air-liquid countercurrent flooding limits in a vertical tube. The analysis is based on interfacial instability and kinematic wave theory. Experiments included work on the effects of fluid properties and entry geometry. The theoretical results can be adjusted to fit the data as well as available correlations (e.g., Wallis) by an appropriate choice of constants. The contractor is the University of California at Berkeley. *EPRI Project Managers: K. H. Sun and Yoram Zvirin*

Review of Entrainment Phenomena and Application to Vertical Two-Phase Countercurrent Flooding

NP-1284 Topical Report (RP1160-1); $3.50

This is a summary of available information on entrainment phenomena in concurrent annular dispersed flows and assesses the current understanding of the role of liquid entrainment in countercurrent flooding. Particular attention is given to entrainment mechanisms and criteria, entrained-drop sizes, flow structure, entrainment and deposition rates, and experimental methods. The limitations of concurrent flow analysis for countercurrent flows are also discussed. The contractor is the University of California at Berkeley. *EPRI Project Managers: Yoram Zvirin and K. H. Sun*

Feasibility Study of Pipe Welding Using a Homopolar Generator

NP-1285 Final Report (RP1122-1); $6.50

This report investigates the technical feasibility of using a homopolar generator as the power supply in making girth welds in type-304 stainless steel BWR pipe. The design and construction of a welding fixture capable of accomplishing these resistance welds in a laboratory environment are described. The technique was compared with conventional fusion welding techniques on the basis of expected production rate and the cost of equipment, materials, labor, and power. The contractor is the University of Texas at Austin. *EPRI Project Manager: K. E. Stahlkopf*

Comparison of Experimental and Predicted Heat Transfer for the Data of the UC-B Reflood Experiment

NP-1290 Topical Report (RP248-1); $5.25

This report evaluates reflooding data obtained from earlier single-tube experiments. The data were augmented by additional measurements of wall temperature variations in the quench region and by photographs of the flow emerging from the tube. The phenomena of quenching, inverse annular flow film boiling, and dispersed-flow heat transfer are analyzed. The analyses and data are compared with existing correlations and models. The contractor is the University of California at Berkeley. *EPRI Project Manager: K. H. Sun*

Fort St. Vrain Experience: First Refueling-Maintenance Outage

NP-1292 Final Report (RP900-3); $4.50

The first refueling and maintenance outage of the Fort St. Vrain high-temperature, gas-cooled reactor is described. The report covers the refueling of six core regions, the inspection of two core regions, the installation of a core motion detector, the replacement of a shim rod drive motor and a helium circulator, and personnel radiation exposure during the outage. Special developmental items, such as the installation of test fuel elements, are also discussed. The contractor is The S. M. Stoller Corp. *EPRI Project Manager: M. E. Lapides*

Auxiliary Processor to Improve Cost-Effectiveness of Inelastic Structural Analysis

NP-1296 Final Report (RP971-3, RP1242-1, RP1242-2); $6.50

Finite element code improvements aimed at reducing computer charges and developing an on-line error estimation capability were investigated. Novel techniques are described that might result in large computer cost reductions in high-degree-of-freedom, inelastic problems. A plan is laid out for the development of the needed computer software. The contractors are Entropy Limited, Washington University, and SRI International. *EPRI Project Manager: S. T. Oldberg*

Analysis of Steam-Chugging Phenomena

NP-1305 Final Report (RP1067-1); Vol. 1, $6.50; Vol. 4, $6.50

Volume 1 describes the development and verification of an analytic model to simulate steam-chugging phenomena. The model is based on fundamental mass, momentum, and energy conservation laws and includes the important effects of turbulence and gas dynamics. Two computer codes were also developed. Volume 4 is a user's manual for one of these codes, SAMPAC1, which is designed to simulate the gas-liquid interface during rapid condensation events in LWR steam suppression pools. Only the two-dimensional free-surface fluid motion is calculated and presented here. The contractor is Jaycor. *EPRI Project Manager: J. P. Sursock*

Analysis of Ductile Crack Extension in BWR Feedwater Nozzles

NP-1311 Final Report (RP1241-1); $2.75

The stability of ductile crack extension in very deeply cracked BWR feedwater nozzles was investigated by analyzing a conservatively idealized two-dimensional elastic-plastic model. The assumed ratio of crack length to nozzle thickness was varied from 0.5 to 0.95, and bilinear stress-strain relationships were used. The fracture parameters were then compared to measured material properties in order to define critical pressure for failure. The contractor is Washington University. *EPRI Project Manager: T. U. Marston*

Acoustic Monitoring of Relief Valve Position

NP-1313 Interim Report (RP1246-1); $3.50

Six types of safety and relief valves commonly used in LWRs were instrumented with sensors that respond to the noise of steam flowing through a valve and were activated under simulated plant conditions. Background noise was measured in both PWR and BWR plants so that relative signal levels (valve open versus valve shut) could be determined. Data are presented that will help system designers predict acoustic levels encountered when a relief valve opens. The contractor is Technology for Energy Corp. *EPRI Project Manager: Gordon Shugars*

URSULA2 Computer Program

NP-1315 Final Report (RP1066-1); Vol. 1, $4.50; Vol. 2, $5.25; Vol. 4, $2.75

Volume 1 describes the mathematical model embodied in the URSULA2 code. It presents the governing partial-differential equations for transient three-dimensional two-phase flow and heat transfer as encountered in a PWR steam generator and expresses them in polar coordinates. The equations are described for a homogeneous model, a two-fluid model, and an algebraic slip model. Volume 2 presents (1) the results of numerical sensitivity studies consisting of steady homogeneous flow calculations with various grid sizes and transient homogeneous flow calculations with various time steps; (2) the results of physical sensitivity studies in which parameters for primary partitioning of flow, flow resistance, and heat transfer resistance are varied; and (3) demonstration calculations of code predictions of steady and transient flows under normal and abnormal operating conditions. Empirical correlations are summarized in the appendix. Volume 4 presents a separate computer code that takes information in the form usually used by equipment designers and calculates the geometrical parameters required by URSULA2 for thermal-hydraulic analysis. The contractor is Cham of North America, Inc. *EPRI Project Manager: J. P. Sursock*

Study of the State of Design for Pipe Whip

NP-1320 Final Report (RP1324-2); $3.50

This report discusses the parameters designers address when considering the consequences of a postulated pipe rupture in a nuclear plant and assesses current design practice. The parameters are break opening time and size, blowdown characteristics of the effluent from the broken pipe, jet reaction and impingement loading, pipe motion, and pipe impact loading on steel and concrete structures. The effects of these parameters on overall plant design and conservatisms are evaluated qualitatively, and recommendations for further study are made. The contractor is the Tennessee Valley Authority. *EPRI Project Manager: H. T. Tang*

Demonstration of Fiber-Optic Link Applications in Utility Plant Multiplexed Instrument and Control Systems

NP-1322 Final Report (RP1173-1); $5.25

The design, fabrication (using commercially available components), installation, operation, and testing of a fiber-optic system in a utility plant instrumentation system are described. Data transmission via fiber-optic cables was demonstrated over a 10-month period. Plastic fiber-optic cables were evaluated for applications of up to 140 ft, and glass fiber-optic cables for applications of up to 1330 ft. The contractor is E-Systems, Inc. *EPRI Project Manager: R. E. Swanson*

Role of Microscale Processes in the Modeling of Two-Phase Flow

NP-1325 Interim Report (RP888-1); $5.25

Three investigations of microscale processes that influence two-phase flow and its modeling are described. The first study dealt with the physical processes in pipe blowdown, the second with the role of interfacial pressure forces in determining the character of two-phase flow model equations. In the third study a model of the detailed phase interactions in vertical two-phase flow was developed that avoids the mathematical pitfalls of theories based on averaging processes. The contractor is Jaycor. *EPRI Project Manager: Lance Agee*

Stress Corrosion Cracking of Zircaloys

NP-1329 Final Report (RP455-1-6); $6.50

This report presents the results of experiments that explored how variations in vendor-specific fabrication processes, crystallographic texture, and inside-surface finishing treatment affect the resistance of unirradiated Zircaloy tubing to iodine-induced stress corrosion cracking. The effects of the ratio of axial stress to hoop stress, stress change, temperature, and alloy composition were investigated. Work on the thermochemistry of the zirconium-iodine system is discussed. The contractor is SRI International. *EPRI Project Manager: Howard Ocken*

Combined Bottom and Top Reflooding Experimental Program

NP-1331 Final Report (RP341-1); $5.25

This supplements the design work documented in NP-1332 by presenting a general description of the reflood test facility and a detailed description of each component. Data requirements, instrumentation plan, test matrix, and testing procedures are also described. The contractor is the State University of New York at Buffalo. *EPRI Project Manager: R. B. Duffey*

Effects of Upper-Plenum Steam Condensation Phenomena on Heat Transfer in a Rod Bundle

NP-1332 Final Report (RP341-1); $8.25

Coolant was injected simultaneously from the bottom and the top of a 3×3 rod bundle to investigate reflood phenomena in the bundle and associated phenomena in the upper plenum. Experiments covering a range of test conditions of direct interest in reactor safety analysis were conducted. The contractor is the State University of New York at Buffalo. *EPRI Project Manager: R. B. Duffey*

Ultrasonic Field Analysis Program for Transducer Design in the Nuclear Industry

NP-1335 Final Report (RP892-1); $3.50

An ultrasonic field analysis program that can be used for transducer design in the nuclear industry is given. Calculation routines are introduced that use Huygens's principle and enable optimizations of axial and lateral resolution, beam symmetry, and gain variation throughout the ultrasonic field. Mathematical details and sample problems that show comparisons with classical results are presented. Problems such as transducer shape effects, pulse shape effects, and crystal vibration variation are discussed. The contractor is Drexel University. *EPRI Project Manager: M. E. Lapides*

Countercurrent Annular Flow Regimes for Steam and Subcooled Water in a Vertical Tube

NP-1336 Topical Report (RP443-2); $5.25

Experiments on steam-water countercurrent annular flow were performed at atmospheric pressure in a transparent vertical pipe (2-in diam) attached to plenum chambers at the ends. Steam was supplied at the bottom while water with different levels of subcooling was supplied at the top. The flow rates were varied, and the rate of accumulation of water in the lower plenum and its temperature were recorded. Results for two different systems are reported. The contractor is Dartmouth College. *EPRI Project Manager: K. H. Sun*

Prediction of Transient Nonequilibrium Two-Phase Flows: An Extension of FAST

NP-1339 Final Report, Vols. 1 and 2 (RP815-1); $12.00

Volume 1 presents a modified form of the FAST (Finite-Interval Analytic Solution Technique) procedure. Four interphase energy and mass transfer models are used: thermal equilibrium; a subcooled-liquid–saturated-vapor model appropriate for subcooled boiling; a separated-flow model in which neither phase need be at equilibrium; and a saturated-liquid–superheated-vapor model. A variety of real and contrived flows are considered. Volume 2 presents a computer programming manual and a complete listing of the program. The contractor is University of Waterloo. *EPRI Project Manager: Mati Merilo*

Feasibility of an Equipment Qualification Data Bank

NP-1340 Interim Report (RP1707-2); $4.50

This study examined the feasibility of establishing an equipment qualification data bank, which would be a centrally located, comprehensive data system concerning all available environmental qualification work for safety-related (Class 1E) electrical equipment in nuclear plants. Stored information would include equipment identifiers, environmental parameters, qualification test parameters, and sources of documentation. Various storage and retrieval schemes were studied, and potential sources of information and users were identified. The contractor is NUS Corporation. *EPRI Project Manager: G. E. Sliter*

POLICY PLANNING

Analytic and Demonstration Experience With Changing Load Profile

PS-1293 Final Report (TPS79-715); $5.25

A bibliography of completed and ongoing EPRI load management and supply management projects was developed. Selected projects are summarized, along with six utility load management demonstration projects. The contractor is Systems Control, Inc. *EPRI Project Manager: James Mulvaney*

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