Number One 1986

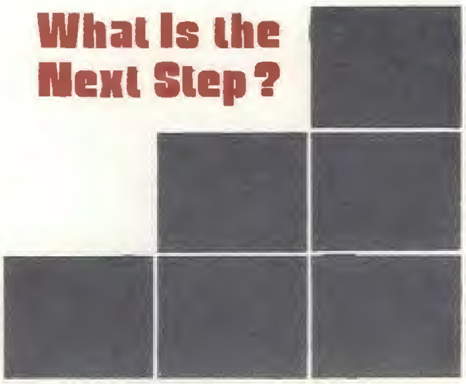
Oak Ridge National Laboratory

review

Nuclear Energy

What Is the Next Step?

Nuclear Energy



THE COVER: Nuclear power facilities showcased in a staircase raise the question, What is the next step for nuclear power in the United States? To provide some perspective on the uncertainties, this issue is dedicated to examining the past and possible future for nuclear energy. The facilities, some of which are shown here during their construction days, are, from top to bottom clockwise, Turkey Point, St. Lucie, Catawba, Sequoyah (early construction), Sequoyah (control room), and Watts Bar.

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EDITORIAL: The Nuclear Power Option Must Be Kept Alive

By FRED MYNATT, ORNL Associate Director for Nuclear and Engineering Technologies

In the United States 24 nuclear power plants are under construction and 98 are in operation, supplying 15% of the nation's electricity. This year the number of operating plants will reach 100. Nuclear energy is the second largest provider of electricity consumed in the United States; the largest, coal energy, is the source of 57%. The nation has 10% more power-producing capacity than it needs to meet current demands for electricity. So why worry?

One reason to worry is that most of the idle generating capacity consists of oil-fired power plants. The world has been awash with cheap oil, but an international crisis could suddenly escalate the cost of oil and cut back supplies needed for transportation fuel and chemicals. In such a situation, oil for generating electricity may not be available or affordable.

A second reason to worry is that the nuclear-plant construction pipeline is emptying. Only one new plant, if any, will enter service after 1990. A long gap will follow. Even if a utility were to order a reactor today, planning and building a new plant would take at least 10 years. No new service would be available until 1996 at the earliest. More likely, no new orders will be placed until about 1995, and no new plants will begin operating until about 2005. Furthermore, the 10% excess in the reserve margin will disappear some time between 1991 and 1995, according to projections of the National Energy Resource Council and the Energy Information Administration of the U.S. Department of Energy. The United States, they say, will need to increase its generating capacity in the early 1990s to meet the projected growth in demand. New capacity will be needed, but planning is not under way now for either nuclear or coal facilities.

A third reason to worry is that coal may become less acceptable as an energy source. The health and environmental costs of coal-generated electricity may become more obvious with large increases in coal mining, transportation, and sulfur dioxide pollution, the combination of which is already being blamed for 10,000 deaths a year. Furthermore, an increasing number of scientists agree that emissions from coal-fired power plants are partly responsible for acid rain, which poisons lakes and streams. And, according to a growing scientific consensus, carbon dioxide emissions from fossil fuel combustion may warm the climate enough through the greenhouse effect to trigger droughts and coastal floods. These concerns may constrain coal's future use.

The U.S. nuclear enterprise could save the day if it were not in such disarray. The government's uranium enrichment business is floundering, and funding for advanced enrichment technologies is greatly reduced. The breeder reactor research program is practically dead; the only way that the United States can preserve its breeder reactor and fuel reprocessing expertise is through cooperative programs with nations like Japan and France that are committed to developing and using breeder and fuel-recycle technology. This is one way to keep the nuclear option alive for the long term.

Designing improved light-water reactors that are simpler and safer and, therefore, more acceptable to the utilities and the public than today's versions is another way to ensure nuclear energy's viability. A third way is to develop and refine reactor concepts like the modular high-temperature gas-cooled reactor and the modular liquid-metal reactor to provide new options for power generation. A fourth way is to develop military reactors to power military installations, ground-based lasers, or weapon systems in space.

Through these efforts, the U.S. Department of Energy hopes to preserve the nuclear option. Oak Ridge National Laboratory—the birthplace of the light-water reactor and the home of a research reactor that has far outperformed other reactors during its 20-year lifetime—endorses the DOE strategy and plans to develop technology in support of these reactor options.

Regrettably, our pursuit of better reactors that promise less financial risk and greater safety is jeopardized by the U.S. commitment to cut spending to reduce the federal deficit. We are not opposed to cutting the deficit, but we question the sacrifice of an energy-supply option that likely will be needed to stave off a possible energy deficit. The United States should not turn its back to the future, but rather face it with sufficient resources and expertise to ensure a secure energy supply.

Civilian Reactor Power in the United States:

By FRED MYNATT, JOHN JONES, and WILLIAM BURCH

The two major economically viable energy sources for electricity generation in the future are coal and nuclear energy. Coal provides about 57% of the electricity generated in the United States, whereas nuclear energy provides about 15%. Nuclear energy is plagued with a host of unresolved technical and institutional problems that threaten to limit its use. However, a growing consensus in the scientific community suggests that carbon dioxide emissions from fossil fuel combustion may warm the climate enough to produce undesirable effects, such as droughts and coastal flooding. This growing concern may very well reduce the use of coal and other fossil fuels in the 21st century. At the same time, however, the national demand for electricity is projected to increase; therefore, we believe that the risk of allowing the U.S. civilian nuclear energy option to deteriorate, as it has during the last decade, is unacceptable.

Civilian nuclear power in the United States has a checkered

Fred R. Mynatt (left) is ORNL's Associate Director for Nuclear and Engineering Technologies. He is responsible for civilian nuclear energy programs, nuclear and chemical waste programs, and work for the U.S. Department of Defense. From 1982 to 1984 he was director of the Instrumentation and Controls Division, and from 1977 to 1981, he was director of Nuclear Regulatory Commission programs at ORNL. In 1979 he coordinated the ORNL assistance provided after the accident at the Three Mile Island Nuclear Power Plant. From 1971 to 1977, he was a member of ORNL's Neutron Physics Division, where he headed the Nuclear Engineering Analysis Section. He came to ORNL in 1965 as a member of the Scientific Applications Department at the Computing Technology Center. Mynatt, who holds a Ph.D. degree in nuclear engineering from the University of Tennessee, has contributed his technical expertise to nuclear reactor theory and operation, radiation shielding, reactor safety, and scientific application of large-scale computers. In 1978 he was elected a Fellow of the American Nuclear Society, and in 1981 he received the prestigious Ernest Orlando Lawrence Memorial Award from the U.S. Department of Energy.

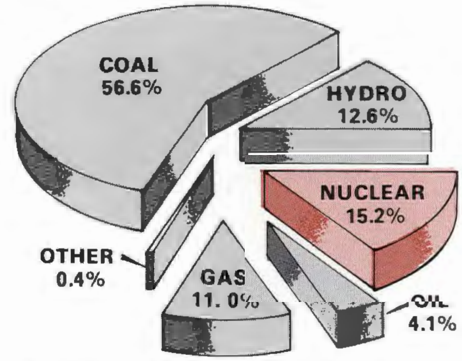
John E. Jones Jr. (right) is director of Civilian Reactor Programs at ORNL. He is responsible for the Laboratory's Liquid-Metal Reactor, Gas-Cooled Reactor, and Light-Water Reactor programs. Before assuming this position in mid-1985, he headed the Engineering Analysis Section of ORNL's Engineering Technology Division (ETD), where he led new initiatives in advanced reactor technology and multimegawatt space reactors. In 1977 he was appointed manager of Fossil Energy Programs in ETD and later was named head of the Fossil Energy Technology Section. In this position, he redirected the Laboratory's fluidized-bed coal combustion program toward industrial cogeneration and developed new programs with the Tennessee Valley Authority for utility application of fluidized-bed combustion and coal preparation. He originated a research program for cleaning coal using high-gradient magnetic separation; the development from this program received one of Ten Outstanding Engineering Achievements Awards from the National Society of Professional Engineers and an I•R 100 Award from *Industrial Research* magazine. Jones, who came to ORNL in 1958, participated in many of ORNL's early experimental and research reactor programs, including the Homogeneous Reactor Test, Molten Salt Reactor Experiment, Oak Ridge Research Reactor, and High Flux Isotope Reactor. He has a B.S. degree in mechanical engineering from the University of Kentucky and has taken numerous graduate courses from the University of Tennessee. He is a member of Oak Ridge City Council.

William D. Burch (center) is director of ORNL's Fuel Recycle Division and the Consolidated Fuel Reprocessing Program. He is responsible for activities in civilian reprocessing development throughout the United States. After earning an M.S. degree in chemical engineering from the University of Missouri at Rolla, he came to ORNL in 1952. He was a supervisor for the shift technical operations of ORNL's Purex Pilot Plant, which developed the basic process used for fuel reprocessing in every major reprocessing facility in the world. In 1965 he became manager of ORNL's Transuranium Processing Plant. He left ORNL for a year (1973–1974) to work with a privately funded group, Uranium Enrichment Associates. He returned to ORNL in 1974 as director of the Consolidated Fuel Reprocessing Program and, in 1981, became director of the newly formed Fuel Recycle Division. In 1976 Burch served as technical chairman of an International Atomic Energy Agency Workshop on the Development of Technology for Reprocessing Spent Breeder Fuels. Currently, he is providing technical leadership for U.S.–DOE exchange agreements in breeder reprocessing with the United Kingdom, Japan, France, and the Federal Republic of Germany.

A Strategy for ORNL

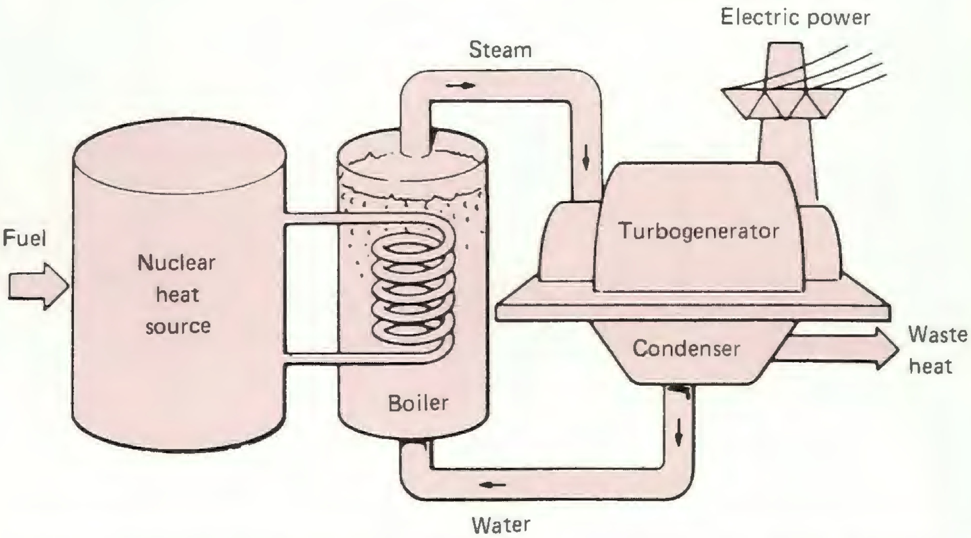
history. Between 1957 and 1977 nuclear power grew significantly. A total of 98 commercial nuclear plants, having an aggregate capacity of over 80,000 MW(e), are licensed for full-power operation. That is the bright side.

On the dark side are the numerous and substantial problems in the U.S. nuclear industry. No nuclear plants have been ordered since 1978, principally because the growth in demand for electric power since the oil embargo in 1973 has been much slower than projected (about 3% per year, instead of the projected 7%). In addition, many plants have been cancelled, and construction schedules for others have been



Electricity generation in the United States in June 1985.

ORNL's reactor technology expertise has been applied to many problems over the years. In the future, ORNL's strategy will be to contribute to improving light-water reactors, continue technology support for advanced reactor concepts, and collaborate with foreign groups in fuel-recycle work and breeder reactor technology.



Schematic diagram of a nuclear power station. In a pressurized-water reactor, ordinary water serving both as a neutron moderator and coolant transfers heat from nuclear fuel sealed in bundles of rods to water in pipes. Heat from these pipes boils water, turning it to steam. Steam drives the turbogenerator, producing electric power. The heated steam is cooled in the condenser; the removed heat is discharged as waste heat. The condensate is returned to the boiler, where it will be converted to steam again.

The Graphite Reactor was operated from this control room.

stretched out, resulting in substantial cost overruns largely attributable to interest on construction loans. Licensing delays and uncertainties have contributed to these cost overruns. Regulatory "ratcheting," resulting in numerous engineered safety systems, also has contributed additional cost and complexity to these plants. In spite of outstanding exceptions, the recent operating performance, or availability, of U.S. nuclear plants lags behind that of the rest of the world; on the average, U.S. plants are available to operate about 65% of the time, compared with 75 to 80% in Japan and Western Europe. Nuclear waste management continues to be a controversial issue, as does the lack of public confidence in nuclear plant safety, although these concerns often appear to be overshadowed by doubts about the economic benefits of nuclear power.

Concern over all these problems has prompted a critical Congressional review of the civilian reactor research and development (R&D) program of the U.S. Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC). The lack of demand for nuclear plants, along with the lack of public confidence, ultimately resulted in cancellation of the Clinch River Breeder Reactor Project (CRBRP) in 1983. This project had been the centerpiece of the civilian reactor R&D program for more than a decade. Without a strong, clear focus, the program appears to be drifting, and erosion of support continues. With record national budget deficits contributing to the pressure to curtail federal spending, the civilian reactor R&D program has been and continues to be a prime target for budget cuts. As emerging problems signal the need for improved technology, support for the civilian reactor R&D program continues to decline rapidly.

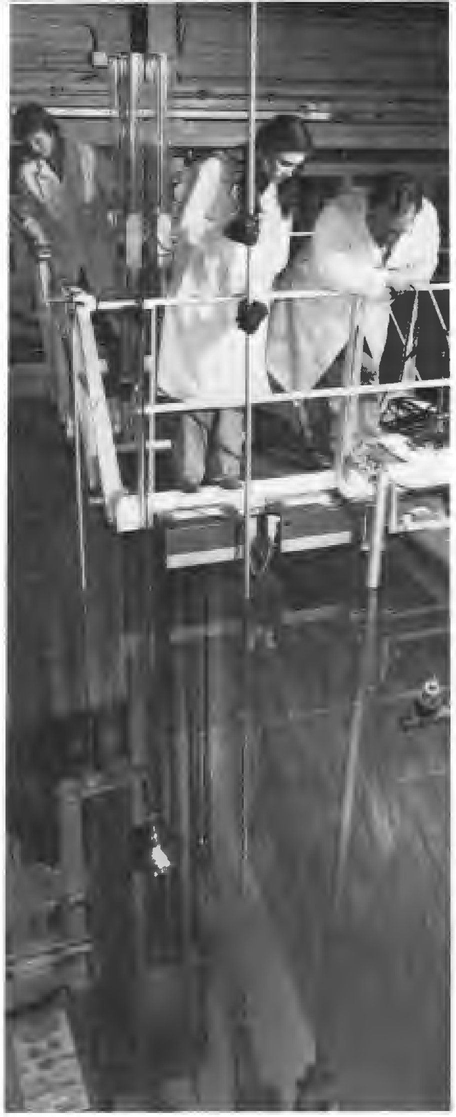
DOE is responsible for ensuring the nation's energy security, stability, and strength. In carrying out this responsibility, DOE, with broad participation from the public and private sectors, is developing a comprehensive strategic plan for the civilian R&D program. This plan is a vital first step in establishing a consensus direction for a program that can gain broad support. Although the plan is still in a formative stage, three overall

objectives for the DOE program are
• Cooperating with industry to improve light-water reactor technology
• Providing leadership in the development of innovative advanced reactor concepts
• Placing a reduced but continuing emphasis on long-term energy security through exploitation of the breeder reactor option.

In view of the status of the industry and the emerging national strategic plan, what strategy should Oak Ridge National Laboratory pursue?

History of ORNL's Role in Reactor Technology

Before discussing the future, it is appropriate to review ORNL's past role in reactor technology development—an impressive history. It all began with the Graphite Reactor, built by ORNL (then Clinton Laboratories) shortly after the successful operation of the



Technicians working from a bridge over the pool of the Oak Ridge Research Reactor adjust an experimental rig that extends through the top of the containment tank to the reactor core. All procedures are monitored carefully to prevent overexposure.

"Chicago Pile" and placed in operation in November 1943.

ORNL designed the Materials Testing Reactor (MTR), which was constructed in Arco, Idaho, in 1948. An MTR mockup, built and tested at ORNL, was later upgraded for power operation as the Low Intensity Test Reactor in 1950. These efforts significantly influenced the development of nuclear reactors that power submarines.

The MTR concept was subsequently modified in 1952 to produce an inexpensive "swimming pool" reactor at ORNL called the

W. D. Kennemore works at the Low Intensity Test Reactor, an early swimming pool reactor at ORNL.

Bulk Shielding Reactor (BSR), which formed the basis of similar research reactors at many universities and at the Atoms for Peace Conference in 1955 at Geneva, Switzerland. The concept was later adapted to produce the Army Package Power Reactor. The BSR is operated intermittently.

Further improvement and adaptation of the MTR concept led to a high-performance, flexible research reactor; completed in 1959, the Oak Ridge Research Reactor is still in operation. ORNL's Health Physics Research Reactor was built in 1962. The last reactor built at ORNL was the High Flux Isotope Reactor, which began operation in 1966; it was the world's first high-performance, flux trap research reactor and, after 20 years of operation, maintains a lifetime availability of 90%—a remarkable achievement considering its 20-day refueling cycle.

Experimental and special-purpose reactors built by ORNL have included the Homogeneous Reactor Experiment, the Homogeneous Reactor Test, and the Molten Salt Reactor Experiment. Development of special-purpose reactors began in 1954 with the Aircraft Nuclear Propulsion Project, including the Aircraft Reactor Experiment, and continued with extensive space reactor R&D. The direct Rankine boiling potassium cycle Medium Power Reactor Experiment concept for space application received considerable R&D support in the 1950s and 1960s and serves as the technological basis for ORNL's current participation in the selection of a multimegawatt space reactor concept for the national Strategic Defense Initiative program.

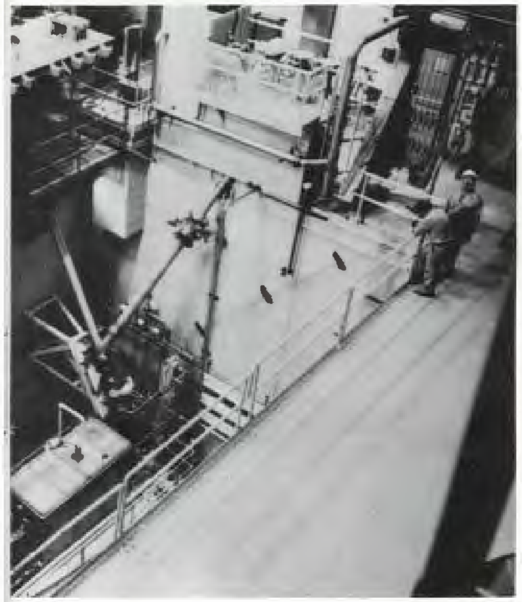
Most of the early personnel in both the military and civilian reactor programs were trained at the Oak Ridge School of Reactor Technology. Extensive technology development has been carried out by ORNL in support of each of the major commercial reactor concepts, including light-water reactors (LWRs), high-temperature gas-cooled reactors (HTGRs), and liquid-metal reactors (LMRs). The first patent for an LWR was granted in 1948 to former ORNL Director Alvin Weinberg, who collaborated with Nobel Laureate Eugene Wigner (former ORNL Research Director) in changing the original high-flux reactor design to a simpler, more compact design that uses ordinary water instead of heavy water for cooling. Under Weinberg ORNL initiated the U.S. R&D program on gas-cooled power reactors in 1957. During the 1940s ORNL researchers studied the potential of liquid metals (lithium, sodium, rubidium, and potassium) to serve as heat transfer media.

Major technology development areas involving ORNL researchers over the years have been thermal hydraulics, heat transfer, corrosion, component development, materials, structural design methods, reactor physics, fuel and fission-product behavior, shielding, and instrumentation and controls. In recent years, ORNL's reactor technology expertise has been applied in safety research for the NRC with principal emphasis on LWRs and relatively modest efforts on HTGRs and LMRs. The Heavy Section Steel Technology Program at ORNL has dominated the field of pressure vessel integrity (determining the risk that reactor vessels will fail in response to rapid changes in temperature and water pressure) and is considered by many to be the most important and cost-effective of all technology programs concerned with reactor safety.

ORNL's past contributions to the nuclear fuel cycle have in many ways paralleled the reactor technology developments. In its very early days during World War II and just after, ORNL played a key role in the development of techniques for recovering plutonium from spent reactor fuel. The initial batch precipitation processes and the follow-on solvent extraction processes were all tested at ORNL pilot plants. In the early 1950s ORNL developed the Plutonium Uranium Extraction (Purex) process, now used worldwide in all civilian plants for reactor spent-fuel reprocessing—the recovery by chemical processes of fissile and fertile materials from reactor fuels. Until the mid-1960s, refinements to the chemical processes were investigated. The initial work on the mechanical head-end, chop-leach processes, now used in all power reactor reprocessing plants to break the fuel cladding into small pieces before chemical separation, was performed at ORNL in the late 1950s and early 1960s.

Remotely operated manipulators and transport systems at ORNL verify the feasibility of remote maintenance concepts. This protypical fuel reprocessing equipment is located in the Remote Operations and Maintenance Demonstration area of the Integrated Equipment Test Facility.

When a commercial LWR reprocessing plant was started in the United States by Nuclear Fuel Services near Buffalo, New York, the fuel cycle R&D program at ORNL was geared up to support the technology needed for that venture. However, as the commercial plant went into operation, the R&D program at ORNL was largely phased out. Efforts to begin the commercial LWR reprocessing industry at this time also included the construction (but not operation) of two more plants: one by the General Electric Company (GE) near Chicago and the other by Allied-Gulf Nuclear Services at Barnwell, South Carolina. Unfortunately, the combination of marginal economic benefits and complexities associated with



licensing and operating new large, costly nuclear facilities halted these projects and almost assuredly precluded any subsequent actions to close the LWR fuel cycle by reprocessing in the next decade or two.

ORNL's Strategy

ORNL's distinguished history and extensive expertise in reactor technology development indicate that the Laboratory can make a major contribution in reactor technology. In spite of recent disappointments over declining funding experienced by ORNL and other program participants, we believe that ORNL can remain a major force in this important field. Our strategy is (1) to promote a new initiative in advanced reactor technology in support of both improved LWRs and advanced concepts, (2) to continue our technology support for the modular HTGR and LMR concepts, and (3) to participate in a broad collaboration with foreign programs in fuel-recycle work and related breeder reactor technology.

These directions have emerged from our analysis and planning efforts over the last year. It is not entirely coincidental that they closely parallel the stated directions in the recent DOE Strategic Plan because we have worked closely with DOE on plans and strategies.

Advanced Reactor Technology: A New Initiative

ORNL proposes to focus on the key technical issues of concern to the nuclear industry. One immediate goal is to improve the performance of operating LWRs. A long-term goal is to incorporate innovative technology in advanced LWRs and other advanced concepts. ORNL's approach is to help establish a national consensus within the nuclear industry based on a comprehensive advanced reactor technology program with broad participation from universities, industry, and national laboratories. We would seek to establish a prominent role for ORNL in such an initiative, but not a dominant one, because of the importance of establishing a national consensus and encouraging teamwork among participants. The program is organized into four major activities. Many of the activities have near-term application to LWRs as well as to advanced HTGR, LMR, and breeder concepts.

Availability improvement technology. The goals of this effort are to improve annual plant availability and extend plant operating life by solving technical problems.

Significant improvement in plant availability will require a broad program aimed at reducing the frequency and duration of both scheduled and unscheduled (forced) outages. We believe this role is appropriate for government (DOE) leadership and support because it will result in a more economical, reliable, and plentiful supply of electric power for the American public, enhance the future economic viability and growth of the nuclear power industry, and allow U.S. nuclear plant vendors to compete more effectively for foreign business. Currently, the utility industry is too fragmented and too heavily regulated to mount an effective national effort without the government's help. Besides, in a regulated industry, the benefits of improved availability accrue primarily to the public, not to utility stockholders.

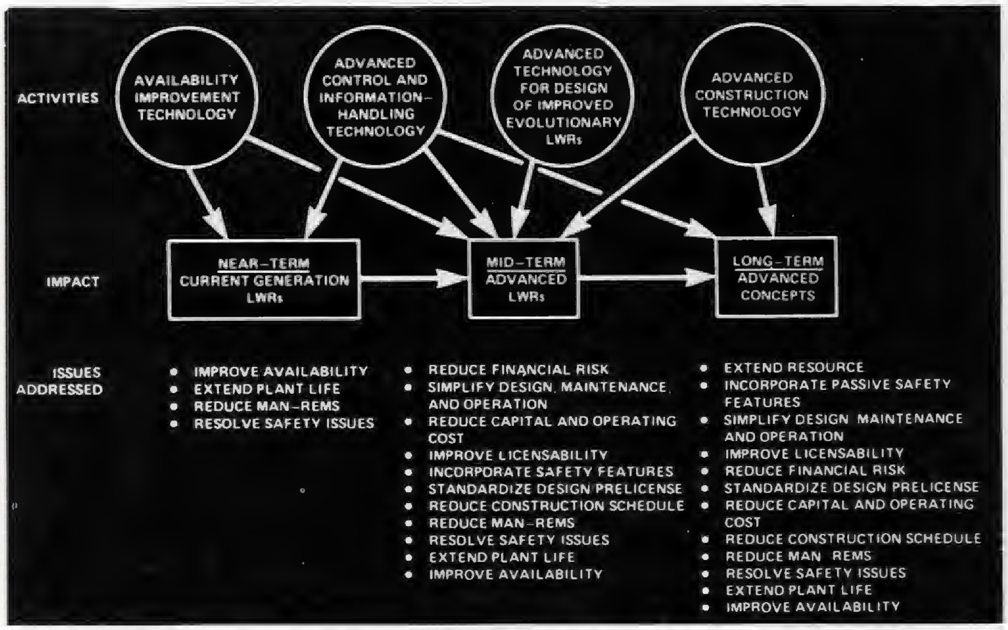
Advanced control and information-handling technology. Major advances in control and computer technology have been largely overlooked by the nuclear industry. Operators continue to be burdened by overly complex systems, inadequate human-machine interfaces, too many signals coming to the control room, and an inability to recognize which signals are most important under given circumstances. As a result, human error accounts for many of the abnormal conditions that develop in the operation of a nuclear power plant. Operator error, in fact, contributed significantly to the 1979 loss-of-coolant accident at Three Mile Island, the worst reactor accident in the history of nuclear power.

This situation strongly suggests a need to employ the new technology, already successfully used in some industries, to improve current instrumentation and control systems and the operator-machine interfaces in nuclear power plants. A large amount of the needed base technology exists; however, a considerable R&D effort is needed to address the unique requirements of nuclear plants. Furthermore, some R&D will be required in the areas of "smart" sensors, intelligent control systems, fault tolerant systems, and analytic redundancy to accommodate a greater degree of automation. Adapting the existing proven technology to the reactor environment will also require the expertise of persons knowledgeable about the latest advances in automated-control and reactor systems.

Advanced technology for design of improved LWRs. The utility industry has initiated a five-year program for the period 1985 to 1989 to critically assess features of current LWRs and to establish a standardized set of characteristics and requirements for advanced reactors that could evolve from improved LWR designs. Such an assessment could lead to a revitalized nuclear electric power industry in the 1990s. The Electric Power Research Institute (EPRI), the research arm of the utility industry, is leading this effort. The studies will be performed under cost-sharing contracts with nuclear steam-supply-system vendors, architect-engineering firms, and specific nuclear utility companies. The utility industry has budgeted more than $20 million for this five-year program and expects that the contractors will contribute a similar amount.

To foster consideration of promising advanced technologies within the industry program, ORNL proposes to assess (with the help of universities and industry) whether selected advanced technologies are ready to be incorporated into advanced standardized LWR designs. The application of artificial intelligence in the control and safety systems is an example of an emerging technology with high potential.

Advanced construction technology. Experience shows that construction problems and extended construction periods are the leading reasons for the escalating cost of nuclear plants. The average time it takes to construct a nuclear plant in the United States has increased consistently since the early 1970s and has reached 12 or 14 years in some cases. Several recent studies, such as those by the Construction Research Council of the American Society of Civil Engineers, the Construction Industry Cost Effectiveness Project, the NRC (NUREG-0030), and ORNL through its Nuclear Power Options Viability Study, have suggested a number of technical, social, and economic reasons why nuclear power plants have not been completed efficiently and on time.



The interrelation and impact of proposed activities for ORNL's advanced reactor technology initiative.

Explanations include technical, engineering, and safety-related problems; slower electricity demand growth; licensing ratchetting; equipment retrofits to meet new safety regulations; and adversary interference by environmental groups. A myriad of other complex and interrelated problems caused by poor organization and project management include labor slowdowns to increase overtime work, absenteeism, and insufficient flexibility in job assignment.

EPRI has a strong interest in advanced construction technology, but the lack of construction plans for new nuclear plants has led EPRI to delay its planned constructibility research program. ORNL recommends a comprehensive program involving key contributions from universities and industry to address major areas that need more attention—construction R&D and construction management.

Advanced Concept Support

Both HTGRs and LMRs are promising advanced reactor concepts. For many years, efforts were focused on large-scale designs of these concepts. Recently, several programs have been restructured to focus on smaller, simpler, and safer plants in response to studies calling for modularization, reduced financial risk, and more passive safety features—that is, inherent properties of the reactor that make it safe without reliance on operator action or mechanical, electrical, and electronic controls. ORNL provides technical support to each program in key technology areas.

HTGR Program. For the national HTGR Program, ORNL is the lead laboratory; it has major responsibility for planning the

ORNL welder joins a pipe made of a modified chromium-molybdenum (9 Cr: 1 Mo) steel alloy to a type 304L stainless steel safe end before it is installed for a one-year test in the Sodium Components Test Loop at the Energy Technology Engineering Center in California. The center is operated by Rockwell International. The test loop is used to test liquid-metal reactor components. ORNL helped to develop the steel alloy.

technology development program to provide data for the design team led by GA Technologies, Inc. (Other participants are Combustion Engineering, Inc., Bechtel National Corporation, Stone and Webster Engineering Corporation, GE, and Idaho National Engineering Laboratory.) The HTGR Program is guided largely by DOE and Gas-Cooled Reactor Associates, a group of about 30 utilities.

The ORNL program on HTGRs focuses on fuels, fission product release and transport, metallic materials, and graphites. Program support is also provided in other areas such as shielding and physics analysis. ORNL also participates in international exchanges with HTGR groups in the Federal Republic of Germany and Japan.

LMR Program. ORNL's work in the LMR Program is focused on supporting development of generic technology and advanced concepts. DOE-sponsored advanced concept development emphasizes two modular plant concepts: the Power Reactor Inherently Safe Module (PRISM) concept, designed under the leadership of GE, and the Sodium Advanced Fast Reactor (SAFR) concept, whose design is promoted by Rockwell International. Each concept is based on a small modular system with passive safety features. ORNL is DOE's technical support organization for the evaluation of these advanced concepts. In addition, DOE sponsors the design of the Large-Scale Prototype Breeder (LSPB), which also has received funding from EPRI. Portions of the LSPB design effort are coordinated by Alan Levin of ORNL's Engineering Technology Division, who is on assignment to EPRI's Consolidated Management Office in Chicago.

ORNL is the lead DOE laboratory for developing advanced materials and high-temperature structural design techniques for components of LMRs. One such material is the modified chromium-molybdenum (9 Cr: 1 Mo) steel that ORNL has helped to develop. The Laboratory has been working on evaluating and code-qualifying this advanced ferritic alloy for use in LMRs.

ORNL is providing support in developing and testing measurement and control instruments for monitoring normal reactor operation and detecting abnormalities, analyzing and validating shield designs, and directing the Centralized Reliability Data Organization (CREDO), a joint effort between the United States and Japan for collecting, analyzing and disseminating reliability, maintainability, and availability information concerning LMRs.

ORNL's technology support activities in both shielding technology and CREDO are jointly funded by DOE and the Power Reactor and Nuclear Fuel Development Corporation of Japan. In addition, ORNL has been selected to develop in-service inspection technology to make possible visual inspection of the MONJU reactor in Japan as part of an international exchange currently being negotiated by DOE.

Fuel-Recycle and Breeder Technology

About 1970 the United States began supporting large programs to develop a liquid metal fast breeder reactor (LMFBR) in the United States. Efforts were focused on developing and deploying commercial breeders before the end of this century. Work in the fuel cycle was revived, again with major responsibility at ORNL, to address the special problems of recovering plutonium from breeders to make new fuel for them (recycle). A facility to recycle fuel from the first four to six commercial breeders was conceptually designed as the focus of the ORNL program, which included a technology program to develop processes and equipment for that facility.

In 1983 ORNL built the Integrated Equipment Test Facility (IET), which simulates the head-end of a small reprocessing plant for breeders. The IET can disassemble, shear, dissolve, and chemically extract fuel from nonradioactive (cold) fuel rods. The IET also has a sophisticated remote maintenance system for repair of failed equipment (which would be highly radioactive in an actual reprocessing plant). Some technology in ORNL's remote maintenance system is the most advanced in the nuclear field anywhere in the world.

In the 1980s, however, the easing of the energy crunch has resulted in dramatic changes in the pace of the reactor program and has altered the role and mission of ORNL's fuel-recycle work. When it appeared that the only large U.S. demonstration LMFBR being constructed—the CRBRP in Oak Ridge—would be completed but that no other reactor projects would follow soon thereafter, our fuel-recycle efforts were refocused on a small facility to be incorporated within the Fast Flux Test Facility at Hanford Engineering Development Laboratory (HEDL). Through a collaboration between ORNL and HEDL, planning for this project was rounding into shape when the CRBRP was cancelled in late 1983. Since that time, DOE has been searching for a nuclear strategy.

The long-term mission of the breeder and its fuel cycle is still recognized, although the earliest date for operating commercial breeders has been pushed far into the future. Thus, the fuel cycle in the United States has a rather obscure focus. DOE and its laboratories have reacted to this situation by searching for collaborators in countries already heavily involved in breeder development. This strategy will allow the United States to stay abreast of technical developments, maintain a core of expertise, and develop its own commercial breeders when needed. DOE's main effort focuses on establishing ties with a European consortium and with Japan.

As part of that effort, ORNL has been involved in a technical exchange with Japan in fuel-recycle work and has engaged, with DOE, in early exploratory talks for a much broader collaboration. Conceivably, this collaboration could involve U.S. participation in the breeder reprocessing pilot plant that Japan expects to build over the next ten years. Close ties between the R&D programs in the two countries would be maintained, and the United States would probably supply major equipment systems to the facility. In return, the United States would have access to all phases of the project, including the operating data. Such a collaboration, while unthinkable in the days when the United States was the world leader in every phase of nuclear power, may be the only satisfactory means of maintaining vitality in fuel-recycle work in this country for the next two decades.

Summary

Sometime during the next decade, when demand for electricity and concerns about the climatic and environmental effects of coal combustion are expected to increase, the United States will have to set the course for its energy future in the 21st century. One action will likely be accelerating the deployment of commercial nuclear power plants to provide economical electrical power. We must act now to preserve the nuclear power option by developing the technology needed to ensure safe, reliable, efficient, and economical civilian reactor power to meet the energy needs of future generations. ornl

ORNL played a lead role in writing and publishing the 15-volume* Nuclear Systems Materials Handbook. *The handbook is expected to reduce the cost of compiling and analyzing materials data and facilitate reactor licensing because it provides a well-documented, authoritative collection of design data. The handbook provides up-to-date information on mechanical, physical, chemical, nuclear, and tribological properties of reactor materials. Some data in the handbook can be used for all advanced reactors.

ORNL-UT Distinguished Scientist Speaks on Nuclear Power

Robert E. Uhrig, former vice-president of Florida Power & Light Company, became an ORNL-UT Distinguished Scientist in January 1986. He was chairman of nuclear engineering (1960–68) and dean of engineering (1968–73) at the University of Florida and is a recognized expert in the field of nuclear reactor noise analysis. At ORNL's Instrumentation and Controls Division, he will focus on the application of advanced control technologies, including artificial intelligence, to commercial nuclear power plants. On November 7, 1985, Uhrig gave an ORNL-UT Distinguished Scientist Lecture at ORNL on "Nuclear Power: Getting from St. Lucie–2 to the Next Generation." Below are excerpts from his talk.

"St. Lucie–2 [a nuclear power plant of Florida Power & Light Company (FPL)] has been heralded as the 'nuclear success story of the decade.' It was put into commercial operation in August 1983, only 74 months after its construction permit was issued. It was only two months behind schedule despite such setbacks as a labor strike, damage from Hurricane David, and disagreements with the Nuclear Regulatory Commission.

"What are the secrets of St. Lucie–2's success? The answers include an unqualified commitment of top FPL management, an experienced management team, a commitment to schedule, reliance on a previously used design and vendor, early start-up planning and implementation, and use of innovative construction techniques. It is hoped that the 'spirit of St. Lucie' will inspire other electric utilities to achieve similar successes . . .

"Since the very beginning, the economy of scale has been put forth as the way to make nuclear power plants competitive with fossil plants. In the early 1970s we entered what in the automotive industry would be called the 'horsepower race'; each vendor was competing to see who could bring out the biggest plant. The subsequent performance of large, complex nuclear plants (and I might add large, complex fossil plants) has been less reliable than that of their smaller, simpler predecessors.

"Most of the power plants being discussed today are either in the range of 500 to 800 MW or they are small enough that they can be modularized and produced in a factory environment. Studies indicate that the economy of automated shop manufacture coupled with short construction times and parallel preparation of the site facilities can compensate for the loss of economies of scale . . .

"Safety is and will continue to be the No. 1 critical nuclear issue in the years ahead. The industry cannot have another Three Mile Island accident. Furthermore, it cannot continue to have incidents in which instruments fail because of inadequate maintenance, significant transients are not recognized until long after the fact, operators open the wrong valve and trip the plant, or arbitrary testing requirements subject the systems to severe transient conditions. Our plants have become too sophisticated and complex to rely too heavily on engineered safeguard features.

"Recently a great deal of effort has been devoted to designs that take advantage of inherent shutdown mechanisms as a means of protecting the plant, even under the conditions in which coolant flow is lost without shutting down, or scramming, the power generation. Tests being planned on advanced reactor concepts could go a long way towards resolving some of the technical issues that support the concept of 'walk away safe' reactors . . .

"The role of reactor operators in the future remains to be defined. Needless to say, they will be required because no one envisions completely automatic operation of nuclear reactors. Recent incidents have shown that the action of a reactor operator in an emergency condition may save or jeopardize the plant, depending upon the action taken and the nature of the problem. In the case of the Browns Ferry fire, the action taken by the reactor operators probably saved the plant. On the other hand, if the reactor operators at Three Mile Island had simply put their hands in their pockets and stood back and watched what was happening for the next two hours, the incident would probably have been buried in the NRC archives as another abnormal occurrence . . .

"My personal view is that standardization is essential and that the antitrust rules should be modified sufficiently to allow a joint architect-engineer–vendor standardized design to be duplicated on several sites. Indeed, this is the whole concept associated with modular designs. However, standardization cannot be a straitjacket that would preclude advancements in the technology and improvements dictated by operational problems and experience . . .

"Artificial intelligence approaches are essential to the revival of the nuclear power industry. It is my vision that the utilization of artificial intelligence techniques can help us get from St. Lucie–2 to the next generation of nuclear power."

James D. White (right) managed an ORNL program that studies innovative reactor designs and determines what criteria must be met to make future nuclear reactors more attractive to U.S. electric utilities and the public. From 1982 to 1984 he served as manager of a program to assess the probability of pressurized-thermal-shock events in three commercial nuclear power plants. Before that, he served for two years as a technical assistant to ORNL's Associate Director for Nuclear and Engineering Technologies. White came to ORNL in 1973 from the Y-12 Plant, where he worked as a development engineer in nondestructive testing development related to nuclear weapons components. At ORNL he first worked as group leader of the Thermal Hydraulics Program, which studied conditions associated with loss-of-coolant accidents in light-water reactors; from 1978 to 1980 he managed this large experimental program. White holds an M.S. degree in

The Next Generation of Reactors:
The Nuclear Power Options Viability Study

By JAMES D. WHITE and DONALD B. TRAUGER

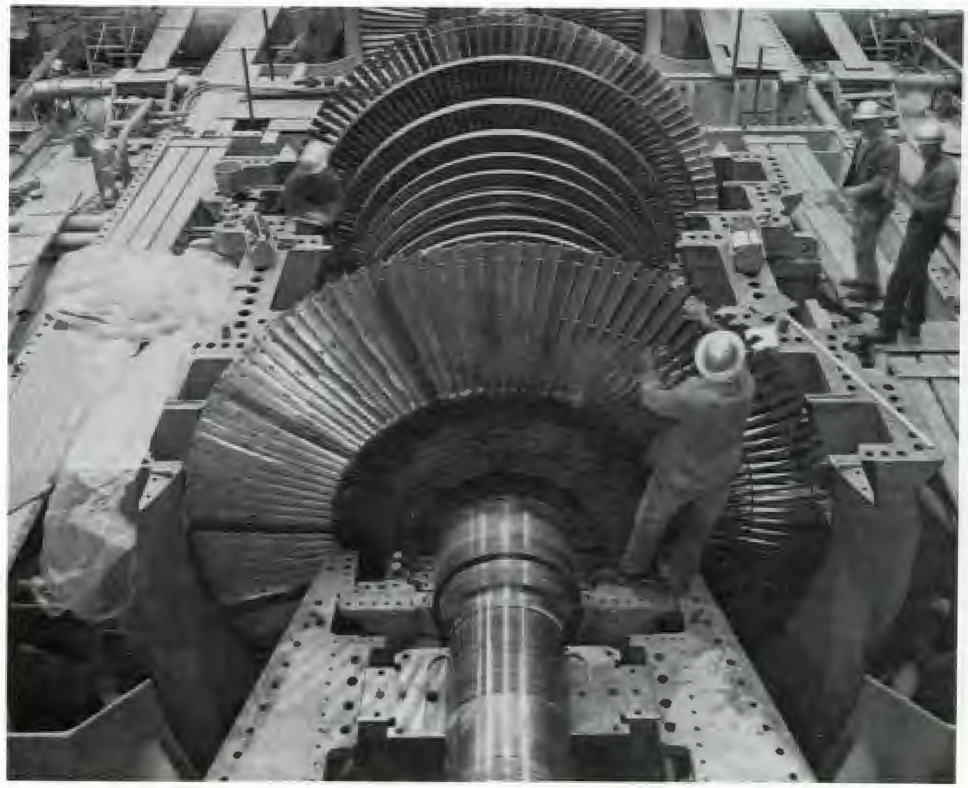
Since 1978 the commercial nuclear power industry in the United States has been in trouble. No new nuclear power plant has been ordered since then, and many others on order or under construction since 1974 have been cancelled. The accident at the Three Mile Island (TMI) nuclear power plant in March 1979 increased public doubts about nuclear safety and forced the industry to add components and make other costly changes to address concerns about light-water reactor (LWR) safety.

In the early 1980s electric utilities lost interest in nuclear power as it became clear that the future demand for electricity would be far less than previously projected. At the same time, other institutional factors have further diminished the appeal of nuclear power in the United States.

- Although nuclear power plants can be built in 6 years, a combination of institutional factors—e.g., changing regulations, lack of standardization, low labor productivity, and a highly fragmented utility structure—have delayed completion of many plants by up to 8 years. Many construction delays occur because reactors are being built before their design is complete and because construction changes often are made to meet design alterations requested by regulators.
- Because of construction delays, some large nuclear power plants have become very expensive, making it difficult for utilities to raise sufficient capital in a single bond issue to cover the cost.
- Because of concerns about nuclear safety, construction delays, and unpredictable changes in regulations, nuclear plants are a risky investment.

nuclear engineering from the University of Tennessee.

Donald B. Trauger (left) is senior staff assistant to the Director of Oak Ridge National Laboratory. Beginning in 1970 he served for 14 years as the Associate Director for Nuclear and Engineering Technologies at ORNL. Before that he was director of ORNL's Gas-Cooled Reactor Program. He joined the Manhattan Project in 1942 as a graduate student at Columbia University and he continued to work on the project until 1946. Trauger then worked for eight years at the Oak Ridge Gaseous Diffusion Plant. In 1954 he joined ORNL's staff as manager of the Irradiation Engineering Test program. Trauger is a fellow of the American Nuclear Society and holds honorary doctor of science degrees from Tennessee Wesleyan College and Nebraska Wesleyan University (his alma mater, from which he also received an Alumni Achievement Award in 1962).



Construction of Duke Power Company's Catawba Nuclear Station, Unit 2. One problem of U.S. nuclear power plants studied by ORNL recently is construction delays.

A study done at ORNL with help from other institutions found that the United States will need additional electrical generating capacity by the years 2000–2010. Several advanced reactor concepts with safety features inherent in their designs are judged to be potentially available in this time period and are estimated by their promoters to be economically competitive with coal-fired power plants.

- Because U.S. nuclear power plants have each been one of a kind—that is, each one was built according to a unique design using different combinations of standardized parts—they incurred licensing and construction delays and unnecessary costs.
- Because of the complexity of nuclear power plants, combined with the inept operation of many of them, they produce electricity at less than 60% of capacity on the average—much less than is desirable for utilities to reliably supply low-cost power to their customers.
- Because of changing regulations, nuclear plants have been retrofitted with many additional components that increased their costs and made them even more complex, although not necessarily safer.

ORNL Starts Study

By late 1983, reactor experts at Oak Ridge National Laboratory became increasingly concerned about the floundering nuclear enterprise because nuclear fission is an important segment of our research and development program. So we set out to determine how the problems of reviving the nuclear industry could be solved.

We started a study to identify new directions for the LWR industry, drawing first on the newly created Director's Discretionary Fund at ORNL and later on funding provided by the Department of Energy. The objective of the study was to explore the possibility that several nuclear power options could be economically attractive to electric utilities and acceptable to the public in this country by the years 2000 to 2010. After some casting about, we chose the name Nuclear Power Options Viability Study (NPOVS) for our project. We first thought that, in addition to finding a title that was descriptive of the study, we had also found an unpronounceable acronym. Not so, but for those who have not heard it, the pronunciation is left as an exercise for the reader.

Our study attempted to identify and develop methods and criteria for evaluating the future market appeal of new reactor concepts. To make the scope of the study manageable, we established certain ground rules to limit the number of reactor concepts to be considered. We decided to include concepts that could be deployed for commercial power generation in the 2000 to 2010 time frame, that could be economically competitive with coal-fired power plants, and that have passive safety features. (Passive safety refers to inherent characteristics of the reactor that follow simple laws of physics; a reactor with these characteristics does not depend on engineered safety systems and operator response to prevent overheating, core melting, and releases of large amounts of radioactivity to its containment building during accidents.)

Recognizing the need for a broad base of knowledge and experience, we engaged the Tennessee Valley Authority (TVA) and the University of Tennessee (UT) as partners in the study. TVA concentrated its efforts on concept evaluation and licensing, and UT helped evaluate construction costs and public opinion issues.

Many problems encountered by the nuclear industry are institutional in nature and relate to the organization and functioning of the utility companies, designers, builders, and regulators. We attempted to identify and define these institutional factors but did not address them in detail in this study. Some institutional problems stem from technical features, which, in turn, originate at least in part in the large size, complexity, and exacting requirements of nuclear plants. For example, most LWRs require a quick response by the safety equipment and operators during a loss-of-cooling incident, making it possible for errors to occur in the haste of handling an emergency situation; advanced reactors now being designed have inherent features that permit a more deliberate response to abnormal events. Our study emphasizes the technical aspects that have potential merit and improved designs that can help solve institutional problems.

Criteria for Reactors

We first developed criteria that reactor designs would have to meet to become acceptable to the public and economically appealing to utilities in the future. The evaluative criteria established in this study are as follows:

1. The calculated risk to the public from accidents involving advanced reactors must not exceed the calculated accident risk associated with the best modern LWRs.
2. The probability of events leading to a loss of investment must not exceed 10^{-4} per year (calculated from plant costs). In other words, no more than 1 out of 10,000 such reactors per year could be expected to experience a TMI-type accident or some other problem that significantly damages the plant or prevents it from being completed or operated.
3. The economic performance of the nuclear plant must match or exceed that of coal-fired power stations. That is, the nuclear plant's operating costs should be competitive with those of coal power plants, and the busbar costs (actual costs of electricity leaving the generator) should be acceptable to the public utility commissions.
4. The design of each plant must be complete enough for analysis to show that the probability of significant cost overruns and construction delays is acceptably low.
5. Official approval of a plant design must be given by the U.S. Nuclear Regulatory Commission to assure the investor and the public of a high probability that the plant will be licensed in a relatively short time if constructed according to an approved design.
6. For a new concept to become attractive in the marketplace, it must be demonstrated that a plant can be designed, built, licensed and started on time and at projected cost.
7. The design should include only those nuclear technologies that can be managed competently by the prospective owner and operators of the plant. Operators should be adequately trained on simulators to run the plant.

These criteria are obviously related: items 1 and 2 deal with the probabilities for successful operation or failure, items 3 through 6 are primarily economic, and item 7 deals with operation. However, we deem each criterion to have sufficient merits when considered separately.

Our criteria were augmented by a list of characteristics which were judged to be important for enhancing the appeal of nuclear power. Four essential characteristics that are difficult to quantify as criteria are

- **Acceptable front-end costs and risks.** These include capital costs, the risks to the investor, and other risks of accidents, construction and regulatory delays, adverse environmental impacts, and changes in demand for electricity.
- **Minimum cost for reliable and safe operation.** The availability of each reactor should be increased to more than 80% to reduce the cost to the utility (which often has to obtain more expensive electricity from other sources to meet customer requirements when the reactor is down).
- **Practical ability to construct.** Adequate financing, qualified

vendors, reliable technology, appropriate licensing regulations, and suitable designs must be available.

• **Public acceptance**. The public is more likely to accept new reactors if the operation of existing power plants has been safe and reliable, if the transportation and disposal of wastes pose no hazards, and if the impact on electric power rates of reactor construction and operation has been reasonable.

In addition, we recognized the importance of other characteristics (not all of which are applicable to each concept). These characteristics include practical research, development, and demonstration requirements; ease of siting; load-following capability (ability to increase or decrease power production as demand changes); sabotage resistance; ease of waste handling and disposal; good fuel utilization to increase the amount of energy extracted from the fuel; applicability of the technology to breeder reactor designs; ease of fuel recycle; high thermal efficiency; low radiation exposure to workers; high versatility (able to produce not only power but also heat for making process steam and other industrial applications—the so-called cogeneration concept); high resistance to nuclear fuel diversion and proliferation; on-line refueling (most reactors have to be shut down for refueling, but some advanced reactors could be designed to allow refueling during operation); ease of decommissioning; and low visual profile.

Concepts Selected

The selected reactor concepts, which are described in more detail in accompanying sidebars and other articles in this issue, were

• **Advanced light-water reactors,** including the PIUS (Process Inherent Ultimate Safety) reactor promoted by ASEA-ATOM of Sweden and the small boiling-water reactor promoted by General Electric Company (GE).

• **Liquid-metal reactors,** particularly the PRISM (Power Reactor Intrinsically Safe Module), a concept advanced by GE and supported by DOE; the SAFR (Sodium Advanced Fast Reactor), a concept advanced by Rockwell International and supported by DOE; and the LSPB (Large-Scale Prototype Breeder), a concept of the Electric Power Research Institute's Consolidated Management Office, which is supported by EPRI and DOE.

• **The high-temperature gas-cooled reactor (HTGR),** particularly the Side-by-Side Modular HTGR promoted by Gas-Cooled Reactor Associates and several industrial firms and supported by DOE. The core and steam generator are in separate steel vessels in a side-by-side configuration. The HTGR's appeal stems from its efficiency and passive safety features—it can withstand a loss of coolant without core damage.

Findings from the Study

These concepts, as evaluated, were judged to be potentially available in the chosen time period, are estimated by their promoters to be economically competitive with coal-fired power plants, and have varying degrees of passive safety attributes.

An early finding of the study was that the United States will need additional electric generating capacity by the years 2000 to 2010. This increase in demand was confirmed by a more comprehensive study by Garland Samuels of ORNL's Energy Division. Thus, the potential exists for reviving the nuclear industry within the time frame of the study.

We observed that most advanced reactors, as presently conceived, would be smaller than current LWRs. Therefore, they suffer an economic disadvantage (either real or perceived) associated with economy of scale. This disadvantage is claimed to be offset in varying degrees by the improved match with load growth requirements, reduction in capital risk, increased shop fabrication, shorter construction time, increased standardization, design simplification, and simpler construction management requirements. Licensing may also be simplified when passive safety features are taken into account. However, some of these attractive features would require a large front-end investment. In particular, a substantial backlog of orders will be required if automated shop fabrication of standardized components is to be practical.

In summary, the nuclear option can be made economically attractive to utilities and acceptable to the public by

• standardizing nuclear plants of a particular type so that they all have the same design and use the same components (which can be fabricated automatically in shops),
• tailoring regulations to the specific features and needs of individual reactor concepts,
• improving availability through better operating plans and improved control systems, and
• simplifying designs by incorporating passive safety features.

All of the concepts selected for the study appear to offer potential for commercial application in 2000 to 2010. However, if additional nuclear power is needed before the year 2000, we believe that only existing plant designs with modest improvements are practical. In short, as the need for additional nuclear power arises, innovative as well as tried-and-tested designs can be available to help the U.S. nuclear power industry out of its doldrums. ornl

Nuclear Power Options: Light-Water Reactors Today and Tomorrow

In 1984 about 13.6% of the total amount of electricity generated in the United States came from nuclear power plants. Of the 86 commercial nuclear power reactors in operation in this country at the end of 1984, 84 were light-water reactors (LWRs). According to projections made by DOE's Energy Information Administration, the percentage of U.S. electricity generated by nuclear plants will increase to nearly 20% by 1990, and the number of LWRs will increase by about 34. The projected increase is based on the completion of plants ordered many years ago.

Since 1978, however, no new orders have been placed for commercial nuclear power plants in the United States; in fact, about 100 units have been canceled or deferred indefinitely since 1975. Nevertheless, new studies, including one by ORNL (the Nuclear Power Options Viability Study), have concluded that additional U.S. generating capacity will be needed by around the year 2000. The U.S. nuclear industry is taking several approaches to meeting this need.

Current large LWRs. Of the nation's four LWR vendors, three offer the pressurized water reactor (PWR) and one the boiling water reactor (BWR). Babcock and Wilcox (B&W) is not actively promoting an improved version of its basic large PWR. The other three vendors—General Electric Company (GE, the BWR manufacturer) and Combustion Engineering, Inc., and Westinghouse Electric Corporation—are offering improved versions of their basic product line. The improvements in these standard large LWRs, although limited in scope, are said to result in plants that are more reliable, more maintainable, more economical, and safer than those currently in operation.

Advanced large LWRs. Of the four vendors, only GE and Westinghouse have major programs aimed at new or substantially advanced designs of large LWRs. Both companies have cooperative ventures with Japanese utilities and industry aimed at advanced designs with power levels of about 1300 MW(e).

The GE Advanced Boiling Water Reactor (ABWR) program is aiming at a favorable project decision by the Japanese in 1986, which could lead to a construction permit by about 1989 and operation by about 1994. GE plans to discuss with the U.S. Nuclear Regulatory Commission (NRC) the possibility of introducing the ABWR but has made no effort yet to obtain U.S. licensing of the new design.

The ABWR differs from earlier GE designs by including internal recirculation pumps and eliminating external recirculation loops, thus reducing the probability of large-break loss-of-coolant accidents. Other design changes will result in extraction of more energy from the fuel and give the reactor an improved ability to change power production as demand changes. In addition, the ABWR will be easier to maintain and will be able to achieve full power from hot standby much more quickly than current BWRs.

Westinghouse has designed an advanced PWR (APWR) and expects to complete testing of components in Japan and the United States in 1987. The APWR's innovations include a taller pressure vessel to provide additional safety margins against overheating of the fuel during loss-of-coolant accidents, more conservative thermal design margins for coping with anticipated transients, improved steam generator design and materials, a larger pressurizer, and upgraded control and safety systems.

Westinghouse also hopes for early selection of a Japanese site and a firm APWR order, possibly as early as 1986, which could lead to operation by 1993–94. Meanwhile, Westinghouse is vigorously making an effort to have the APWR licensed in the United States as a standard plant.

EPRI Program. A five-year U.S. program is under way to define the best nuclear power plants that can be made available to meet projected energy needs. This Advanced LWR Program is managed by the Electric Power Research Institute (EPRI), the research arm of the nation's electric utility industry, and all major segments of the nuclear industry are participants. The nuclear plant sought would make maximum use of utility experience and would emphasize simplicity, safety, licensability, ease of construction, operability, reliability, and maintainability.

A key element of this program is the development of an appropriate "requirements document," which defines simplified large PWR and BWR power plants that have high potential for producing electricity at a cost competitive with power costs of other fuel sources over the plant's lifetime.

A second element of the EPRI Advanced LWR Program is the development of conceptual designs for small BWRs and PWRs—that is, reactors with capacities no greater than 600 MW(e). Interest in designing smaller reactors stems from concerns about the greatly increased costs and uncertainties of building large nuclear power plants. Although large plants can offer electricity at a relatively low cost because of economy of scale, this study is based on the hope that design and construction techniques can be developed to make small reactors economically competitive with large plants when financial considerations are taken into account. Like the EPRI-conceived large reactors, these small plants also are to be designed to provide enhanced safety, operability, availability, and maintainability. However, design improvements in small reactor concepts that would require a prototype demonstration project are *explicitly excluded* [EPRI's emphasis] from consideration. Thus, no radical departures from existing designs are anticipated.

Advanced small LWRs. All four vendors have considered small reactors, and all but Combustion Engineering are participating in the EPRI study of advanced small LWRs by developing and evaluating several reactor concepts.

The B&W basic concept is a 600-MW(e) version of a unit proposed some years ago as a 900-MW(e) power plant. The reduction in power level provides additional safety margins against overheating of the fuel during anticipated transients or accidents; other modified features, such as the possible use of improved main coolant pumps, system simplification through elmination of boric acid in the primary coolant, and variations of steam generator design, are being studied.

GE has proposed a small BWR with many improvements aimed at safety and operability. Of particular note are features designed to minimize reliance on active decay-heat-removal systems, improve the ability to cope with transients (sudden changes), and reduce demands on the operators.

The Westinghouse concept is based on a standard two-loop design similar to a plant presently nearing completion in the Philippines. The heart of the reactor (the "nuclear island," including safety and control systems) would be built and tested at a shipyard or factory and then transported by water or overland to the site where the rest of the plant would have been constructed in parallel. Westinghouse claims that increasing the proportion of work carried out in the shipyard or factory environment would reduce uncertainty about cost and schedules, lessen impact at the plant site, allow reuse of capital equipment, and reduce licensing risks.

PIUS—the reactor of ultimate safety. The U.S. vendors did not focus on designing simpler, smaller reactors until the early 1980s, when it was already abundantly clear that the nuclear industry was in deep trouble. In the 1970s, however, Europeans had already begun to develop new reactor concepts with a primary emphasis on safety and a secondary emphasis on cost reduction.

Many countries have studied the application of nuclear power to district heating to reduce dependence on expensive, unreliable foreign sources of oil for warming city buildings. Starting about 10 years ago, Sweden and Finland cooperated on developing a district heating reactor; because such a system would have to be sited near large city populations, their effort centered on achieving a high degree of safety. Designated SECURE-H, this system relies for safety on simple laws of nature—that is, upon inherent safety characteristics rather than the array of engineered safeguards systems based on pumps, valves, and emergency power supplies typical of conventional nuclear power plants.

ASEA-ATOM of Sweden extended this design philosophy to a power generating reactor in the late 1970s. Development of criteria and application of the inherent safety approach led to the reactor design generally called PIUS. PIUS is an acronym for Process Inherent Ultimate Safety, a name that incorporates the principles embodied. The PIUS reactor is also called SECURE-P to designate it as a power-producing version of the SECURE line of reactor designs.

In the PIUS concept the reactor is submerged in a large pool of low-temperature, borated water contained in a large, prestressed concrete reactor vessel, generally acknowledged to be superior to the conventional steel pressure vessel because it is more resistant to pressurized thermal shock and other stresses that could lead to catastrophic failure. The entire high-pressure primary coolant loop of the reactor is contained in the vessel to minimize the risk of a loss-of-coolant accident. Also, because of the large volume of water, overheating or melting of the core after shutdown (which is ensured by the neutron-absorbing properties of boron) would not be an immediate concern. This intrinsic protection of the core is designed to last for at least one week following the original accident, thus providing ample time for the operator to take any corrective actions needed.

PIUS and LWRs. The PIUS/SECURE-P reactor design attracted attention in the United States at about the same time that studies were begun to identify problems in the U.S. nuclear industry and to lay the groundwork for a nuclear power role in meeting future growth in demand for electricity. The PIUS safety concept, combined with possibilities of reducing financial risk to the utilities by building plants of lower power levels (which can be built in less time at lower cost than conventional plants), led to an upsurge of interest in smaller, safer plants in the United States. However, because the U.S. nuclear industry takes a dim view of designs requiring a prototype demonstration at this time and because it judges that PIUS requires such a demonstration (unlike ASEA-ATOM), it does not embrace the PIUS approach to commercial nuclear power. ASEA-ATOM is working with the U.S. NRC on the possibility of licensing its design. However, without the support of the U.S. government or a major segment of the U.S. industry, it does not appear that the PIUS design can become a reality in the United States.

Charles Forsberg of ORNL's Chemical Technology Division has proposed a PIUS-BWR that incorporates the basic PIUS goals and concepts related to safety. In his concept, however, the reactor primary loop is based on a BWR rather than the PWR of SECURE-P. To adapt the BWR (which operates with a two-phase coolant regime—that is, rapid boiling occurs in the core) to the PIUS concept, Forsberg proposes incorporating "valves" between the primary coolant system and the large volume of borated water contained in the prestressed concrete vessel. The proposed valves contain no moving parts and are of the type termed "fluidic." This PIUS-BWR proposal, while interesting, has not yet addressed questions regarding the stability of the system and the dynamic behavior under upset conditions. More studies are required to provide reasonable assurance of operational feasibility.

Advocates of the PIUS approach to LWR design claim several advantages: the absence of reliance on engineered safety systems or devices that could fail; the lack of dependence on capricious human intervention; and the drastic simplification of total plant design, resulting in lower costs, reduced quality-assurance requirements, less regulatory interference, shortened construction time, and economy in power production by smaller units.

Perhaps most important, the PIUS safety approach is much easier to comprehend ("more transparent") and, therefore, should increase public confidence in reactor safety and the acceptability of nuclear power. But the probable higher capital cost of LWRs incorporating PIUS features suggests that society may have to pay more for a closer approach to "ultimate safety."—*Tom Cole, Group Leader, Reactor Systems Analysis, Engineering Technology Division.*

Nuclear Power Options: HTGRs—Small Units Show Big Benefits

High-temperature gas-cooled reactors (HTGRs) are promising reactor systems for electricity generation, for cogeneration of steam and electricity, and for production of high-temperature process heat. But despite the versatility and appealing features of this reactor type, only one commercial HTGR is operating in the United States—the Fort St. Vrain reactor near Denver, Colorado. This situation may change as HTGR concepts are modified to meet new expectations.

HTGRs employ a graphite moderator to slow down the neutrons from the reactor core and a helium coolant to transfer heat from the reactor core to convert water to steam to generate electricity. The fuel consists of ceramic forms, oxides and carbides, of uranium and thorium (UO_2, UC_2, and ThO_2). It is contained in ceramic coatings of pyrolytic carbon and silicon carbide, which keep fission products from being released from the reactor core, under both normal and postulated-accident conditions.

For many years the reference HTGR concept used prestressed concrete vessels to contain the reactor core. The early HTGRs were sized to generate relatively large amounts of electrical energy [860 to 1160 MW(e)]. The reactor core was designed to be constructed of prismatic, or hexagonally shaped, graphite blocks [36 cm (14 in.) across the "flats" and 76 cm (30 in.) long] with vertical holes for cooling channels and with fuel rods located in "blind" holes. While the fuel elements remain similar, some features of the reference HTGR concept have been altered to meet changing needs.

During the last few years a number of studies has focused on the future of the nation's nuclear power industry. These studies indicate the desire for smaller, simpler nuclear power plants that would be easier to construct, that would be less expensive and, therefore, easier to finance, and that would facilitate compliance with regulations. As a result, although the large HTGR has attractive features for operation and safety, about two years ago the U.S. HTGR program was realigned to evaluate the potential for small HTGR reactor concepts.

By decreasing the core power and core power density, it appears possible to design an HTGR with a high degree of passive safety—that is, natural heat removal processes can limit fuel temperatures to levels at which the release of fission products from the reactor system to the environment is insignificant even for extreme postulated accidents. The passive-safety features of the lower-power reactor show promise of reducing the amount of nuclear grade equipment required in the rest of the power plant, thus reducing plant costs.

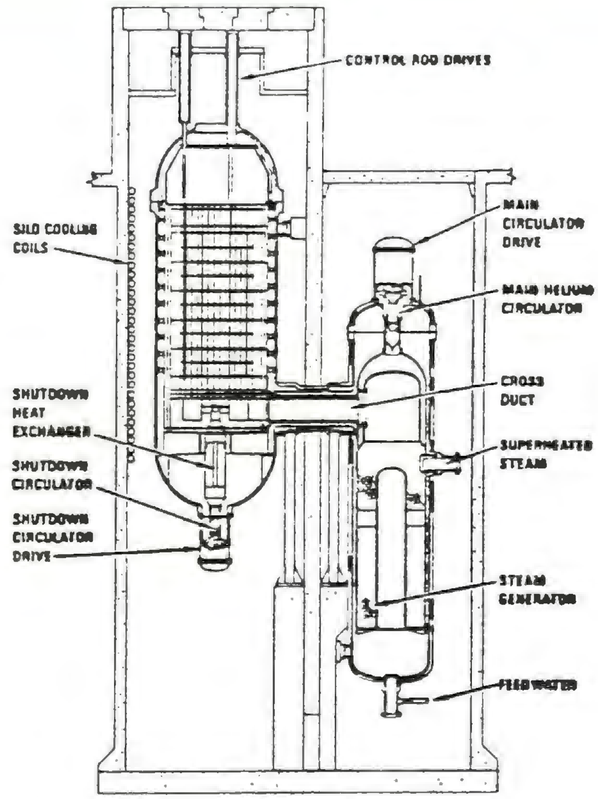
Another advantage of low-power HTGRs is that steel pressure vessels instead of prestressed concrete vessels can be used to contain the reactor core, thus making plant construction easier, faster, and less expensive because the vessels can be fabricated in shops instead of built on-site. However, to make the plant as economical as possible, the power output per unit should be as high as practicable without compromising the desirable passive safety features.

To achieve this end, the U.S. HTGR program participants, led by DOE's Office of Advanced Reactor Programs, developed and assessed various concepts. Besides DOE the participants include Oak Ridge National Laboratory; Gas-Cooled Reactor Associates; GA Technologies, Inc; Combustion Engineering, Inc; General Electric Company; Bechtel National, Inc; Stone & Webster Engineering Corporation; and Idaho National Engineering Laboratory.

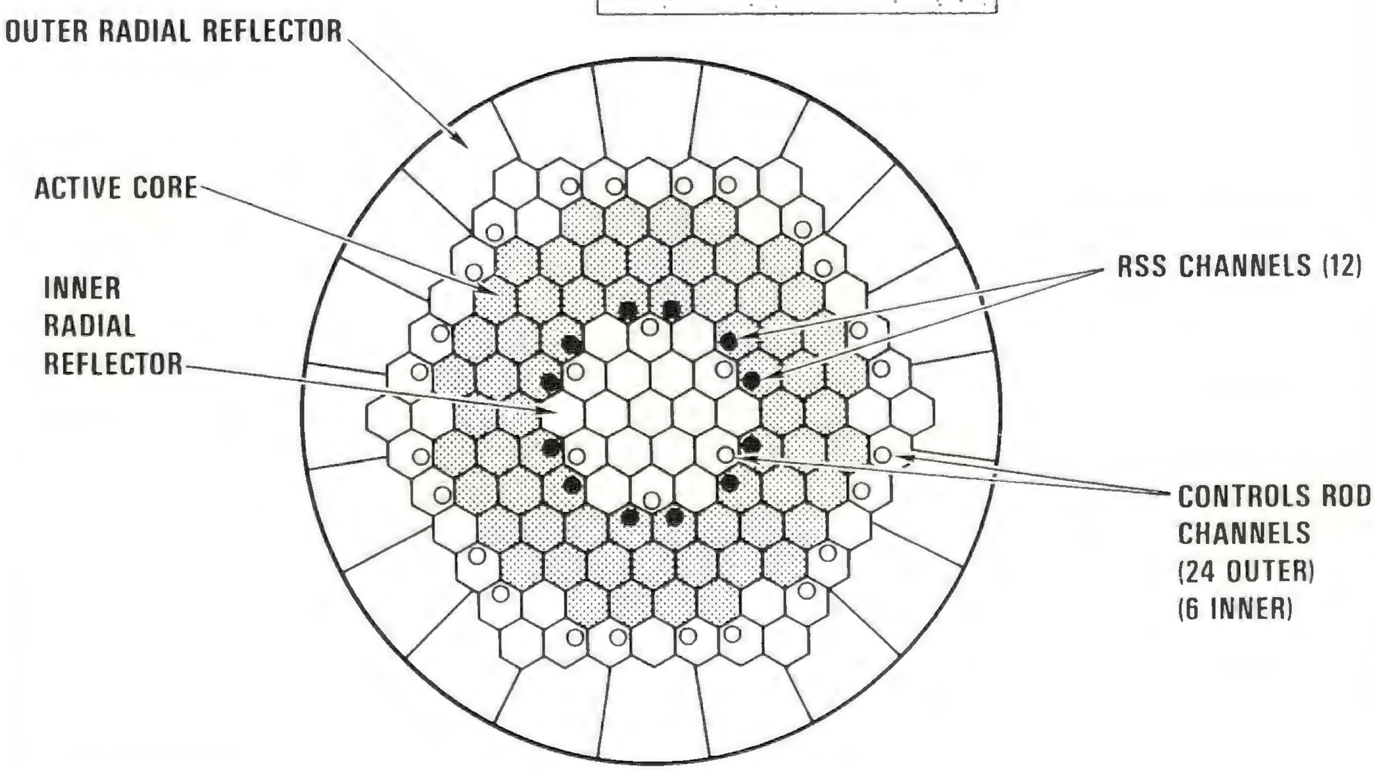
The participants selected an HTGR concept that best offered safe, reliable, and economic performance and that they believed would be perceived by utilities as low-risk and by the public as acceptable. The selection, made in September 1985, is a 350-MW(t) HTGR unit with an annular core with prismatic fuel elements. Several such HTGR units would be located at one plant site.

In this HTGR concept, two steel pressure vessels of different sizes would be arranged side-by-side. In one vessel is the reactor core; in the other, the heat removal equipment. The annular core, reflector, and associated core supports and restraints are located in the larger pressure vessel. Control rods operate in the inner and outer regions of the reflector; a reserve shutdown system is provided in the inner row of the active core fuel blocks. The smaller pressure vessel contains the steam generator and the main circulator. The entire unit is located belowground in a silo to facilitate economic decay-heat removal using natural-convection heat transport processes. Placing the reactor unit in the ground enhances natural-convection heat transfer, allows decay heat from the reactor to be conducted to the ground, and makes the nuclear plant less intrusive visually.

Based on the latest studies, small (modular) HTGR units of this type appear well suited to an era when investors are reluctant to risk putting money into large projects, long-range energy demand is unknown, construction costs vary widely, and the duration for licensing is uncertain. Because of their passive safety, modular HTGRs may also be suitable for siting close to population centers and industry. If close siting is possible, modular side-by-side HTGRs could provide process heat to industry and district heating to communities, as well as meet the growing need for electricity, particularly in the industrial sector.—*Paul R. Kasten, Technical Director, Gas-Cooled Reactor Programs at ORNL.*



Silo installation of modular HTGR.



Layout of the modular HTGR's prismatic annular core fuel block and control rods.

Nuclear Power Options: Liquid Metal Reactors—New Challenges for Designers

The termination of the Clinch River Breeder Reactor Project in 1983 did not mark the end of three decades of U.S. interest in reactors cooled by liquid metal. In fact, the liquid-metal reactor (LMR) attracted new attention about that time because of the growing interest in reactors with passive safety features.

DOE, EPRI, Rockwell International, and GE are leading the U.S. effort to develop attractive LMR concepts. Their goal is to design a nuclear power plant that, compared with previous designs, is inherently safer, less expensive, more acceptable to the public, faster to build, and easier to license.

ORNL has evaluated three LMR concepts developed with DOE funding: the large-scale prototype breeder (LSPB), which also has funding from EPRI; the sodium advanced fast reactor (SAFR); and the power reactor inherently safe module (PRISM).

These LMR concepts differ from light-water reactors (LWRs) in that they use sodium rather than water to cool the core and, for safety reasons, they have a secondary loop of nonradioactive sodium that transfers heat from the primary sodium coolant to the steam generator. Because of the extra loop, an LMR is potentially more costly than an LWR with the same generating capacity. However, their advocates believe that LMRs could be made cost-competitive with LWRs by designing LMRs to be more compact, shortening the construction time, and exploiting passive safety features to reduce the number of expensive safety systems now required in LWRs.

Sodium is the coolant of choice for LMRs because its physical and chemical properties give the reactor inherent safety. Sodium can be kept at low pressures as its absorbs heat from the fissioning fuel and transfers it to make steam to drive electric-power generators. As the coolant for the primary and secondary heat transfer loops, sodium has a large heat capacity; thus, it can retain considerable heat without boiling—another inherent safety feature. In addition, sodium requires little energy for pumping, and it is amenable to heat-driven natural circulation. This natural circulation facilitates completely passive removal of decay heat (heat generated by decaying fission products in the fuel) through air-cooling of the reactor vessel, which contains the reactor and primary sodium. Finally, sodium is compatible with the fuel-pin cladding.

Sodium does, however, offer potential hazards that reactor designers must guard against; for example, it reacts violently with water, so physical barriers and isolation systems have been designed to ensure that the sodium and water remain apart. Another challenge facing LMR designers is determining the optimal size of the reactor core for the required power output. To achieve economy of scale and relatively simple control of the power station, it is desirable to have a power output of about 1000 MW(e), which one large reactor core could generate. But designers are considering producing the same power with several smaller cores. A multiple-core design offers several advantages over a single large core: easier and faster fabrication of components, enhanced passive safety against loss of forced flow of the primary coolant, and greater flexibility in the design of passive systems to remove decay heat. (Because large core designs may not be able to remove decay heat with a completely passive system, some forced circulation of coolants may be required.)

In addition, the safety features of these smaller cores can be demonstrated in full-scale prototypic tests, thereby making it easier to license this reactor design. Power stations with multiple cores would also have a lower investment risk, a better match of completion schedules with additional demand for power, and higher availability because a simultaneous shutdown of three small reactors is much less likely than a shutdown of one large reactor.

All of the LMR designs evaluated at ORNL include innovations to reduce capital and operating costs and enhance passive safety. These designs have many similarities (e.g., they all use uranium and plutonium for fuel) and several differences. Some distinguishing features are described below.

The 1300-MW(e) LSPB, sponsored by DOE and EPRI, is designed to be economically competitive with both coal and LWR plants. A four-loop configuration has been designed, and work has begun on a pool-type design. One way that the LSPB differs from the SAFR and PRISM is in its safety-grade decay-heat-removal system: it uses two independent, diverse, and redundant systems (one of which is passive) to remove heat directly from the primary coolant, while the other two concepts rely on air-cooling of the reactor vessel as their single, passive, safety-grade system. The LSPB incorporates both evolutionary design changes and additional innovations to reduce capital and operating costs and increase constructibility.

New features of the LSPB include the capability of operating the reactor at reduced power by using three loops while the remaining loop undergoes maintenance, smaller buildings placed closer together to reduce the lengths of sodium piping, cable multiplexing to reduce cable requirements, and preassembly of subsystems on-site prior to installation in the plant. In short, to save money and speed up the building of the reactor, modular construction is emphasized in the LSPB concept.

SAFR, which is being designed for DOE by a team from Rockwell International, Bechtel, and Combustion Engineering, consists of four independent power generating units called Power Paks. These Power Paks have shared facilities—the control building, the plant service building, the nuclear island maintenance building, and the fuel cycle facility. A 350-MW(e) size for each Pak was selected because of such considerations as cost, passive safety, utility acceptance, licensability, and constructibility.

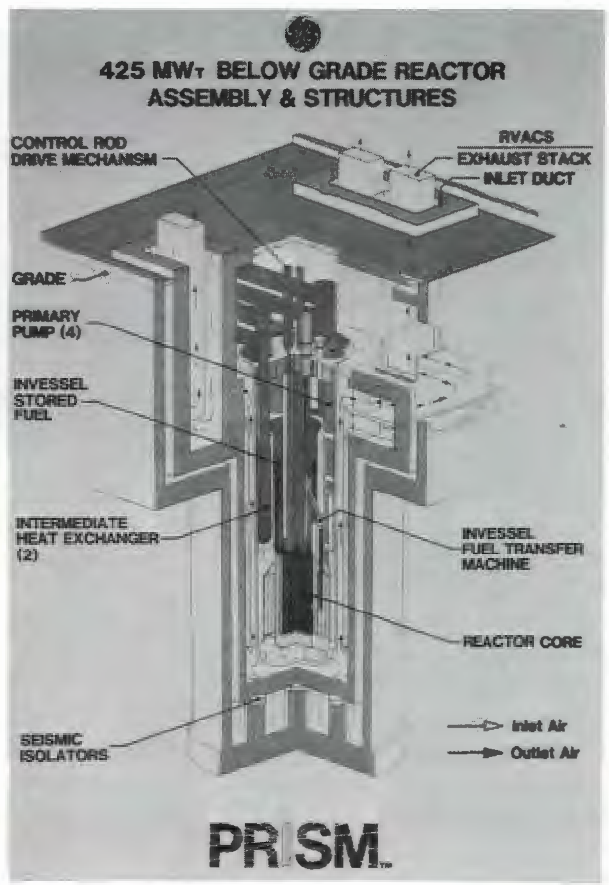
Advanced LMR technology and enhanced passive safety features introduced into the SAFR design include (1) metal fuel and associated innovations for enhanced passive safety and a potential for simpler reprocessing and fuel refabrication, (2) redundant and passive decay-heat-removal systems, including a dedicated passive sodium loop that cools the primary coolant, and (3) an intermediate loop made of an advanced material (the chromium-molybdenum alloy 9 Cr:1 Mo that ORNL helped to develop), thus allowing a high core-exit and primary system temperature for higher plant efficiency.

The PRISM concept, developed by GE, consists of three pool-type reactors and three steam generators but only one turbine, which produces about 400 MW(e) of power. Three such units are built next to each other to form a 1200-MW(e) power station. The concept emphasizes the incorporation of passive safety through the use of (1) a lower power reactor output of only 133 MW(e); (2) a pool design with low primary sodium temperatures; (3) a passive decay heat removal system, which uses air-cooling of the outside walls of the steam generators as well as the reactor vessel; and (4) a core designed to expand if temperatures rise, in order to limit the effect of a loss of forced primary-coolant flow.

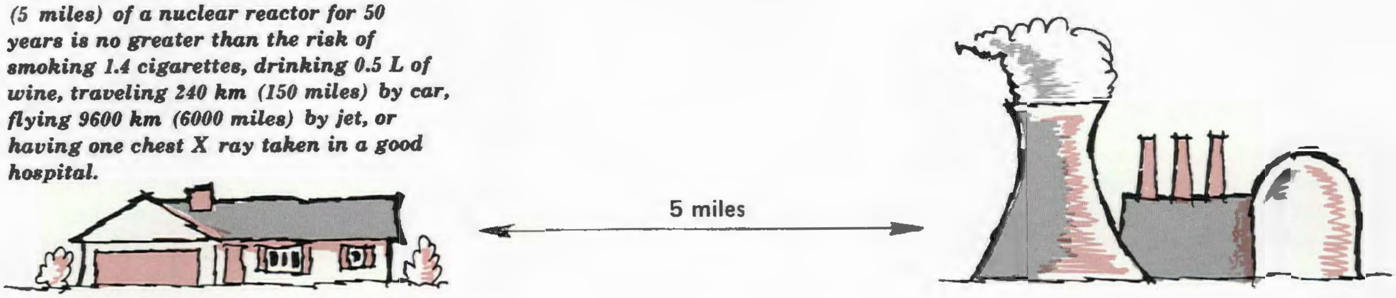
According to the ORNL study, "Commercialization and marketing of an LMR in the anticipated market between now and around the year 2010 may be difficult to accomplish. Not only do LMRs have the same negative market factors as other concepts (including an uncertainty in the need for power, licensing challenges, and financial uncertainties), but LMRs must also overcome additional concerns such as their traditionally higher capital costs, their perceived role only as breeders, a lack of utility experience with LMRs, and uncertainties associated with an adequate and cost-competitive fuel cycle.

"One could argue that LMRs will penetrate this market only if they have a unique and very important advantage over other power generating concepts. Such an advantage may arise from the innovative LMR designs evaluated at ORNL. Their strong emphasis on cost reduction, passive safety, rapid construction, licensability, and low economic risk are certainly appropriate to meet the challenges of future markets."—*Ray Booth, Instrumentation and Controls Division.*

One concept for a liquid-metal reactor (LMR) is the Sodium Advanced Fast Reactor (SAFR), developed by Rockwell International. At left is an artist's conception of a 1400-MW(e) SAFR plant consisting of four Power Paks—independent power-generating units that share the control building, the plant service building, the nuclear island maintenance building, and the fuel cycle facility. At right is a cutaway view of a 425 MW(t) below-grade reactor assembly and structures of another LMR concept—the Power Reactor Intrinsically Safe Module (PRISM), developed by the General Electric Company.



The health risk of living within 8 km (5 miles) of a nuclear reactor for 50 years is no greater than the risk of smoking 1.4 cigarettes, drinking 0.5 L of wine, traveling 240 km (150 miles) by car, flying 9600 km (6000 miles) by jet, or having one chest X ray taken in a good hospital.



Nuclear Power: Who Needs It?

An essay by CAROLYN KRAUSE

Nuclear power. Who needs it? Many European countries find nuclear power attractive because they want to reduce their dependence on expensive, unreliable foreign sources of oil for power production and district heating. Several less developed countries are ordering nuclear power plants for the same reason.

But in the United States, where nuclear power was born (remember the Experimental Breeder Reactor-I in Idaho in 1951?), nuclear energy has a bad image problem. From the standpoint of safety and finances, it is considered too risky. More and more Americans are shrugging their shoulders and asking, "Who needs it?"

Recently, dozens of experts and lay people were asked to rank the risk of dying in any year from 30 different activities or technologies (see *Science 85*, October, page 41). The experts, whose ranking closely matches known fatality statistics, rated nuclear power 20th, whereas they ranked motor vehicles first. This ranking makes sense because statistics show that nearly 45,000 Americans died in auto collisions in 1984, whereas in 30 years in the United States, nuclear power has claimed no lives of the public in accidents.

So how did the American public rank nuclear power's risk to health and safety? First—not 20th. Motor vehicles were ranked second. Partly as a result of the public's attitudes about risk, no new nuclear power plants have been ordered since 1978. But Americans are still buying cars and still driving; even more remarkable, only one out of seven American drivers puts on a seat belt before hitting the road despite expensive campaigns informing people that seat belts save lives. Do these perceptions of risk and actions in response to known risk values by the American public make sense?

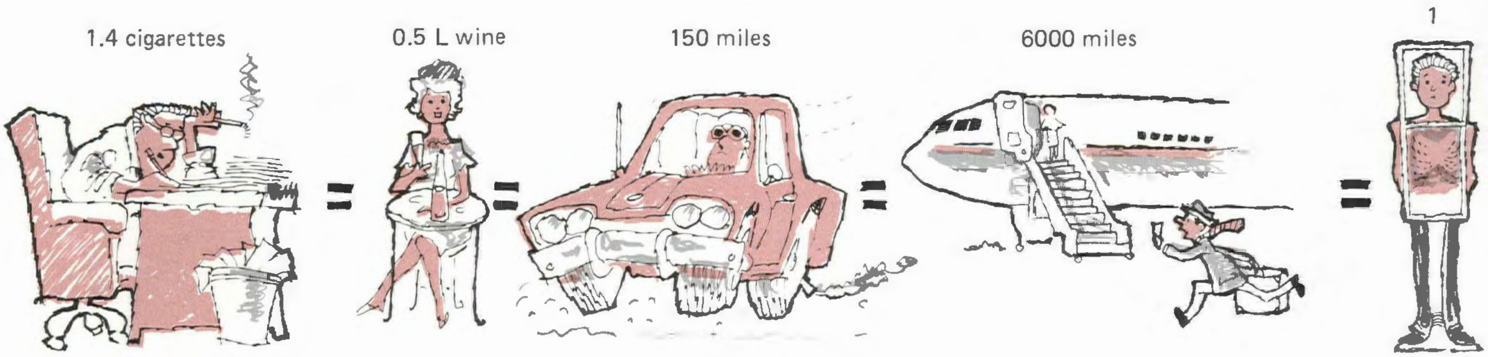
Hardly. As *Science 85* puts it, this is the "same public that smokes billions of cigarettes a year while banning an artificial sweetener because of a one-in-a-million chance that it might cause cancer; the same public that eats meals full of fat, flocks to cities prone to earthquakes, and goes hang gliding while it frets about pesticides in foods, avoids the ocean for fear of sharks, and breaks into a cold sweat on airline flights."

Coal Believed Safer

This is the same public that pictures high-level waste (including spent fuel from nuclear power plants) as a mountain of material that will glow in the dark for a million years, says nuclear safety expert Harold W. Lewis, who presented a seminar at ORNL in November 1985. In reality, he noted, only a small amount of high-level wastes (about the size of a speaker's podium) is produced yearly in the United States, and this short-lived, highly radioactive waste requires isolation for no more than the life of the Pyramids.

This is also the same public that ignores the death rates associated with coal mining and coal combustion to produce electricity. Some experts estimate that coal-generated electricity costs some 10,000 lives a year through mining and transportation accidents and pollution (*Science 85*, October, page 35). Yet according to nuclear physicist Bernard Cohen of the University of Pittsburgh (and formerly with Oak Ridge National Laboratory), 80% of the American public believes that coal burning is safer than nuclear power. Partly because of this public perception, Cohen believes, utilities are building coal plants rather than nuclear power plants, "thus condemning many hundreds of innocent Americans to an early death."

With a public attitude like this, electric utilities in the United States are asking themselves who needs nuclear power. Says Robert Uhrig, former vice-president of



Who needs nuclear power? Any country with a growing demand for electricity that wants to reduce its dependence on expensive, unreliable foreign sources of oil or health-threatening coal combustion. In countries like the United States where fears of nuclear power border on the irrational, the revival of interest in nuclear power will not occur until benefits clearly outweigh perceived risks to the investor.

Florida Power and Light Company and now an ORNL-UT Distinguished Scientist: "I know of no chief executive officer of a utility today who is giving serious consideration to ordering a new nuclear power plant." In a democratic country like the United States, where public opinion has a strong impact on public policy, government regulations, and the economy, it is no wonder that nuclear power has lost some of its commercial appeal.

A Nuclear Comeback?

Will nuclear power ever recover its good name in the United States? Uhrig believes that reason will eventually prevail, that the public's fear of nuclear power will subside as the growth in the annual demand for energy increases markedly and as people become more conscious of the harmful environmental and health effects of coal-fired power generation.

According to Uhrig, the facts suggest that the United States must return to an aggressive nuclear power program starting in the mid-1990s and continue it through the early decades of the next century.

"Almost everyone agrees," he says, "that the consumption of electricity is growing and that it will probably continue to grow, at least at a moderate rate. The excess capacity that we enjoy today is already beginning to disappear in certain parts of the country, and it is clear that most of this excess capacity will be used by the mid-to-late 1990s. Furthermore, most of the current excess capacity is oil-fired, and it is anticipated that urgent demand for this capacity will coincide with a new world-wide oil production 'crisis.'

"At the present time, the United States has a little over 600,000 MW of capacity," he explains. "If we assume that our electrical consumption grows at the very modest rate of about 2.5% per year and that our capacity eventually will have to grow at this rate, then we are looking at the addition of about 15,000 MW per year in the late 1990s and the early 21st century. This is 15 1000-MW plants per year, or 30 500-MW plants per year, or perhaps 150 100-MW modules that have to be installed per year. Furthermore, the need to replace most the current capacity because of aging will occur in the same period.

"If it takes four years to plan and site each 1000-MW power plant and six years to build it, then in any given year in that time frame, an average of 60 1000-MW plants will be sited and 90 will be under construction," says Uhrig. "If we assume that the 15 1000-MW plants that come on-line in any given year are all coal plants, the increase in coal mining capacity may be prohibitive.

"A 1000-MW coal plant burns 10,000 tons of coal a day. If we operate each of these 15 plants for 250 days a year, that's 2.5 million tons of coal per plant, or about 40 million tons of new mining capacity needed every year. If this trend continues for 10 to 12 years, we would have to double the production of coal in the United States, with all of the attendant environmental and safety considerations.

"Doubling the coal-mining capacity of the United States will be extremely difficult," Uhrig continues. "The alternative is to become as dependent on foreign coal from Colombia, South Africa, and Poland as the United States has been on foreign oil supplies. I would like to think," he concludes, "that the Arab oil embargo and the resultant energy crisis of the last decade have at least sensitized us to the folly of such dependence."

How Risks Are Perceived

Surely, many Americans have read in the newspapers that the risk of occupational death and injury is highest for workers in the coal industry and lowest for those in the nuclear industry. They may also have read that the public health risk from nuclear power generation is lower than that of coal power generation. They might have heard that the risk of total cancers from routine and catastrophic radiation releases from nuclear facilities is much less than is the risk of cancer and fatal respiratory diseases caused by air pollution from coal-fired power plants (which includes radioactive gases, by the way).

The arguments seem quite sensible, so why are Americans afraid of nuclear power? Why don't they agree with the risk experts who found nuclear power to be much safer than bicycles? Why do they not believe the risk analysts who have found that the health risk of living within 8 km (5 miles) of a nuclear reactor for 50 years is no greater than the risk of smoking 1.4 cigarettes, drinking 0.5 L of wine, traveling 240 km (150 miles) by car, flying 9600 km (6000 miles) by jet, or having one chest X ray taken in a hospital? Each of these activities is estimated to increase a person's chances of dying in any year by one in a million.

ORNL's Curtis Travis and Elizabeth Etnier, editors of the 1983 book *Health Risks of Energy Technologies*, say that the public will accept health and safety risks posed by a technology if it is familiar, if the public is given the choice of whether to assume the risk, and if the risk is not catastrophic—that is, not a potential killer of hundreds of people. But, they add, nuclear power falls into a different category. As former ORNL director Alvin M. Weinberg puts it, nuclear energy is "special." Says Etnier, "People are afraid of the technology because it is new. They are unwilling to take on the involuntary risk of exposure to radiation, which is widely regarded as a mysterious, invisible menace. Finally, they are frightened of the possibility of a catastrophic nuclear accident even though the probability of such an accident is quite low."

Paul Slovic, former president of the Society for Risk Analysis and a psychologist with Decision Research, Inc., in Eugene, Oregon, has spearheaded a study to determine how people perceive risks of different technologies. According to William F. Allman's article "Staying Alive in the 20th Century" in the October issue of *Science 85*, Slovic found that the "respondents overwhelmingly regarded the risks of nuclear power as involuntary, uncontrollable, unknown, inequitably distributed, likely to be fatal, potentially catastrophic, and evoking feelings of not just fear but dread. Automobiles, which kill far more people per year, evoked few of these concerns."

Who needs nuclear power? If the experts are right, the United States will need an increasing amount of it by the mid-1990s. Another energy crisis—primarily a shortage of liquid fuels—may occur by then. Furthermore, the demand for electricity is expected to grow as industry consumes more power to meet environmental regulations and improve productivity. As Lewis puts it, when Americans realize that a serious energy shortage exists, they will see that the benefits of nuclear power clearly outweigh the risks.

In addition, new interest in nuclear power may develop as it becomes evident that the United States has lost its ability to shape the future of nuclear energy use throughout the world. According to an ORNL planning document, "In the electrical energy area, the rest of the world will continue to accelerate the movement toward nuclear energy, and it will become evident that this nation's forfeiture of its leadership position in nuclear technology cost it dearly in terms of lost opportunities in international trade and lost influence over important matters such as direction, safety standards, and fissile material control; this realization on the part of the federal government will result in a revitalized national effort in fission power reactors."

If the experts are right about why the public dreads the low-risk technology of nuclear power, can anything be done to put nuclear power back in the driver's seat among energy technologies 10 years from now?

Chances are, the passage of time will help. Many Americans used to be afraid of electricity, trains, and automobiles, but after enough time elapsed and their usefulness became evident, we adopted these technologies without a second thought. Nuclear power won't seem so new in the 1990s.

Current efforts to design small reactors that can be hidden away underground in isolated rural areas (the "low visual profile") should help allay the fears of urbanites who think they are being exposed involuntarily to radiation from nuclear power plants. Also, the latest efforts to design ultimately safe, or "walk-away safe," reactors should help ease fears of catastrophic accidents.

And who knows, if another oil embargo occurs or if heavy coal combustion threatens to cause serious environmental problems, nuclear power could offer a shining ray of hope. orn

awards and appointments

Oak Ridge National Laboratory has received the President's Award for Outstanding Safety Performance from Martin Marietta Energy Systems, Inc. On January 22, 1986, ORNL completed one calendar year without a recordable occupational injury resulting in days away from work. ORNL also earned the distinction of having the lowest occupational incidence of injuries and illnesses (0.28 per 100 full-time employees) ever achieved by an Energy Systems facility. By contrast, National Safety Council statistics show that research and development facilities in 1984 had an average incidence rate of 1.79.

Abraham W. Hsie has been selected as a Distinguished Visiting Scientist with the U.S. Environmental Protection Agency's Office of Research and Development.

Vic Vaughen has been appointed a member of the State Ethics Committee of the Tennessee Society of Professional Engineers and of the Ethical Issues Subcommittee of the American Nuclear Society Planning Committee.

Warren D. Siemens has been appointed director of technology transfer for Martin Marietta Energy Systems, Inc.

Research co-directed by **R. B. Perez** and **Dan Cacuci** is the subject of a prize-winning paper authored by Jose March-Leuba, a student in the nuclear engineering department at the University of Tennessee who did his thesis research in ORNL's Engineering Physics and Mathematics Division. March-Leuba received the prestigious Mark Mills Award, an American Nuclear Society award for graduate students, for the paper "Non-Linear Dynamics and Stability of Boiling-Water Reactors."

Robert F. Limburg has been appointed head of the Operating Budget and Accounting Department in ORNL's Finance and Materials Division.

Douglas L. Selby has joined the Program Planning and Analysis Office, where he coordinates the Exploratory Studies (Seed Money) Program.

Robert W. McClung has been appointed a member of the Panel for Nondestructive Evaluation by the National Research Council. He has also been named a member of the U.S. delegation to the Fifth Plenary Meeting of Technical Committee 135 on Nondestructive Testing of the International Standards Organization.

Earl W. McDaniel has been elected to the 12-member editorial advisory board of the journal *Nuclear Technology*.

Steven E. Lindberg has been awarded the Alexander von Humboldt Foundation Research Fellowship. Lindberg will spend a year at the University of Göttingen in the Federal Republic of Germany studying the effects of nitrogen and trace metal deposition on forests.

F. W. Wiffen is a co-winner of the American Nuclear Society's 1985 Best Paper Award for "Fusion Materials Activation Characteristics as Related to Waste Disposal Requirements."

Eight employees who work at ORNL won Bronze Quill awards in December from the International Association of Business Communicators, East Tennessee Chapter. **Bill Clark** of the Information Resources Organization (IRO) and **Steven Wyatt** of the Public Relations Department won an award of merit for the design of the brochure *Career Opportunities*; **Clark Cynthia Allen** of IRO, and **Helga Gerstner** of the Central Management Offices received an award of excellence for the brochure *Biomedical and Environmental Sciences at ORNL*; and **Jeanne Dole** and **LaWanda Klobe** of IRO, along with **Allyn Zerby** and **Karol Mitchell** of the Instrumentation and Controls Division, received an award of merit for the newsletter *The RAMbler*.

David K. Trubey has been appointed a member of Committee N17 of the American National Standards Institute. This committee, whose secretariat is the American Nuclear Society, approves national standards for research reactors, reactor physics, and radiation shielding.

Robert E. Uhrig, **David C. White**, **J. Alan George**, **Robert Hatcher**, **David Joy**, and **Philip Siemens** have been appointed Distinguished Scientists at the University of Tennessee at Knoxville and Oak Ridge National Laboratory. (See "News Notes" on page 45 for details.)

Nations with successful nuclear programs tend to have low amounts of fossil fuels, high labor productivity, and a commitment to using standardized reactor designs.

Where in The World Is Nuclear Energy?

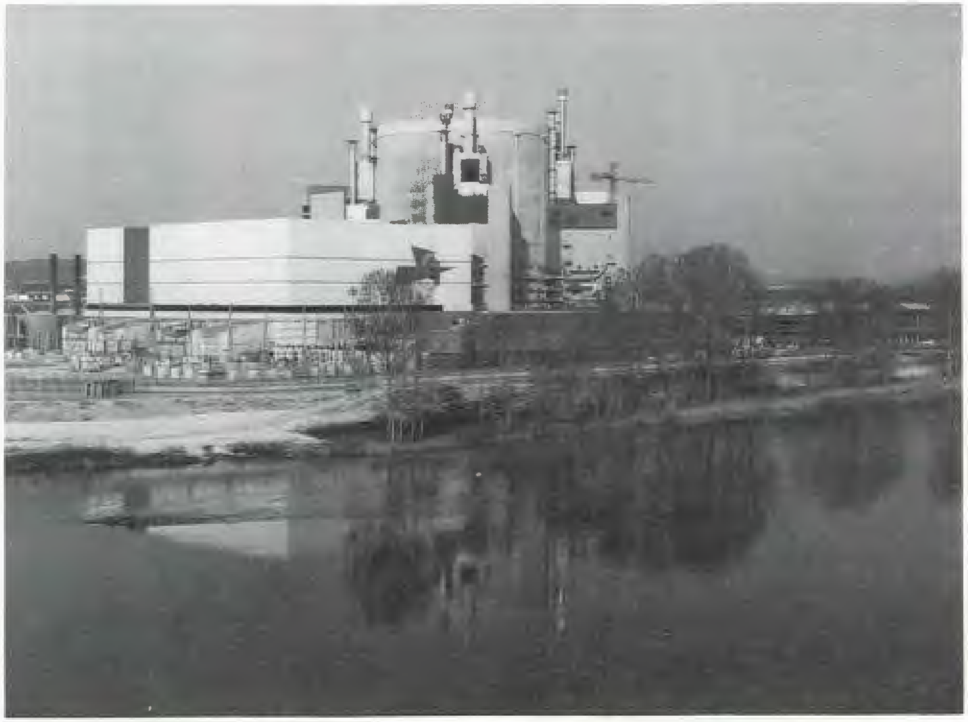
By DONALD B. TRAUGER

Nuclear power was born in the United States 35 years ago, but lately it has been more appealing to other parts of the world, including less developed countries. One of the most recent reactors to start operation is in the Philippines, making it the 27th nation to join the nuclear energy club. In 1984 eight commercial units were planned by four countries. By contrast, no new nuclear power plant has been ordered in the United States since 1978, and all orders placed since 1974 have been cancelled. Why has the market for nuclear power plants been changing in the United States and throughout the rest of the world, and how might this changing market affect future research and development work at Oak Ridge National Laboratory?

Recently, during the 70th birthday celebration for Alvin M. Weinberg, former ORNL Director, someone noted that he holds or shares 14 basic patents for current light-water reactor (LWR) designs and technologies. Through analysis and experimentation, many others at ORNL contributed to LWR technology, which now provides 13% of the world's supply of electricity. The Laboratory continues to contribute to improving the safety of LWRs, spending about 6% of its budget on this mission, which is about one-third of ORNL's total effort in nuclear fission. Where will the major impact of these contributions finally be felt, within our own country or in the rest of the world?

Let's look first at some specific nations that are expanding their nuclear energy programs. France is widely recognized as having the most vigorous program for deployment of commercial LWRs and is a world leader in the technology and demonstration of liquid-metal fast breeder reactors. In 1984 in France, nuclear plants supplied 55% of the total electricity generated, and one new order was placed. France and much of Europe continue to build nuclear plants, although at a reduced pace. The other active center for deployment of nuclear reactors is in the islands and peninsulas of Eastern Asia (e.g., Japan).

What do the nations that are expanding their nuclear energy programs have in common? First, with few exceptions, they do not have significant resources of coal as an alternative energy source.



The Super Phénix Nuclear Power Plant in France is a liquid-metal fast breeder reactor. It began operation at low power in September 1985.

Second, most have expanding economies and a favorable balance of trade and hence have access to financing to meet the high capital costs of nuclear power stations. Third, they have developed methods for constructing nuclear power plants on a short time scale. For example, Japan recently completed construction of its Takahama Plant No. 4 in a little over three years, whereas the corresponding time in the United States is frequently 10 to 14 years.

It is often stated, particularly by utility company representatives, that cumbersome U.S. regulations discourage orders and delay the completion of nuclear power plants in the United States. Although the statement is probably true to some degree, regulation can be only a contributing cause. All of the Asian countries with successful nuclear programs have adopted most U.S. Nuclear Regulatory Commission (NRC) regulations. France has its

Table 1. Capacity projections, by country, for 1986[a]

Country	Units	MW(e)
Argentina	2	935
Belgium	8	5,485
Brazil	1	626
Bulgaria	4	1,632
Canada	17	10,037
Czechoslovakia	5	1,980
Finland	4	2,310
France	46	38,983
East Germany	5	1,694
West Germany	21	17,655
Hungary	3	1,215
India	6	1,240
Italy	4	1,321
Japan	33	23,664
Korea	5	3,650
Netherlands	2	508
Pakistan	1	125
Phillipines	1	620
South Africa	2	1,842
Spain	8	5,577
Sweden	12	9,455
Switzerland	5	2,882
Taiwan	6	4,918
United Kingdom	38	10,164
USA	98	83,285
USSR	54	31,112
Yugoslavia	1	632
Total	392	263,547

[a]From the International Atomic Energy Agency Power Reactor Information System.

Nuclear Power in France

By 1990 nuclear reactors will generate 73% of France's electricity, predicted Jean Rastoin, director of the French fast-breeder reactor and light-water reactor programs, at an ORNL seminar November 18, 1985. Nuclear power, which provided only 8% of French electricity in 1973, now generates over 55% of the electricity consumed in France. By contrast, only 15% of the electricity used in the United States comes from nuclear plants.

The French nuclear program has been growing fast ever since the 1973 Arab oil embargo. Rastoin said that to reduce its dependence on unreliable, expensive sources of foreign oil, France turned primarily to nuclear energy because its domestic supplies of fossil fuels, including coal, are poor.

Most of France's 42 operating nuclear power plants (and 19 plants under construction) are light-water reactors, primarily standardized pressurized-water reactors, reported Rastoin. Two of the operating plants are liquid-metal fast breeder reactors. The Phénix breeder has been operating since 1974, and the new Super Phénix breeder began operation at low power in September. Unlike the United States, France is committed to fuel recycling. According to Rastoin, 350 tons of fuel have been reprocessed and a pilot plant for producing new nuclear fuel from spent fuel will be operating in 1988.

Steam generators for French nuclear power plants are manufactured in Framatome's facility.

own regulations and enforcement system, but they are basically as stringent as those in the United States. In short, regulation abroad has not stopped the development of nuclear power programs.

In a recent study by the Electric Power Research Institute (EPRI) in which French and U.S. nuclear power plant construction experiences were compared, it was observed that the amount of commodities, and hence their cost, was essentially the same. However, the required labor force was quite different for the two nations. France required only one-half to one-quarter as many laborers as the United States to build the same size nuclear power plant. Because the productivity of French labor forces is thought to be comparable to ours, except that craft specialties are not as strictly compartmentalized, it seems apparent that the high degree of standardization of nuclear plants in France is a principal factor. Most French plants are built using components and designs that are standardized throughout their nuclear industry, while most U.S. plants have been one of a kind.

Because French plants are standardized, they are, by definition, completely designed before construction starts. U.S. practice frequently has been to initiate construction with only a fraction of the design completed. Thus, approval of the design by the regulators must be obtained during construction. Resolving the differences between the designers and the regulators often leads to delays and extensive retrofitting and rework.

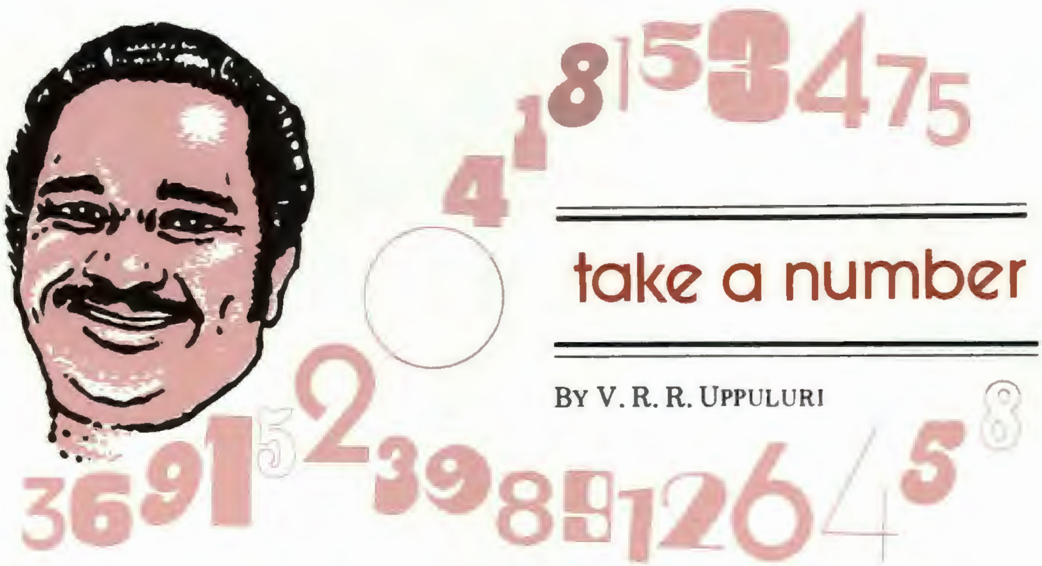
In the Eastern nations, labor productivity is usually higher than in the United States. Thus, American companies operating in the Far East have been able to build reactor stations more efficiently there than at home. Reactor construction times for Japan, Korea, and Taiwan have averaged between five and seven years.

The reasons for success or failure of national nuclear programs are very complex. However, regulations, lack of standardization, low labor productivity, and a highly fragmented utility structure probably have contributed to delays, cancellation of orders, and the lack of new orders for nuclear power plants in the United States.

Nations with highly centralized economic systems or more carefully planned modes of operation seem more likely to have successful nuclear programs than democratic countries like the United States and Federal Republic of Germany. European nations and Japan apparently devote more effort to central planning than has been the practice in the United States. Their plans are made for extended periods (five years or more). Although in most cases appropriations for government-supported work are made annually, those other countries have a better record than the United States in following a long-range plan to completion.

Nuclear energy is alive in the world. Other nations have taken the technology and designs developed largely in the United States, and they now lead in performance of nuclear plants. In part, this success abroad derives from necessity because few countries are blessed with the multiple energy resources found in the United States. Their success also may be attributed to better organization and dedication to the task. Nevertheless, the United States still leads the rest of the world in total experience in operating nuclear power plants, highly trained and skilled nuclear staffs, good manufacturing facilities, and advanced nuclear reactor designs. America should be able to regain the lead in performance.

ORNL continues a tradition of broad technological programs in nuclear energy, although the Department of Energy programs in nuclear energy have declined in recent years. ORNL's Nuclear Power Options Viability Study (see article on page 12) indicates that more power plants will be needed in the United States by the year 2000 to meet an increased demand for electricity. However, for nuclear energy to be called upon to meet this energy need in the United States, safer, less costly nuclear plants may be required. ORNL research programs can help develop the advanced, standardized nuclear plants needed in the future. ORNL can also expect to be prominent in nuclear energy development for the future if we remain alert to the opportunities for making nuclear energy a more acceptable option for generating electricity at home and throughout the world. ornl



take a number

By V. R. R. Uppuluri

Double-Digit Pairs and Inversions with Same Product

Certain pairs of positive integers with two digits have an interesting property when they are multiplied together. Consider 12 and 84. The product of the two integers is also equal to the product of the inverted integers—that is, integers obtained by interchanging the digits. Thus, $12 \times 84 = 1008 = 21 \times 48$.

If all the cases in which inversion of the original pair gives an identical pair (e.g., $11 \times 11 = 11 \times 11 = 121$ and $13 \times 31 = 31 \times 13 = 403$) are excluded, only 14 pairs of two-digit integers yield the same product as their inversions.

Products Leading to Single Digits

Take any positive integer, such as 61324. Multiply all its digits: $6 \times 1 \times 3 \times 2 \times 4 = 144$. Take the resulting integer, 144, and multiply all the digits in it: $1 \times 4 \times 4 = 16$. Continue this process and obtain $1 \times 6 = 6$, which is a single digit.

No matter how many digits the initial integer has, you will always end up with a single digit in relatively few steps. Even if the initial integer has large digits, as in 679, a single digit can be obtained rather quickly. Thus, $679 = 6 \times 7 \times 9 = 378$; $3 \times 7 \times 8 = 168$; $1 \times 6 \times 8 = 48$; $4 \times 8 = 32$; $3 \times 2 = 6$.

The author does not know which of the ten digits (0, 1, 2, . . ., 9) winds up most frequently as the final digit when all positive integers are considered as initial integers. Perhaps a reader can come up with the solution to this relative-frequency problem.

Douglas L. Selby is coordinator of the Exploratory Studies (Seed Money) Program and member of ORNL's Program Planning and Analysis Office. Until recently, he was project manager of the Integrated Pressurized Thermal Shock (IPTS) Program sponsored by the Nuclear Regulatory Commission (NRC). A native of Knoxville, he holds an advanced degree in nuclear engineering from the University of Tennessee. He began work at ORNL in 1974 as a member of the Computer Sciences Division (now the Computing and Telecommunications Division) and, two years later, joined the Neutron Physics Division (now the Engineering Physics and Mathematics Division). He became involved in the design and development of light-water reactors and liquid-metal fast breeder reactors, including the Clinch River Breeder Reactor Project. In 1983 he started work on the IPTS Program. In 1985 he received a Martin Marietta Technical Achievement Award for Technical Excellence, and he is currently chairman of the Oak Ridge/Knoxville Section of the American Nuclear Society.

Pressurized Thermal Shock:
A Hot Issue for the Nuclear Industry?

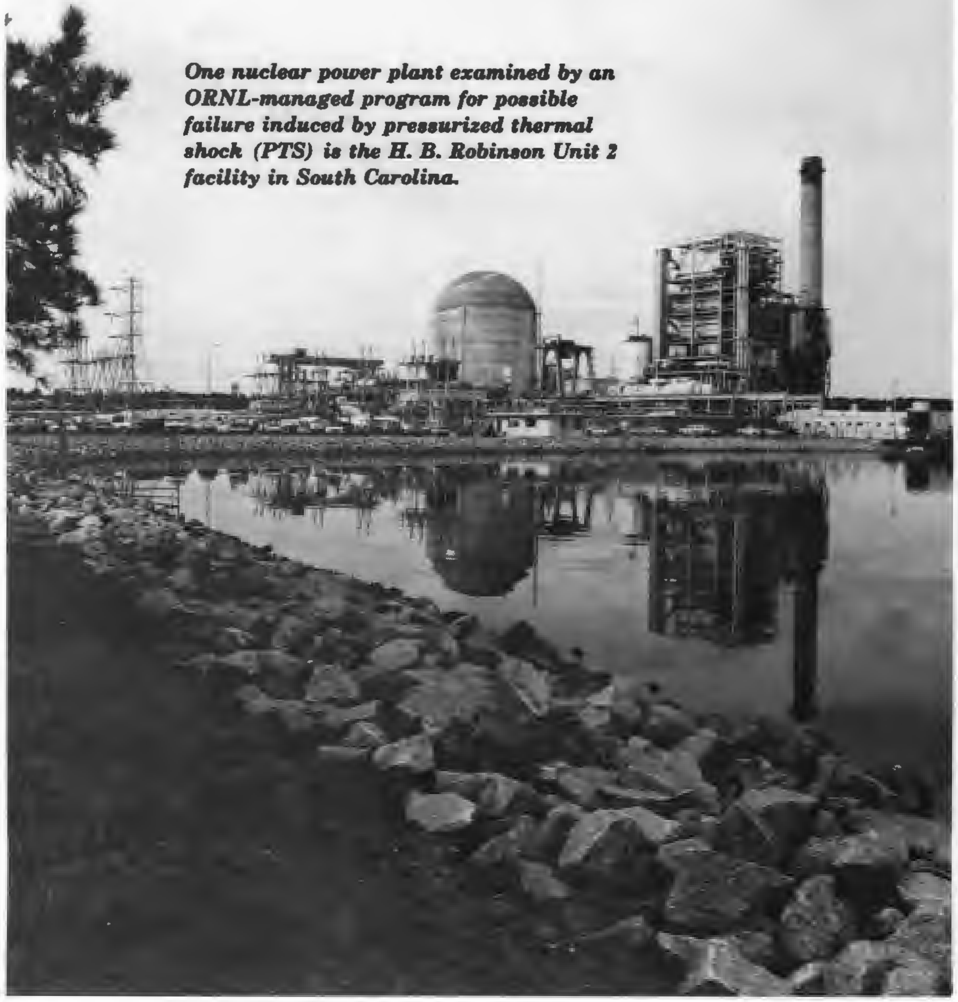
By DOUGLAS L. SELBY and RICHARD D. CHEVERTON

The reactor pressure vessel in a commercial pressurized-water reactor (PWR) plant contains the reactor core (fuel) and the coolant for removing heat from the core. A failure of the vessel could result in loss of the coolant, which, in turn, could lead to melting of the fuel and release of radioactivity to the environment. Thus, to ensure public health and safety and to protect the utilities' investment, the probability of vessel failure must be kept very small.

One of the important characteristics of the reactor vessel is its fracture toughness (the ability of a material to resist the propagation of a sharp crack-like defect). Reactor pressure vessels are carefully designed and fabricated according to the American Society of Mechanical Engineers Pressure Vessel Code, which takes account of, among other things, a reduction in the fracture toughness of the vessel material caused by neutron irradiation. To monitor the reduction of fracture toughness, surveillance specimens are included in the vessels of power reactors and materials-testing reactors to provide a check on the radiation-damage rate.

Some years ago it became apparent that the rate of radiation damage was greater than expected for vessel materials that contain "high" concentrations of copper, an impurity in reactor-vessel materials. Furthermore, reactor

Richard D. Cheverton has been studying the potential for thermal shock in pressurized-water reactors since 1974. He has been responsible for these studies as a part of the NRC-sponsored Heavy-Section Steel Technology (HSST) Program at ORNL. Cheverton came to ORNL in 1953 after earning a master's degree in mechanical engineering at the Georgia Institute of Technology. In 1956 he completed his course of study at the Oak Ridge School of Reactor Technology at ORNL. As a long-term member of the Engineering Technology Division (previously the Reactor Division), he devoted much of his time to analyzing, designing, and developing reactor components. Cheverton was responsible for the design of the nuclear part of ORNL's High Flux Isotope Reactor (HFIR) and helped prepare proposals for more advanced research-reactor concepts, including the proposed replacement for HFIR—the Center for Neutron Research. Here, Selby (right) and Cheverton examine a flawed vessel that cracked at water pressures three times the design pressure in a series of experiments conducted by the HSST Program in the 1970s.



One nuclear power plant examined by an ORNL-managed program for possible failure induced by pressurized thermal shock (PTS) is the H. B. Robinson Unit 2 facility in South Carolina.

The results of a large study managed by ORNL indicate pressurized thermal shock may not be a problem at three commercial nuclear power plants. Thus, the possibility that the nuclear industry would be required to invest millions of dollars in vessel annealing or other expensive mitigating measures for these three plants may have been avoided.

events that cause an abnormal drop in the temperature of the primary system have been occurring more frequently than anticipated. Many of these events subject the vessel to rapid cooling as well as high pressure. This rapid cooling in PWRs under pressure conditions has come to be known as *pressurized thermal shock* (PTS) because of the thermal and pressure stresses induced in the vessel wall. The thermal stresses occur as a rapid drop in coolant temperature produces a large difference between the temperatures of the inner and outer wall surfaces of the vessel.

As a result of the growing awareness of the effect of copper on radiation damage to reactor vessels and the increasing number of events (transients), the PTS issue attracted increasing attention and in December 1981 was declared an unresolved safety issue by the U.S. Nuclear Regulatory Commission (NRC). The PTS issue concerns the possibility of failure of a PWR pressure vessel as a result of the combined effects of (1) pressure and thermal-shock loadings, (2) radiation damage to the vessel material, and (3) the existence of a sharp, crack-like defect (flaw) on the inner surface of the vessel. Because of the cumulative effect of radiation damage, the tendency for vessel failure increases with reactor operating time.

Thermal shock can contribute significantly to the possibility of vessel failure when surface flaws are present because the shock can induce relatively high tensile stresses and reduce fracture toughness near the inner surface, where the intensity of neutron irradiation is the greatest. This combination of conditions may lead to propagation of very shallow, preexisting, inner-surface flaws that are difficult to detect by inspection.

ORNL Leads PTS Studies

The behavior of flaws in reactor pressure vessels under pressure and thermal-shock loading conditions has been under investigation at Oak Ridge National Laboratory since 1967 as a part of the ORNL-managed Heavy-Section Steel Technology (HSST) Program, now sponsored by the NRC.

From 1978 to 1981, HSST vessel-integrity studies related to postulated PWR transients and to actual PTS transients indicated that if such transients occurred late in the life of a high-copper vessel with appropriate inner-surface flaws, the chances of vessel failure could be high. However, these analyses were of a deterministic nature and were believed to be quite conservative—that is, they assumed a combination of a very severe PTS transient, high concentrations of copper, lower-bound fracture-toughness data, and flaws of appropriate size.

Because of the apparent conservative nature of ORNL's analytical approach, it was generally believed that the probability of vessel failure was actually very small. To obtain a better understanding of the nature and magnitude of the problem, the NRC proposed the development of a comprehensive probabilistic approach and in May 1981, established the Integrated Pressurized Thermal-Shock (IPTS) Program, managed by ORNL.

Major contributors to the program besides ORNL were Idaho National Engineering Laboratory (INEL), Los Alamos National Laboratory (LANL), Brookhaven National Laboratory (BNL), Pacific Northwest Laboratory (PNL), Science Applications International Corporation (SAIC), Purdue University, and three utilities (Duke Power, Baltimore Gas and Electric, and Carolina Power and Light). Besides the authors, ORNL employees who worked on the program were Jim White (Instrumentation and Controls Division), Tom Burns (Engineering Technology Division), Dave Ball (Computing and Telecommunications Division), George Flanagan, and Lorraine Abbott (Engineering Physics and Mathematics Division).

The IPTS Program examined the possible PTS-induced failure of the reactor vessels in three commercial PWR plants: the Oconee-1 reactor, designed by Babcock and Wilcox, Inc., and operated by Duke Power; the Calvert Cliffs-1 reactor, designed by Combustion Engineering, Inc., and operated by Baltimore Gas and Electric; and the H. B. Robinson-2 reactor, designed by Westinghouse Electric Corporation and operated by Carolina Power and Light.

These plants represent each of the major vendor types and were selected out of a group of plants considered by the NRC to have a potential PTS problem. With cooperation from each plant owner, repeated meetings were held between IPTS participants and plant engineering and operations staff members. As a result, the participants gained an improved understanding of the operating characteristics of each plant.

The scope of the IPTS Program included (1) the development of a methodology and models for estimating the probability of vessel failure and the uncertainty in the estimate, (2) an estimate of the probability of failure of the reactor pressure vessels in the three commercial PWR plants selected for evaluation, and (3) an assessment of the effects of proposed remedial measures to reduce the potential of PTS-induced vessel failures.

Two other nuclear power plants examined for possible PTS-induced failure are the Calvert Cliffs–1 reactor in Maryland (above) and the Oconee–1 reactor in South Carolina (right).

Estimating the probability of failure of the three PWR vessels involved (a) postulation of PTS transients, (b) an estimate of their frequencies, (c) a systems analysis of each transient to determine temperatures and pressures, (d) a probabilistic fracture-mechanics analysis that uses the results of the systems analysis as input, and (e) a means of combining uncertainties across multiple disciplines. The probabilistic fracture-mechanics analysis provides an estimate of the conditional probability of vessel failure, $P(F|E)$. This estimate can be multiplied by the expected frequency of the corresponding transient, $\Phi(E)$, and the products for all postulated transients can be summed to obtain the total estimated probabilistic risk of vessel failure, $\Phi(F)$, for a specific plant. The individual products are also of interest because they help indicate the extent to which individual transients contribute to $\Phi(F)$.

Before the IPTS Program was established, the NRC, with the help of ORNL and others, estimated the frequency of vessel failure as a function of accumulated radiation

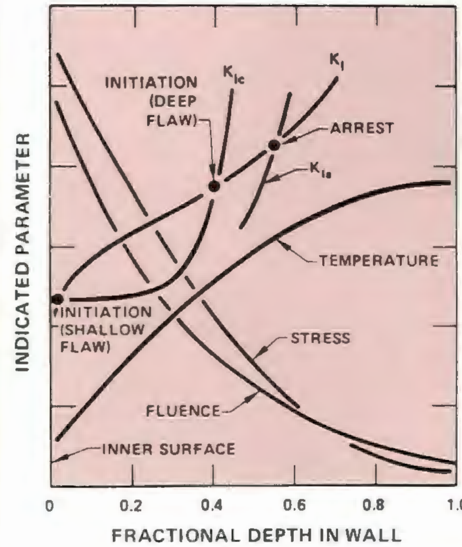
damage, which is characterized by a material property referred to as the (RTNDT). (RTNDT is a function of material chemistry and fast-neutron fluence and can be calculated by using empirically derived correlations.)

The NRC proposed the development of screening criteria that would include a maximum value of RTNDT that corresponded to a maximum acceptable risk of vessel failure. Those plants exceeding the RTNDT screening value would then be required to perform a detailed plant-specific analysis to determine if continued operation of the plant would represent an unacceptable risk. Therefore, objectives of the IPTS Program included developing a methodology for the plant-specific analysis and providing information to the NRC that could be used to assess the validity of the proposed screening criteria. The methodologies developed and the results obtained from the IPTS Program for the specific plants are documented in three reports: NUREG/CR-37701 (Oconee), NUREG/CR-40222 (Calvert Cliffs), and NUREG/CR-41833 (H. B. Robinson).

Probabilistic Fracture Mechanics

The behavior of flaws in reactor pressure vessels can be evaluated by applying the theory of fracture mechanics, which characterizes conditions at the tip of the crack by means of a stress-intensity factor, K_I, that increases with increasing load (stress) and size of the flaw. In addition, a critical value exists for a given material and temperature at which propagation of the flaw will take place (K_{Ic}). At another value (K_{Ia}) a fast-running crack will arrest.

K_{Ic} and K_{Ia}, which constitute fracture-toughness properties of the material, are measured in the laboratory over a range of temperatures and fast-neutron fluences. Both K_{Ic} and K_{Ia} increase with increasing temperature and decrease with increasing fast-neutron fluence. In a reactor pressure vessel the fast-neutron fluence decreases with increased penetration into the wall. In addition, during a thermal-shock transient a positive gradient in temperature occurs through the wall—that is, the temperature of the wall is incrementally higher toward the outer surface because of



Radial distribution of PTS fracture-mechanics-related parameters in the wall of a reactor pressure vessel in a pressurized water reactor.

the rapid cooling of the inner surface. Thus, during PTS transients, positive gradients in fracture toughness occur in the wall of the vessel—that is, fracture toughness is lower near the inner surface and is highest at the outer surface. Positive gradients favor the propagation of shallow inner-surface flaws and the arrest of an initially shallow fast-running flaw.

A positive gradient also tends to occur in K_I, and for a given thermal transient, the higher the pressure, the steeper the gradient and the smaller the chances of crack arrest. Thermal shock alone will not normally drive the flaw completely through the wall, but a full-pressure PTS transient can. Thermal shock alone, however, can drive a flaw deep enough into the wall so that the vessel would not be usable thereafter without repair.

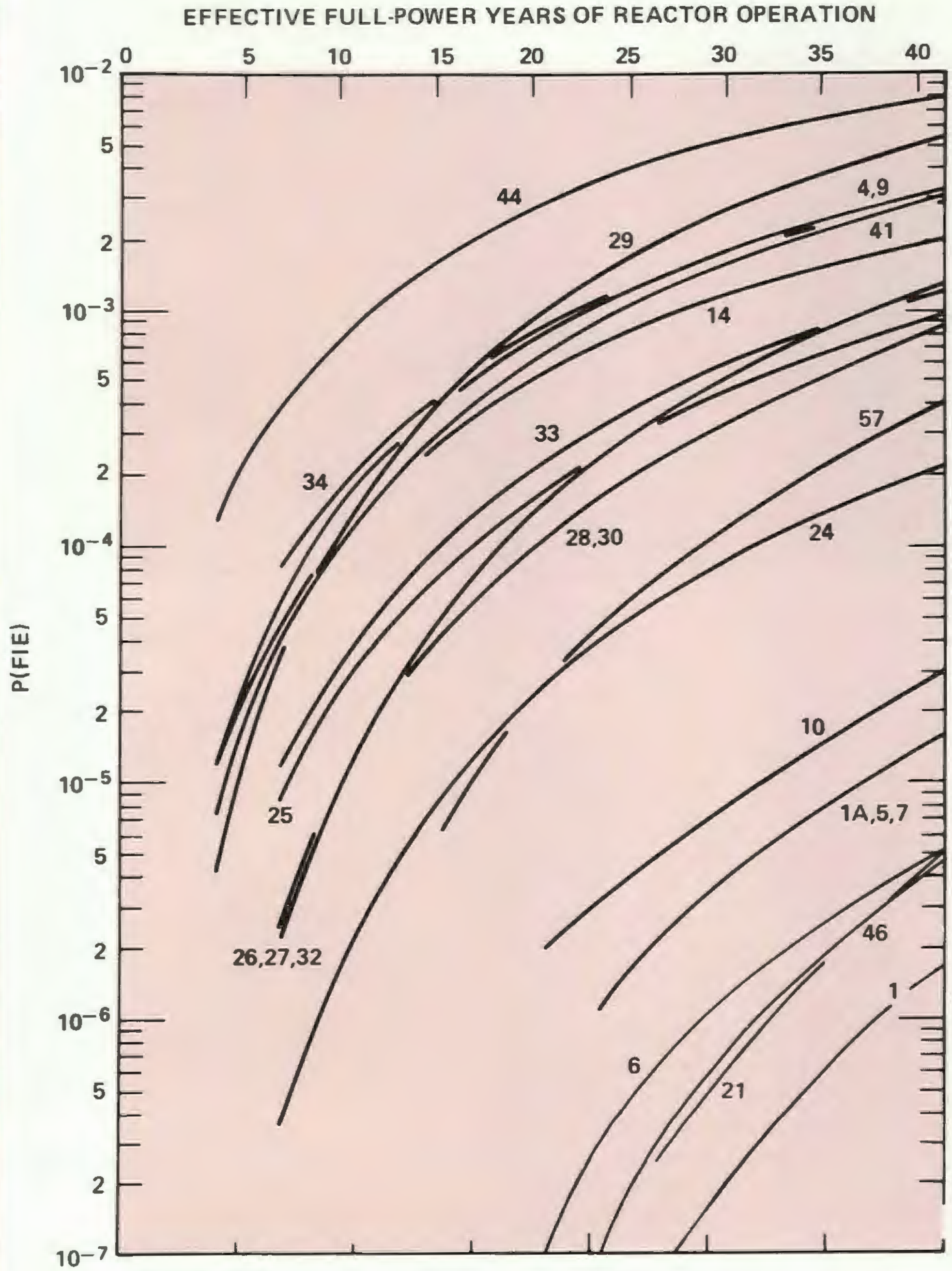
A deterministic fracture-mechanics analysis involves the calculation of K_I and then a comparison of K_I with K_{Ic} to determine whether propagation will take place; if it does, K_I is compared to K_{Ia} to see if arrest will take place. By repeating this process for a range of crack depths and a number of times in the transient, it is possible to determine whether failure of the vessel will occur.

As previously mentioned, K_{Ic} and K_{Ia} are functions of temperature and fluence, and the effect of fluence is a function of the concentrations of copper and nickel. Significant uncertainties are associated with each of these parameters, as well as with the number and size of surface flaws. Thus, even if it is assumed that a particular PTS transient occurs, a probabilistic approach to the evaluation of vessel integrity is appropriate.

The probabilistic fracture-mechanics model used for the IPTS studies was developed at ORNL. Based on Monte Carlo techniques, the model simulates a large number of vessels and subjects each vessel to a fracture-mechanics analysis to determine whether the vessel will fail. Each vessel is defined by randomly selected values of the several parameters that are judged to have significant uncertainties. The calculated probability of vessel failure is simply the number of vessels that fail divided by the total number of vessels simulated. It is a conditional probability of failure because the assumption is made that the PTS transient (event) takes place.

In connection with the IPTS Program, ORNL researchers Cheverton and Ball were responsible for estimating the probability of a flaw propagating through the wall of the vessel. A failure of this type would not necessarily result in an inability to adequately cool the core; thus, an additional analysis was required to estimate the probability of core melt. Such an analysis was performed by PNL, which found that if full penetration of the vessel wall were achieved, the probability that the opening would be large enough to preclude adequate cooling of the core is approximately 0.5 (i.e., one potential core melt out of two vessel failures involving full penetration of the wall).

As discussed in greater detail later, the IPTS studies postulated literally hundreds of thousands of PTS transients for the three nuclear plants under consideration. Probabilistic fracture-mechanics calculations were made for approximately 200 typical transients for each reactor. Because of the wide variation in the apparent severity of the transients, the calculated values of P(F|E) had



P(F|E) vs years of operation for selected posulated PTS transients (numbers identify transient).

a broad range, and P(F|E) for all cases increased as plant operating time was accumulated.

Postulation and Frequency of PTS Transients

Values of P(F|E) by themselves are not particularly informative because they do not tell how often transients might occur nor help identify potential transients. Thus, before performing the probabilistic fracture mechanics analysis, it was necessary to postulate PTS transients and eventually to estimate their potential frequency. ORNL developed a systematic means of identifying transients that provides a high degree of assurance that important transients are not overlooked.

Postulation of PTS transients begins with the identification of plant states that could constitute such transients. Next, initiating events that could lead to these plant states are identified, and event trees are constructed to represent the series of paths leading from initiating event to plant state. Using plant-specific, vendor-specific, and/or generic PWR data, frequencies of occurrence are assigned to each branch of a tree. Branches with frequencies less than a specified amount are placed into one or more groups that are intended to contribute little to the overall frequency of failure, $\Phi(F)$, and therefore are treated as a "group" rather than as individual transients in the remainder of the analysis. Each of the remaining branches is subjected to detailed thermal-hydraulic and then fracture-mechanics analysis to obtain an estimate of the conditional probability of vessel failure, P(F|E). For the IPTS Program about 200 end states (transients) for each of the three plants were subjected to the detailed analysis, and the cutoff frequency used in the analysis was 10^{-7} per year.

Postulating and quantifying PTS transients requires the evaluation of direct and indirect coupled failures that could result from failures in support systems, such as the electrical power supply, instrument air, or component cooling-water systems. In addition, it is necessary to evaluate the operator's role and the potential for failure of the operator to perform as required.

The use of the systematic approach described above for postulating and quantifying PTS transients led to very large event trees for the IPTS studies, with a total of several hundred thousand end states (transients). The inadvertent-reactor-shutdown tree alone had over 130,000 end states. Of course, a large number of event-tree end states does not by itself necessarily ensure a low probability that important transients were overlooked. However, we believe that the overall systematic approach for postulating transients for the IPTS studies is reasonably thorough.

Thermal-Hydraulic Analysis of PTS Transients

Once a PTS transient is postulated, a detailed systems (thermal-hydraulic) analysis must be performed to obtain the reactor primary system pressure and coolant temperature along the inner surface of the reactor pressure vessel wall as a function of time in the transient. This information is then used as input to the ORNL fracture-mechanics analysis to obtain estimates of P(F|E).

The systems analysis for the IPTS studies is quite complex and required the revision of existing systems codes (TRAC and RELAP5) and the development of appropriate models. Using actual plant data, LANL and INEL developed and validated the models and then performed the detailed thermal-hydraulics systems analyses for various categories of PTS transients. SAIC and INEL developed and used simpler models to interpolate and extrapolate the LANL and INEL results to a larger number of specific transients.

Within the reactor primary system a mixing of cold and hot water can influence the severity of the thermal shock to the pressure vessel. In mixing studies conducted at Purdue University and LANL using both experimental and analytical approaches, it was determined that for most postulated PTS transients, spatial variations in coolant temperatures along the inner surface of the reactor pressure vessel wall were negligible. As a result, the study participants were in most instances able to avoid the complexity that two- and three-dimensional models would have added to the thermal-hydraulic and fracture-mechanics analysis.

Results of IPTS Studies

As mentioned earlier, the overall estimated probabilistic risk of vessel failure for a specific plant is obtained by summing the estimated failure probabilities for each of the postulated transients. Based on the completed calculations performed for the three plants included in the IPTS studies, it appeared that the screening criteria previously proposed by the NRC were appropriate and that the three plants would not be limited within their normal design lifetime (32 effective full-power years).

The uncertainty analysis performed for the IPTS studies and included in the above evaluation indicated an upper bound (99%) uncertainty factor for $\Phi(F)$ of about 10^3. This uncertainty value was determined by using Monte Carlo analysis in which each variable (temperature, pressure, initiating event, and branch-point probabilities, flaw density, etc.) was treated as a distribution. The two largest contributors to the uncertainty were the number of flaws in the pressure vessels and the temperature of the coolant at the inner surface of the pressure vessel wall.

The IPTS studies also provided insights into the importance of different plant design and operating characteristics. Knowing the relationship between various characteristics and risk may eventually provide a means for identifying plants that might be particularly susceptible to vessel failure from PTS transients.

The study identified 10 plant features (no plant had all 10) that may contribute to raising or reducing the PTS risk, depending on design and operation. The features are

- number of plant loops,
- high-pressure injection (HPI) shutoff head,
- main steam isolation valve operation,
- vent valve operation,
- isolation of auxiliary feedwater (AFW) during steam-line break events,
- size of steam generator,
- charging system operation,
- AFW flow rate,
- control system response, and
- steam-line flow restrictors.

Design differences between plants, as associated with these features, were largely responsible for the plants having different risk values and different dominant PTS transients.

At Oconee, the presence of vent valves in the core barrel enhances coolant mixing along the inner surface of the pressure vessel and, thus, greatly reduces the potential of isolated cold spots associated with HPI flow following a small-break loss of coolant accident (LOCA). As a result, the potential is reduced for large thermal stresses that would occur if the cold HPI water contacted the vessel wall without being mixed with the warmer coolant stream. For Oconee, then, the large steam-line-break class of transients was predicted to be the largest contributor to the total estimated probability of vessel failure caused by PTS events, particularly when the auxiliary feedwater system is allowed to overfeed. The auxiliary feedwater system overfeed can be particularly important in generating thermal stresses because the system is somewhat overdesigned and can, therefore, supply large quantities of cold water.

At Calvert Cliffs, the automatic steam-generator isolation system and the presence of main steam isolation valves diminished the risk of a large steam-line break. However, the lack of vent valves and the lower HPI pressure were calculated to lead to loss of mixing of HPI water with the warmer cold leg water for the small-break LOCA event under certain conditions. These conditions included a specific range of break sizes and low decay heat, which decreased the driving force of natural circulation, thus increasing the potential for loss of mixing. This situation would lead to

Table 1. Comparison of final through-wall-crack (TWC) probabilities by initiator type

Initiator type	Final TWC frequency (%) Oconee	Calvert Cliffs	H. B. Robinson
Steam line break			
Large at full power	20	<1	5
Large at low decay heat	<1	<1	<1
Small at full power	13	<1	81
Small at low decay heat	<1	7	<1
LOCAs			
Small at full power	<1	<1	4
Small at low decay heat	NA	67	<1
Medium at full power	<1	<1	<1
Medium at low decay heat	NA	20	<1
Steam generator overfeed	<1	<1	<1
Tube rupture	<1	NA	<1
Residual	67	2	6
Total	100	100	100

Table 2. Comparison of the impact of potential mitigation measures

Potential mitigation measure	Q(F) reduction factor		
	Oconee	Calvert Cliffs	H. B. Robinson
Reduction in fluence rate			
Factor 2	0.48	0.14	0.15
Factor 4	0.16	0.02	0.05
Factor 8	0.07	0.007	0.03
Limit on repressurization	0.02	NA	NA
Annealing at 9 effective-full-power years	0.54	0.54	0.1
Heating HPI water to 100°F	0.9–1.0	0.31	NA

isolated cold streams that approach the temperature of the HPI water. Thus, the low-decay-heat LOCA events were predicted to be the dominant PTS transients for Calvert Cliffs.

In the case of H. B. Robinson, the design of the HPI system averted complete loss of mixing (and isolated cold spots) for the small-break LOCA events. In addition, a large steam-line break on a single line of H. B. Robinson's three-loop design would involve only one-third of the secondary coolant; the same event on the two-loop plants, however, would involve half of the secondary coolant. Thus, less heat would be removed from the primary system in the three-loop design than in the two-loop design, greatly reducing the PTS-related impact of a large steam-line break on a single line. However, because of the additional loop, the three-loop design has additional steam-line relief valves, thus increasing the probability that the design will undergo multiple valve failures. As a result, events in which atmospheric dump valves or turbine-bypass valves on multiple lines fail to close were predicted to be the dominant type of PTS transients for H. B. Robinson.

Mitigation Measures

As part of the IPTS Program, ORNL identified and evaluated the impact of remedial measures for reducing PTS risk. Four mitigating actions were identified for analysis: reducing the neutron fluence rate to decrease the rate of radiation damage, heating the HPI water to reduce the thermal stress associated with certain transients, annealing the vessel to increase the fracture toughness, and limiting the primary system repressurization to decrease the pressure stress associated with certain transients. (These proposed actions were not, and should not be, construed as recommendations, because their safety impacts on other types of events were not determined and the cost-benefit ratio was not evaluated.)

The IPTS evaluation of the effect of fluence reduction was particularly important, because fluence reduction was thought to be the most cost-effective means of reducing the PTS risk. Reducing the fluence rate early in the life of the vessel, before substantial radiation damage has taken place, is advisable. What is not so obvious is that the benefit in reducing the fluence rate is also dependent on the severity and frequency of the dominant transients. The effect of the differences in dominant transients is reflected in the plant-to-plant variations.

Summary

By integrating the disciplines of probabilistic risk analysis, thermal-hydraulics analysis, and probabilistic fracture-mechanics analysis, as well as by adopting a common technique for assessing uncertainties and sensitivities across these disciplines, ORNL has supplied the NRC with a comprehensive probabilistic methodology for evaluating the PTS issue. In addition, the three-plant analyses have provided the NRC with a clearer understanding of the total aspect of the PTS problem and have led the NRC to conclude that the screening criteria are valid. In particular, the uncertainty analysis presents an attempt to rigorously adopt a consistent and mathematically sound approach to the problem of uncertainties in a probabilistic study of this type.

In September 1985 the NRC issued a PTS rule. The *Regulatory Guides* that accompany this rule refer to the ORNL reports for both the structure and methodology of performing an IPTS analysis if such an analysis of a particular plant is deemed necessary by the NRC.

In short, the results of the IPTS study indicate to the NRC that PTS may not be a problem for the three plants examined. Our best estimates of the probabilities of through-the-wall cracking at Oconee, Calvert Cliffs, and H. B. Robinson are substantially lower than the proposed NRC safety goal. Thus, the possibility that the nuclear industry would be required to invest millions of dollars in vessel annealing or other expensive mitigating measures for these three plants may have been avoided. ornl

Anthony P. (Tony) Malinauskas is director of Nuclear Regulatory Commission (NRC) programs at ORNL. In 1985 he received the prestigious Ernest Orlando Lawrence Memorial Award from the Department of Energy for his outstanding contributions to the analysis of the movement of fission products in light-water reactors. His studies helped explain why radioactive iodine releases after the 1979 accident at the Three Mile Island (TMI) Nuclear Power Plant were smaller than expected. For this work he also received in 1981 an American Nuclear Society Special Award for Advancement in Nuclear Technology in Response to Three Mile Island. As a member of several organizations, he has also contributed to the TMI recovery operation. A native of Ashley, Pennsylvania, he holds a Ph.D. degree

Reactor Safety Research:

NRC Programs at ORNL

By ANTHONY MALINAUSKAS and SUSAN WINSLOW

The U.S. Nuclear Regulatory Commission (NRC) regulates civilian activities involving use of nuclear materials and facilities to ensure protection of the health and safety of the general public. Many NRC regulatory decisions are based on technical information developed by NRC programs at Oak Ridge National Laboratory.

To help determine whether NRC reactor safety regulations need to be strengthened, ORNL researchers have studied such problems as the conditions that could lead to reactor vessel failure and the chemical fate of fission products during reactor accidents. ORNL is also engaged in research related to the NRC's interest in extending the operational life of today's nuclear power plants beyond their design life.

NRC regulatory decisions are based on technical information generated by many institutions, including ORNL. ORNL's work on fission products is expected to heavily influence the NRC's upcoming policy statement on severe reactor accidents that involve core damage. ORNL can expect to do an increased amount of research related to extending the operational life of existing nuclear power plants.

About 130 staff members from twelve ORNL divisions are currently involved in NRC work, which constitutes about 7% of ORNL's budget, or put another way, 25% of ORNL's non-DOE funding. The FY 1986 budget for NRC programs at ORNL is $24 million. Highlights from the past several years are summarized here.

Advances in Fracture Mechanics

The Heavy-Section Steel Technology (HSST) Program, which is managed by Claud Pugh of the Engineering Technology Division (ETD), addresses light-water in physical chemistry from the Massachusetts Institute of Technology. He joined ORNL's research staff in 1962 and headed the Chemical Development Section of ORNL's Chemical Technology Division from 1973 to 1983. He serves on the editorial board of *Separation Science and Technology* and is president-elect of the Oak Ridge Chapter of Sigma Xi.

Susan Winslow has been technical assistant for NRC programs at ORNL since February 1984. She holds an M.S. degree in microbiology from the University of Tennessee at Knoxville. Before coming to ORNL in 1976, she served as research assistant in UT's Department of Microbiology. At ORNL she first worked as an information analyst at the Toxicology Information Response Center and then, in the fall of 1979, she became the center's director.

E. L. Biddle (left) and H. D. Haynes (right) of ORNL's Engineering Technology Division and R. C. Kryter of the Instrumentation and Controls Division are evaluating the diagnostic capabilities of a variety of sensors for motor-operated valves. This study will lead to improved methods for detecting age-related defects and monitoring wear over time in motor-operated valves in nuclear power plants.

reactor (LWR) pressure vessel integrity under accident scenarios, including pressurized thermal shock (PTS) events. In addition to Pugh, key technical participants at ORNL include Grady Whitman, Bob Bryan, Dick Cheverton, and John Merkle, all of ETD, Randy Nanstad and Bill Corwin of the Metals and Ceramics Division, and Richard Bass of the Computing and Telecommunications Division (C&TD). Subcontracts with one university, three industrial organizations, and the National Bureau of Standards (NBS) complement the ORNL activities.

Central to this work is an understanding of conditions that would initiate the growth of an existing flaw in a reactor pressure vessel, as well as conditions that would lead to the arrest of a moving crack. The behavior of cracks in the wall of a reactor pressure vessel during rapid cooling while under pressure is of special concern, and results from HSST tests have provided data for evaluating methods of fracture mechanics analysis and for confirming safety margins that have been set. (In the previous article in this issue, Doug Selby and Dick Cheverton address contributions of the HSST Program to the PTS issue.)

A significant recent accomplishment was the completion of the fourth wide-plate crack-arrest test by ORNL and NBS researchers at the NBS large tensile test facility in Gaithersburg, Maryland. These experiments used very large specimens (1 m^3) to demonstrate arrest of a running crack at temperatures and under loading conditions that are far above those at which current safety assessment code rules assume arrest can occur. These results support the position that the fracture assessment criteria currently employed are conservative.

Computer codes developed by Cheverton and Bass for fracture mechanics analysis are widely used. These include a series of programs for performing deterministic and probabilistic elastic PTS fracture mechanics analyses and programs for performing three-dimensional elastic and elastic-plastic fracture mechanics analyses for combined pressure and thermal loads.

The HSST Program has provided data and recommendations for the development of important standards, such as those issued by the American Society for Testing and Materials, and code rules, such as those promulgated by the American Society of Mechanical Engineers. In addition, the program has made significant contributions to various nuclear regulatory guides issued by the NRC. The HSST Program staff members have also served as consultants to the Advisory Committee on Reactor Safeguards and on special NRC Task Groups charged with developing regulatory solutions to generic safety issues.

Aging and Defect Characterization in Motor-Operated Valves

Today's nuclear power plants were designed to have an operating life of about 30 to 40 years. Recently, it has become evident that refurbishing and continuing to operate these plants would cost less than decommissioning them and replacing them with new ones. Because of this economic incentive, the NRC and utilities are becoming increasingly interested in extending the operational life of existing nuclear power plants beyond their original design life.

These plants are, however, licensed to operate for only their design life. Extending their licensing periods will require a technical basis for evaluating whether the refurbished plants can meet new, more stringent safety requirements. Efforts are under way at ORNL to improve the capability of detecting defects made worse by aging as well as service-wear degradation of nuclear plant safety equipment. The goal of this work is to allow utilities to detect and repair or replace faulty equipment before a serious failure occurs.

One important component of nuclear power plants is the motor-operated valve. Following a strategy defined by the NRC's Nuclear Plant Aging Research Program, Dave Eissenberg's group in ETD has assessed motor-operated valves (MOVs) from the standpoint of design features, operating experiences, and maintenance practices. With help from the Instrumentation and Controls (I&C) Division, the group is using an instrumented MOV test stand that was built specifically to study methods for detecting and monitoring degradation of MOVs.

Through these studies, the ORNL group hopes to develop cost-effective methods of detecting wear in MOVs and of predicting how much worse it will become over time and when maintenance or replacement will be required. Such information should help maintain the readiness of safety systems in nuclear power plants.

Surveillance and Noise Diagnostics Research

Since 1963 I&C has been developing surveillance and diagnostic methods based on noise analysis. Because of this expertise, the NRC relies on ORNL for noise diagnosis research and for assistance in diagnosing specific reactor problems.

In 1975, for example, Dwayne Fry and his colleagues were asked by the NRC to investigate the cause of excessive noise in the output of in-core neutron detectors in one class of boiling-water reactors (BWRs). It had come to the NRC's attention that an annual inspection at a foreign BWR of the same class had disclosed a hole in a fuel channel box. The hole was caused by vibration of the instrument tube used to house the in-core neutron detectors. Because holes in the channel box reduce fuel rod cooling and because the box fragments could block coolant flow in the primary system, the NRC was concerned that this problem could lead to overheating of the fuel—a serious reactor safety problem.

The NRC could have ordered the ten U.S. plants that were affected to shut down until the problem could be solved. Instead, it allowed the plants to operate at reduced power because the ORNL diagnosis

James R. Travis checks ORNL's vertical furnace fission product release apparatus used to study the chemical fate of fission products from fuel rods under accident conditions.

had shown that the seriousness of the vibrations could be monitored by analysis of the neutron-detector noise. This decision to keep the plants operating resulted in significant savings. If the plants had been shut down, the affected utilities would have lost an average of $1 million per day in revenue from each plant.

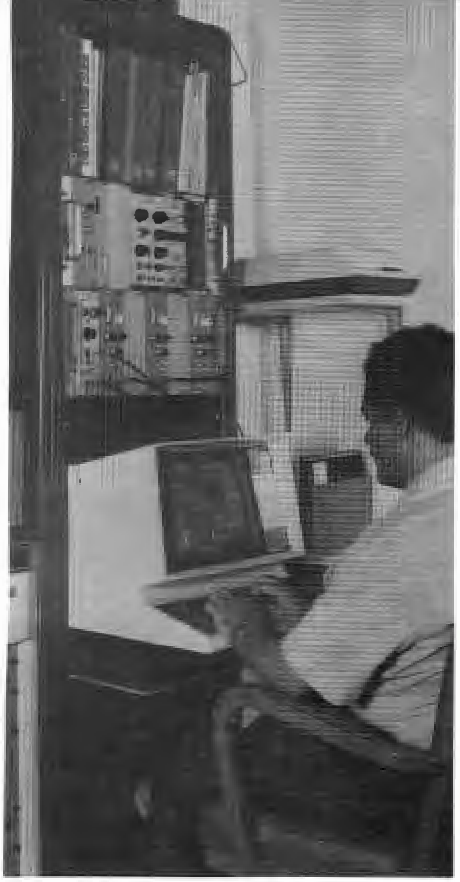
Recently, a two-year demonstration of a prototype on-line surveillance system, based upon noise diagnostics and developed by the I&C Division, was completed at the Sequoyah Nuclear Plant, a 1150-MW(e) pressurized water reactor (PWR) owned and operated by the Tennessee Valley Authority (TVA). A data set of unprecedented detail and completeness was compiled, forming the basis for a number of technical reports, conference papers, and journal articles dealing with the potential application of this technology to the detection of failures in PWRs at an incipient stage and with the behavior of smart surveillance computers that learn from and adapt to the data being monitored. Because of success in this initial endeavor, I&C has prepared a companion demonstration of an upgraded system—one having some diagnostic as well as surveillance capabilities—at the Peach Bottom Nuclear Plant, a 1065-MW(e) BWR near Philadelphia. Data acquisition is currently under way.

New Instruments, New Materials

In the fall of 1977, the United States, Japan, and the Federal Republic of Germany agreed to conduct a joint research program to increase understanding of refill-reflood phenomena during loss-of-coolant accidents in PWRs. Meyer Herskovitz's staff from the Advanced Instrumentation for Reflood Studies Program at ORNL was charged with developing instrumentation that could survive the hostile environments in the refill-reflood tests. Film probes were designed to measure film thickness, film velocity, and film wave velocity on surfaces, and electrical impedance sensors were developed to sense in-vessel two-phase parameters, in particular temperature, void fraction, and flow velocity. The sensors had to withstand relatively short-term exposure to 800°C steam and long-term exposure to 200 to 300°C steam. Probe integrity had to be maintained through repetitive thermal transients of 300°C/s.

These instruments required a unique ceramic-to-metal (cermet) seal system, which was developed at ORNL. After finding that no commercial insulating material met the steam compatibility, impermeability, and thermal shock requirements, the ORNL staff also invented a ceramic insulator. The development by ORNL of several other techniques and procedures, including laser welding techniques, induction brazing, and furnace brazing, were also required to complete the fabrication of the specialized sensors.

The ORNL instruments have been placed in four test facilities—three in Japan, operated by the Japanese Atomic Energy Research Institute, and one in the Federal Republic of Germany, operated by Kraftwerk Union. The instrumentation has provided useful data during refill-reflood experiments. In fact, it has obtained the first-ever measurements of two-phase flow velocity in an electrically heated core. This new class of robust sensors may eventually lead to better techniques for monitoring commercial PWRs.



Charlie Webster operates the multichannel analyzer and gamma detector to identify and quantify fission products released from irradiated segments of fuel rods similar to those used in light-water reactors.

Severe Accident Sequence Analysis in BWRs

The Severe Accident Sequence Analysis Program at ORNL, directed by Steve Hodge of ETD, has completed detailed studies of five BWR accident sequences, resulting in recommendations for improvements in system design, emergency procedures, and operator training. The studies, which involved the Chemical Technology Division (CTD), I&C, and C&TD as well as ETD, concerned Unit 1 of TVA's Browns Ferry Nuclear Plant, a BWR with a containment design typical of most BWRs in operation today. An important byproduct of this study has been the development, modification, or improvement of several computer codes that are used in reactor accident analysis. For example, BWR-LTAS, which was developed at ORNL by R. M. Harrington, is proving to be a practical severe-accident analysis tool for examining that portion of an accident sequence that occurs before severe core damage and, in particular, for evaluating plant response to operator actions during this phase of an accident.

ORNL investigators have also been continuously updating the MARCH code, one of the more important tools used in performing severe accident analyses. (The original version of this program applies strictly to PWRs, but the ORNL version is tailored specifically for BWR analysis.) Nine model improvements, including straightforward modeling of explicit BWR features not found in original MARCH models, have been included.

Fission Products and Reactor Accidents

Regulators of nuclear power plants have long been interested in detailed information on the "source term"—the amount and type of radionuclides that might escape from nuclear power plants into the environment because of an accident. ORNL has made important contributions to the understanding of the source term.

Morris Osborne, Dick Lorenz, and Jack Collins of CTD's Fission

Product Release Program have provided significant new information about the chemical forms of fission products and their behavior following release from LWR fuel under accident conditions. This research program is unique in that real, irradiated LWR fuel rods are used in the experimental studies. The tests performed so far have been conducted over the temperature range of 500 to 2000°C and in three different test atmospheres: dry air, inert gas, and steam-helium mixtures.

The tests in inert and steam-helium atmospheres clearly indicated that iodine was not released from the fuel rods as molecular iodine, as had been assumed previously in the NRC's Reactor Safety Study (WASH-1400), but rather as a considerably less volatile iodide species, probably cesium iodide.

The most recently conducted tests overwhelmingly confirmed that iodine was being released as a less volatile species. In the six high-temperature tests with highly irradiated fuel, up to 53% of the iodine inventories of the fuel were released. The largest percentage of the iodine released and collected as molecular iodine was <0.5%; in most tests it was <0.1%. When total iodine for all tests conducted in steam was considered, the bulk behaved like cesium iodide, with only 0.34% collected as molecular iodine. The cesium iodide was very stable and showed little tendency to react with or be decomposed by zirconium oxide, stainless steel, or quartz surfaces of the experimental apparatus.

These experimental results and the less-than-expected release of radioactive iodine (15 Ci) observed in the 1979 accident at the Three Mile Island (TMI) Nuclear Power Plant have prompted the NRC and the industry to reexamine the source term question. ORNL results are expected to influence the NRC's upcoming policy statement on severe reactor accidents involving core damage.

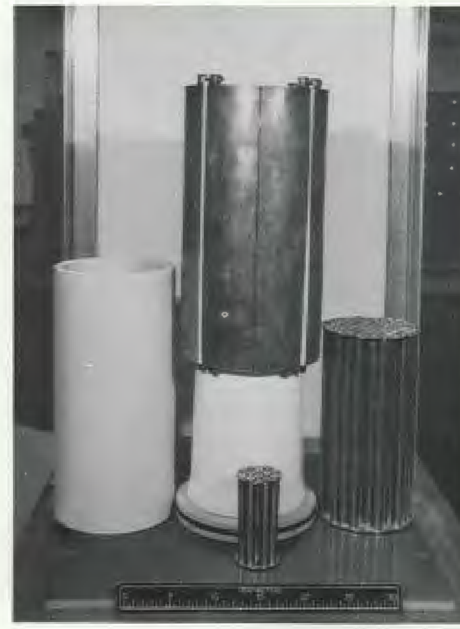
Hard Alloy from Melted Core

The 10-kg Core Melt Facility operated by George Parker of CTD is a unique new facility for studying mechanisms for retention and release of fission products and aerosols under core meltdown conditions. The test assembly uses a 62-rod bundle of unirradiated fuel and control rods, each 26.7 cm (10.5 in.) long, that can be heated to complete melting (2400°C) in a flowing steam atmosphere.

During the first heatup to 1100°C of a bundle, a mock PWR control rod failed, allowing the release of the silver, cadmium, and indium control rod alloy in aerosol form. Examination of the test assembly afterward revealed that an extremely hard, low-melting eutectic alloy had formed between the stainless steel cladding of the control rod and the Zircaloy in the surrounding sheath.

Previously it was thought that the stainless steel claddings of PWR control rods failed at a considerably higher temperature (about 1400°C) as a result of the high pressure exerted by the cadmium in the alloy. Subsequent to Parker's observation, a similar failure of a control rod at low temperature occurred at the Power Burst Facility in Idaho; simultaneously, large amounts of cadmium were released. Parker duplicated the low-temperature failure and simultaneous cadmium release from the control rod alloy in a second test in the Core Melt Facility. Thus a new mechanism for control rod cladding failure in PWRs was identified.

When Parker tried to obtain a portion of the newly observed eutectic for physical characterization, he found that the material possessed a hardness approaching that of metallic tungsten; diamond abrasive was required to remove a sample. Because the experimental conditions leading to the formation of the eutectic were similar to those experienced within the core region of the TMI reactor during the course of the 1979 accident, this observation could have significant impact on the design of tools for core removal at TMI.



Relative scale of the Core Melt Facility furnace and two fuel rod bundles of different sizes (1-kg and 10-kg). This unique new facility is used to study core meltdown phenomena such as the mechanisms for retention and release of fission products and aerosols.

A Computer Model of Maintenance Personnel

Since the TMI accident, NRC human factors research has been directed primarily at operators; however, it was recognized that methods and techniques for analyzing and quantitatively predicting the performance of nuclear power plant maintenance personnel were also important. To this end, an Engineering Physics and Mathematics Division group

This experiment in the Core Melt Facility had graphic results. A bundle of uranium-oxide fuel rods was heated to 1800°C in the facility. As a result, the Zircaloy-clad fuel bundle was partially degraded, and "run-off candling" of a silver-alloy-Zircaloy intermetallic phase is evident at the bottom.

under the direction of Paul Haas and with the assistance of staff members from Applied Technical Associates, Inc., has developed a computer simulation model, Maintenance Personnel Performance Simulation (MAPPS).

MAPPS compares task difficulty with maintainance staff ability and estimates human performance probabilistically. It was designed to be rich in both input variables and output parameters. Information such as predicted errors, personnel errors, personnel requirements, stress and fatigue factors, performance time, and required ability levels for any corrective or preventive maintenance actions in nuclear plants can be obtained using MAPPS.

MAPPS is the first application of this type of human reliability modeling to nuclear power plants and is also an extension of state-of-the-art human reliability modeling. Analysis of collected model evaluation data, formal assessment of MAPPS, and feedback from participants at an NRC-MAPPS workshop and seminar indicate that MAPPS is a practical, acceptable, and useful tool for generating valuable performance data for a number of applications, including probabilistic risk assessment (PRA). Properly used, the human reliability data generated by MAPPS should prove to be an important contribution to efforts to improve reactor maintenance, as well as to studies aimed at minimizing risks associated with nuclear power plant operation.

Risk Studies Results and Inspection Decision Making

An innovative program started by George Flanagan of the Engineering Physics and Mathematics Division and JBF Associates, Inc., seeks to apply results of PRA studies to aid NRC inspectors in deciding how to allocate their time and resources to increase their effectiveness in limiting nuclear plant risks.

Because the total amount of PRA information is large but the amount needed for a particular decision is relatively small, a computer program, the Plant Risk Status Information Management (PRISIM) system, was chosen to catalog and present the needed PRA information. PRISIM is a decision-oriented, user-friendly computer program that tells an inspector the risk status of a plant given its current configuration. The program indicates whether certain systems are especially vulnerable because of the configuration. PRISIM will be installed on a personal computer at the Arkansas Nuclear One–Unit 1 Power Plant and at the NRC's Region IV headquarters in Arlington, Texas.

Study of Contamination from the Rancho Seco Plant

A series of events in 1984 at the Rancho Seco Nuclear Power Plant near Sacramento, California, resulted in the release of radioactive materials to the environment. Shortly thereafter, C. W. Miller and other staff members of ORNL's Health and Safety Research and Environmental Sciences divisions were asked to estimate the concentrations of radionuclides in the environment from Rancho Seco's liquid waste effluents and to estimate the radiation doses to which humans might be exposed. The NRC requested the study after preliminary analyses indicated that liquid effluent releases from the plant might have resulted in doses to the public that exceeded federal guidelines.

ORNL staff members made two visits to Rancho Seco in the fall of 1984 and conducted an environmental sampling program around the site. Although elevated levels of several radionuclides, mainly cesium-137 and cesium-134, were found in the immediate vicinity of the plant, the ORNL researchers concluded that the liquid effluent radionuclide releases from Rancho Seco posed no significant hazard to persons living near the site.

Modular Code System for Licensing Evaluation Analyses

Beginning in 1976, C&TD staff members and the NRC's Office of Nuclear Regulatory Research began a cooperative effort to develop an easy-to-use computational system that could provide the NRC with a tool for licensing evaluation of nuclear fuel facility and package designs. ORNL's development of SCALE (Standardized Computer Analyses for Licensing Evaluation) provided the NRC with state-of-the-art calculational tools in the

This recovered intermetallic residue from the base of the melt residue is an extremely hard material typical of what might be found after a core-damaging accident such as that at Three Mile Island. This low-melting eutectic is formed by reaction of stainless steel in the fuel cladding with Zircaloy in the surrounding sheath. ORNL's observations of melted core materials could affect the design of tools for core removal at TMI.

areas of criticality, shielding, radiation source terms, and heat transfer.

The SCALE system brings together many well-established computer programs, linking them into easy-to-use analytical sequences that are automated to solve specific problems pertinent to the design evaluation. SCALE's features have considerably shortened the technical review time spent by NRC staff members. This system is currently the calculational "standard" used by the NRC to evaluate these design areas, thus providing industry and NRC personnel with a common understanding of how designs will be evaluated. Increasingly, the system is being used not only by the NRC but also by licensees.

Sequence Coding and Search System

Since late 1980 the Nuclear Operations Analysis Center (NOAC), which is directed by Joel Buchanan of ETD, has been assisting the NRC with the development, maintenance, and operation of the Sequence Coding and Search System (SCSS). The SCSS, which is managed by Gary Mays with the assistance of Mike Poore, both of ETD, and Maurice Greene of C&TD, takes the descriptive text contained in licensee event reports (LERs) submitted by utilities operating commercial nuclear power plants and reduces it to coded sequences that are both computer readable and computer searchable. The system provides a detailed coding of component, system, and unit effects as well as personnel errors and is the most efficient and sophisticated LER data-retrieval tool in use today.

Assessing Risk of Core Damage from Events

How can an experimental data base be developed for determining the probability of severe core damage events if the occurrence of such events is rare (perhaps once every century)? One method, which is being pursued by NOAC with the assistance of Science Applications International Corporation, is to examine off-normal events of operating plants to determine if severe core damage could have occurred if proper mitigative actions had not been taken. This effort has resulted in the review of about 30,000 LERs from 1969 to 1981 and the identification of approximately 230 accident-sequence precursors involving the failure of safety-related functions, degradations of multiple functions, and initiating events such as loss of off-site power and small-break loss-of-coolant accidents. These events are typically parts of sequences which, if gone unchecked, could have resulted in severe core damage.

The precursor events were used to estimate average failure probabilities associated with functionally based event trees onto which each event was mapped. Sequence frequencies estimated from the precursor data were then used to estimate the average probability of severe core damage for the nuclear industry to identify dominant historic sequences, and to rank functions based on risk importance measures. This work is the first independent evaluation of the probabilistic approach using actual reactor operational experience.

Outlook

What is the future for nuclear regulatory research at ORNL? The list of issues identified in the wake of the TMI accident is rapidly being exhausted, and the current focus on the characterization of phenomena associated with relatively rare severe-core-damage accidents is waning. In contrast, increasing attention is being given to plant capacity factors and to plant life extension because the reactors currently operating in the United States are a genuine "bargain" compared with the costs of replacing them. As a result, ORNL will undoubtedly experience a decrease in some of the "issues-oriented" activities, such as studies of the source term and PTS, and an increase in efforts associated with the collection and analysis of operational data (especially concerning maintenance operations) and with the development of methods to monitor the degradation of operating equipment. ornl

Structural work on ORNL's $19-million High Temperature Materials Laboratory was completed in March. The eastern (left) wing and central core of the building may be ready for occupancy in September.

ORNL materials on *Voyager*

On January 24, the spacecraft *Voyager 2* swooped to within 80,000 km of the planet Uranus, sending back photographs and a wealth of new data about the planet. The probe's radioactive power source is clad in a protective alloy developed and fabricated at ORNL.

Voyager 2, launched in 1977, is powered by a radioisotope thermal electric generator (RTG), which converts heat into electricity. The heat comes from the steady decay of plutonium-238; the plutonium is clad in a tough iridium alloy developed and fabricated in ORNL's Metals and Ceramics Division. Henry Inouye (now retired) and Chain Liu led the development team, and Dick Heestand headed the fabrication.

According to Mel Martin, manager of the Laboratory's RTG program, the output of *Voyager*'s generator has dropped gradually over its 3-billion-km journey (in fact, the probe has already exceeded its designed lifetime); still, the RTG remains strong enough to power key equipment and transmitters. The craft has now left Uranus far behind and is speeding toward a rendezvous with Neptune in 1989.

Congress considers energy technology funding

A congressional energy subcommittee has moved to reverse sharp cuts proposed for energy technology programs at ORNL and other DOE labs. On March 13, in considering a 1987 DOE reauthorization bill, the House Energy Research and Production Subcommittee, chaired by Rep. Marilyn Lloyd (D-TN), added millions of dollars to the Reagan administration's requested funding for several of the programs, including advanced reactor programs, energy conservation and storage, and fusion energy design work.

The Reagan administration's budget proposal, sent to Congress in February, offered both "encouragement and distress" for ORNL, according to testimony to another subcommittee March 5 by ORNL Director Herman Postma. Postma praised the proposed initial funding for a new research reactor at ORNL and for three new research facilities at other DOE labs. He also commended the funding levels proposed for basic energy sciences, life sciences, and environmental cleanup projects in Oak Ridge. However, he said that the sharp cuts proposed for energy technologies would "cripple the nation's capability to anticipate and to respond when the next energy crisis appears."

The budget proposal included particularly severe cuts for ORNL's advanced reactor programs. Fred Mynatt, ORNL associate director for nuclear and engineering technologies, told Lloyd's subcommittee on February 28 that the administration's budget would cut ORNL's fuel reprocessing program, which is the focus of the U.S. program, from $12.5 million in 1986 to just $1–2 million in 1987. Lloyd's subcommittee boosted the proposed funding for reprocessing by $5.3 million, primarily to maintain ORNL work on remote technology.

The additional funding would provide the budget needed to begin a broader collaborative program with Japan. In mid March, Fuel Recycle Division Director Bill Burch and a team of other U.S. representatives returned from Japan with an initial agreement to pursue an expanded joint program. According to Burch, the program could provide the focus for ORNL's reprocessing work for the next 10 years and could lead to extensive Japanese investment in U.S. equipment.

Lloyd's subcommittee added $22.7 million, including $5 million for ORNL work, to the requested funding for the High Temperature Gas Cooled Reactor Program. The administration had requested only $700,000 for ORNL's HTGR work.

The subcommittee added $4 million to the requested funding for electric energy systems, reversing most of the proposed cut of 37% in that program. In testimony to the subcommittee the day before its action, Roger Carlsmith, director of ORNL's Conservation and Renewable Energy Program, noted that funding for electric energy systems R&D, aiming at increasing the efficiency, safety, and reliability of the nation's power supply, had dropped 70% since 1981.

The subcommittee also added $5 million to the administration's request for energy storage programs and $5 million for fusion-energy design centers at ORNL, Princeton University, and Massachusetts Institute of Technology.

After the subcommittee's action on the reauthorization bill, Postma, Mynatt, and Carlsmith voiced hope that the higher funding levels would also be reflected in an appropriations bill later in the year.

Six new Distinguished Scientists named

Six new appointments in the Distinguished Scientist Program were announced between December and March. The Distinguished Scientist Program is a joint venture of ORNL and the University of Tennessee; the scientists hold joint positions at the two institutions.

Newly named are:

- **David White,** a microbial ecologist and physician from Florida State University. White is currently associate director of Florida State's medical sciences program and co-director of its Center for Biomedical and Toxicological Research. His research interests focus on environmental pollutant monitoring and analysis.

- **Alan George,** dean of mathematics at the University of Waterloo in Ontario, Canada. George specializes in sparse-matrix computations and in parallel computer applications. He has been a consultant to ORNL since 1980.

- **Robert Uhrig,** vice-president of Florida Power & Light Company. Uhrig is former head of engineering and nuclear engineering at the University of Florida and is a recognized expert in the field of nuclear reactor noise analysis. His work at UT and in ORNL's Instrumentation and Controls Division will focus on the application of advanced control technologies, including artificial intelligence, to commercial nuclear plants.

- **Robert Hatcher,** a structural geologist from the University of South Carolina. Hatcher's principal research interests include the structure of the earth's crust, the anatomy of mountain chains, and the causes of earthquakes. He is director of the site-selection study for the Appalachian Deep Core Hole project, which will involve drilling and coring a 10-km-deep hole in the Southern Appalachian mountains to gain a better understanding of their structure. He is a native Tennessean and holds a Ph.D. degree from the University of Tennessee.

- **David Joy,** an analytical electron microscopist from AT&T Bell Laboratories. Joy has been extensively involved in two forefront areas of modern electron microscopy: scanning and scanning-transmission imaging and microcomputer control of these instruments. He was 1983-84 president of the Microbeam Analysis Society and serves as editor of the *Journal of Microscopy*.

- **Philip Siemens,** a nuclear theorist from Texas A&M University. Siemens, who studied under Nobel laureate Hans Bethe at Cornel University, is recognized as a leader in the physics of nuclei heated to very high temperatures by stellar explosions or high-energy collisions.

Uhrig (pictured on page 11) began his appointment in early 1986. Appointments for the others will begin at mid-year.

technology transfer briefs:

Waste-treatment process licensed

A new Oak Ridge company has been granted an exclusive license for commercial applications of an ORNL-developed process for treating municipal sewage. The process, called ANFLOW (for *an*aerobic, up*flow* operation), uses bacteria in an oxygen-free chamber to convert the sewage into methane and carbon dioxide. The company, Anflow, Inc., was formed in late 1985 with funding and assistance from the Tennessee Innovation Center.

Anflow, Inc., is the first Oak Ridge company to negotiate a licensing agreement of this type with Martin Marietta Energy Systems, Inc. The company will pay a royalty fee for the rights to the process; the money will be considered U.S. government property and will be invested by Energy Systems in the development and transfer of other commercially promising inventions.

ANFLOW, developed at ORNL in the 1970s, produces less sludge than conventional aerobic treatment processes, so it poses fewer environmental problems; also, it consumes far less energy. In fact, because it produces methane, a fuel gas, ANFLOW can actually supply useful on-site energy.

In 1976, ANFLOW received an I-R 100 award from *Industrial Research* magazine as one of the year's top 100 technical innovations. From 1976 to 1978, the process was successfully demonstrated in a cooperative pilot-plant project with the City of Oak Ridge; a large-scale demonstration was conducted in cooperation with the City of Knoxville from 1981 to 1983.

The Tennessee Innovation Center, which provides start-up assistance for technology-based companies, will also offer them facilities and supporting services when its permanent quarters are completed this summer. The center is a joint venture of Martin Marietta Corporation and the Utah Innovation Center. In February, David Fitzgerald was named as its president and chief executive officer.

During a demonstration of a new low-level-waste-compaction system at ORNL, a Laboratory health physics technician watches as a Westinghouse-Hittman crew loads a drum of radioactive waste for insertion into the compactor.

The technology for safely disposing of nuclear wastes in the United States is in hand, and a program for dealing with the problem is mandated by law. But many groups disagree about program plans, and many Americans are still questioning whether the technology is safe.

Radioactive Waste Disposal:
Technical Plans, Institutional Delays

By CAROLYN KRAUSE

The technology for safe disposal of nuclear wastes in the United States is in hand, and law mandates that a program for dealing with the problem be implemented. But utility companies, environmentalists, federal officials, members of Congress, and state governments disagree about the program plans, and members of the public are still questioning whether the technology is safe.

"The technology is there but the emotional readiness to accept waste management techniques is far behind," says Tom Row, manager of Nuclear and Chemical Waste Programs at Oak Ridge National Laboratory. "We do not have the institutional ability or public willingness to carry out solutions to waste management problems." As examples, he cites the reluctance of governors to have their states host repositories for radioactive wastes and the public outcry in Tennessee against a plan to site a way station for commercial spent fuel in Oak Ridge.

In response to laws passed by Congress, the U.S. Department of Energy has made plans to deal with the spectrum of nuclear wastes from government reactors that produce isotopes and weapons materials for defense, an assortment of contaminated trash from research and manufacturing in the DOE facilities, and spent fuel produced by commercial nuclear reactors.

Three Types of Waste

Nuclear waste falls into three classifications: low-level waste (LLW), transuranic waste (TRU), and high-level waste (HLW).

LLW includes contaminated glassware, paper, rags, gloves, residues and other trash from commercial nuclear power plants, defense facilities, and research laboratories including ORNL. Similar wastes are produced by hospitals, medical schools, and manufacturers of cardiac pacemakers, smoke detectors, diagnostic isotopes, thickness gauges, devices for criminal investigation, and components for space power plants. About half of the nation's LLW comes from commercial nuclear power plants.

TRU wastes include the by-products of weapons production reactors (e.g., plutonium) and of facilities that produce elements heavier than uranium for smoke detectors (americium), cancer treatment (californium), power production in space (curium), research (einsteinium), and other uses.

HLW comprises wastes from government defense and isotope production reactors as well as spent fuel from commercial nuclear power plants. Although LLW represents the largest volume of the three types of waste, spent fuel, or HLW, is responsible for 90% of waste radioactivity (measured in curies).

DOE and its predecessor agencies have been sequestering many of these wastes from the environment for years, but improved technology is being used to prevent these wastes from later reentering the environment. The handling of LLW is an example.

"In the past," says Row, "shallow land burial trenches have been the predominant way of disposing of low-level wastes. In the Southeast this method poses a problem because of the high water table. We have to worry about contaminating groundwater that may eventually be a source of drinking water. So we at ORNL have changed our way of disposing of radioactive wastes."

Solid wastes once were loaded into bags, placed in 210-L (55-gal) metal drums, and transported to pits or trenches, where they were dumped and covered with dirt. Unfortunately, water entering some of these trenches corroded many drums, sometimes dissolving and carrying away some radioactive materials.

The Waste Isolation Pilot Plant (WIPP), a federal repository for transuranic (TRU) wastes, has been under construction since 1983 in Carlsbad, New Mexico. Beginning in the early 1990s, the facility will accept TRU wastes for permanent disposal. The wastes will be carried underground through the "waste shaft." Sources of these wastes are ORNL and other research, defense, and manufacturing facilities throughout the nation.

Today, the technology for processing low-level solid wastes makes them more leach-resistant. These wastes are pulverized, shredded, or incinerated, to make them more easily compacted before being packaged. Trenches are lined with crushed gravel to allow water to move rapidly through wastes rather than being retained long enough to leach out contaminants. To determine if leaching is occurring, samples are monitored through lines run down into the trenches. The trenches are covered with soil and, in some cases, cobblestones "large enough to keep the standard gopher out," says Row. Around the covered trenches, the land is sloped to permit surface water to move laterally away from the waste site, and mounds built above the trenches may be laced with retardants to prevent the growth of vegetation with deep roots to keep wastes out of the food cycle.

Recycling rather than burying some solid radioactive wastes is attractive economically because it reduces the cost of waste disposal while bringing in revenue. Row recommends recycling contaminated scrap metal, such as that at the Oak Ridge Y-12 Plant and Oak Ridge Gaseous Diffusion Plant, by smelting it into large blocks and selling it for shielding to accelerator laboratories. Recently, DOE invited industrial firms to submit proposals on decontaminating metal to make it marketable.

Disposal of low-level liquid wastes is now becoming more complicated. For years at ORNL, liquid radioactive wastes were cemented into grouts that were pumped down into the ground, where they harden into permanent sheets sandwiched between layers of shale. This method, used until recently at ORNL's Hydrofracture Facility, seemed safe and reliable until monitoring wells showed that water near the disposal site was contaminated.

Grout injections were stopped following the issuance of Tennessee's new underground injection regulations and probably will not be resumed before 1988 (if at all). DOE announced November 1, 1985, that it will delay its application for permits from the Environmental Protection Agency and the state of Tennessee. Two reasons were cited: the high cost of drilling additional deep monitoring wells to determine if area groundwater could be contaminated by future injections and the possibility that all underground injections of hazardous waste will be banned in 1988, unless EPA develops guidelines by then.

ORNL is dealing with the suspension of hydrofracture injections by changing its storage procedures and reducing the volume of low-level liquid waste generated. If hydrofracture injections are permanently stopped, ORNL may have to solidify its liquid wastes using a procedure that costs more than hydrofracture and requires more human handling of radioactive wastes.

Currently, LLW from commercial nuclear power plants is being disposed of at facilities in Nevada, South Carolina, and Washington. The governors of these states have not been happy about the prospect of hosting the nation's commercial waste disposal facilities "forever" and have long been pressuring the other states to shoulder the burden in the 1990s. In 1980 Congress passed the Low-Level Radioactive Waste Policy Act. According to this law, by January 1, 1986, all states were to initiate license applications for waste generators and ratify compacts in which the states in each region would agree on how and where to dispose of wastes generated in the region. In December 1985 the U.S. House of Representatives approved compromise legislation giving 30 states another seven years to place a dozen new regional waste repositories into operation; the House also endorsed seven compacts involving 38 states that had agreed to build or continue operating regional disposal facilities. The compromise legislation reflects the difficulty of solving a technical problem by institutional means.

A TRU Story

Before 1970, transuranic wastes were placed in trenches. Since then DOE has required that wastes containing TRU materials be specially stored in retrievable form for ultimate disposal at a designated federal repository. In 1983–84 ORNL tested a sensitive nondestructive assay system developed by Los Alamos National Laboratory to quantify TRU materials in wastes. Packages containing more than 100 nanocuries per gram of these materials can then be separated from packages containing only LLW, thus reducing the volume of wastes that require special handling. ORNL found that nearly 10% of the suspected TRU wastes stored since 1970 should be reclassified as LLW and could be disposed of by shallow land burial.

At ORNL the TRU wastes that can be handled by laborers are packaged in more than 3000 stainless-steel drums and stored in underground reinforced-concrete bins. These waste packages have been prepared according to federal ground rules and have been certified by DOE. The TRU wastes that must be handled remotely are stored in concrete casks to protect workers. The retrievable TRU wastes will remain at ORNL until a federal repository is ready to receive them.

The federal repository is the Waste Isolation Pilot Plant (WIPP), which has been under construction since 1983 at Carlsbad, New Mexico. In 1981 New Mexico agreed with DOE to store transuranics in a geologically stable salt formation. (For many years, researchers at ORNL studied the characteristics of salt formations for isolating nuclear wastes because of the premise that the existence of large amounts of salt indicates that water has not invaded the site.) The $693-million WIPP facility is being tested without waste and will be tested with TRU wastes in 1988. In the 1990s TRU wastes from ORNL and other research, defense, and manufacturing facilities throughout the nation will be sent to WIPP for permanent disposal.

High-Level Waste

DOE facilities that produce high-level wastes (ORNL not included) use reactors to make weapons materials and radioactive isotopes. These facilities are located at Hanford Engineering Development Laboratory (HEDL), Idaho National Engineering Laboratory (INEL), and Savannah River Plant (SRP). A minor amount of HLW from reprocessing exists at the closed Nuclear Fuel Services facility in West Valley, New York.

In 1983 DOE selected borosilicate glass as the waste form for incorporating HLW from Savannah River, Hanford, and Idaho. To store this waste form, DOE plans to build underground facilities at SRP by 1989, at HEDL by 1994, and at INEL by 2008.

Highly radioactive spent fuel from commercial nuclear power plants presents a special challenge to the nation. Because of the poor economics, spent fuel is not likely to be reprocessed to produce new fuel for advanced reactors.

Vic Fowler, technician, checks the operation of the ion-exchange pilot plant designed and built recently by ORNL to reduce generation of low-level waste at the Process Waste Treatment Plant.

Therefore, facilities will have to be built to store this HLW form. In 1983 about 10,000 metric tons of HLW were being stored temporarily at about 80 nuclear power plants; by 1998, it is expected that the amount of spent fuel requiring storage will reach 38,000 metric tons.

In 1982 Congress passed the Nuclear Waste Policy Act (NWPA), which established a schedule for siting a permanent repository for spent fuel. Such a facility is to begin operating in 1998. In the meantime, Congress asked DOE to determine the feasibility of siting and constructing an interim repository. DOE proposed building a long-term "integral" repackaging facility—the Monitored Retrievable Storage Facility (MRS)—in Tennessee. The MRS would consolidate, package, and store up to 15,000 metric tons of spent fuel—slightly more than the inventory of spent fuel stored at power reactors in the United States today—for future transportation to the permanent repository.

The NWPA has created considerable political fallout for DOE. Politicians in the states that DOE selected for possible siting of the permanent storage repository have not been particularly receptive to the proposal. DOE's proposed sites are three geological formations: volcanic tuff at Yucca Mountain, Nevada; basalt at Hanford, Washington; and bedded salt at Deaf Smith County, Texas. Selection of the first repository site was mandated for early 1987, but program delays have pushed the decision back to March 1991.

The law gives states the right to refuse to host a waste repository; however, a simple majority in both houses of Congress can override a state's refusal. DOE has not found it any easier to win local support for its proposed repository sites in Nevada, Texas, and Washington than for its current MRS experiences in Tennessee.

DOE's proposal to locate the MRS facility near Oak Ridge or Nashville quickly provoked opposition from congressional representatives. The state of Tennessee also took DOE's proposal to court, charging that DOE failed to consult with state officials about siting the MRS facility. In February 1986 a federal judge found DOE guilty of violating the NWPA by not seeking input from state officials. In January 1986 Governor Lamar Alexander of Tennessee discussed his opposition to the MRS project, arguing that it was unnecessary and would discourage industrial development in the Knoxville-Oak Ridge region. On the other hand, the City of Oak Ridge, the preferred location for the project, agreed to accept the MRS if certain conditions are met. These conditions include the improvement of highways, appointment of a board of lay citizens to monitor the operation and decide if shutdown is needed, awarding MRS contracts only to companies located (or willing to locate) in Tennessee, and making payments to the host city and county that are equivalent to the taxes that would be collected if the $1 billion repository were privately owned and operated. Congress is expected to decide in 1986 whether to authorize construction of the MRS.

Row, who as a member of the Clinch River MRS Task Force has closely studied this project, is confident that an MRS facility in Oak Ridge would be safe because the technical knowhow already exists for consolidating, packaging, storing, and transporting spent fuel without releasing radioactivity to the environment. "We do not have problems with the safety and environmental acceptability of the MRS," he says. "Instead, we should focus attention on the fact that this facility is part of the overall solution to a national problem and try to develop the state and local plans that will make siting possible."

The governor of Tennessee would disagree that the MRS is a solution to a national problem. Such differing views point up the difficulty and complexity of finding politically acceptable long-term approaches to nuclear waste disposal as a whole. Any successful solution hinges on both technology and politics; it must reconcile national needs with local and state wishes.

Despite assurances of safety and reliability from scientists and engineers, political leaders remain cautious about nuclear waste disposal, at least in their own territories. And nuclear waste disposal, like other long-term programs (such as energy research), requires a long-term, stable program. That, however, is difficult to achieve in the political sphere, where budget battles are fought from year to year and where "long term" often means four to eight years.

Is the timetable for nuclear waste isolation realistically achievable? An answer may emerge in 1986 when Congress debates whether an MRS facility is needed in the 1990s. ornl

Using a small crane, a Westinghouse-Hittman technician removes a crushed steel drum for loading an overpack container to be stored in the ORNL burial ground.

Nuclear Waste Management and Research at ORNL

Collection, treatment, compaction, and disposal of ORNL's radioactive wastes are some of the responsibilities of the Laboratory's Nuclear and Chemical Waste Programs under the direction of Tom Row of Central Management Offices (CMO). These programs also develop technologies to manage radioactive wastes produced at ORNL and to meet goals of development programs sponsored by DOE.

Radioactive wastes are produced at ORNL primarily through radioisotope production and processing, operation of five nuclear test reactors, nuclear physics research, and research and development on reprocessing of reactor fuels. These low-level wastes occur in solid, liquid, and gaseous form. An aggressive campaign is under way to reduce the volume of low-level waste by asking those who generate it to consider changing their operations.

Solid low-level radioactive wastes are compacted, if feasible, and are disposed of by shallow-land burial in trenches or auger holes. Recently, many drums of low-level waste were compacted to one-fifth their original size by a mobile radioactive waste compactor operated by Westinghouse Electric Corporation. No high-level solid wastes are produced or stored at ORNL, but ORNL has most of the nation's remote-handled transuranic wastes (see accompanying article).

Liquid radioactive wastes are collected in the process waste system and the low-level waste system. Process waste is treated by ion exchange before being released. Recent improvements in the Process Waste Treatment Plant (increasing steam pressure to the evaporator and adding evaporator condenser capacity) has reduced the volume of low-level waste generated at the treatment plant by 75%. Low-level liquid waste is concentrated by a factor of 10 or more before transfer to storage tanks where it awaits decisions on final disposal.

The hydrofracture disposal process for liquid wastes was developed in 1959 at ORNL. The waste solution or slurry is combined with a mixture of cement, fly ash, and clay to form a grout that is then pumped through an injection well into the shale formation at a depth of about 305 m (1000 ft). The injection pressure is sufficient to fracture the shale along bedding planes (nearly horizontal) so that the injected grout spreads out to form an irregular pancake in the shale formation. The grout solidifies shortly after injection, thus permanently fixing the waste within the geologic formation.

So far, ORNL is the only generator of radioactive wastes that has used this process for permanent disposal of liquid wastes. Grout injections, however, have been stopped until the Environmental Protection Agency (EPA) and the state of Tennessee are satisfied that future injections will not lead to contamination of nearby groundwater (see accompanying article). In the meantime, ORNL is making every possible effort to reduce its generation of low-level liquid wastes, which will be held in temporary storage until the hydrofracture issue is resolved.

Gaseous wastes are less of a problem at ORNL. These wastes from process vessels are purified by scrubbing and filtration at the source facility. They are then collected by a cell ventilation system and exhausted through the central stack system.

A new program started at ORNL in fiscal-year 1985 is the Environmental Restoration and Facilities Upgrade (ERFU) Program. The ERFU

Program, managed by Gene McNeese of CMO, was set up to focus on the site problems most recently addressed by EPA and the state of Tennessee. They emphasized the need for ORNL to reduce radionuclide and hazardous chemical discharges to the environment and take comprehensive actions to comply as quickly as possible with environmental regulations.

The ERFU Program will conduct projects to improve or develop systems for collection, treatment, compaction, storage, and disposal of radioactive and hazardous wastes. Such projects include the recently completed sewage treatment plant for on-site treatment of ORNL sanitary wastes, repair and replacement of underground waste collection piping throughout the Laboratory, and installation of various systems to reduce the volume of waste to cut requirements for on-site treatment and disposal (systems under consideration include a high-temperature incinerator and glass melting furnace).

The ERFU Program is also conducting remedial actions for locations where past practices have contaminated facilities or the environment to levels requiring corrective measures. Site decommissioning and closure activities will be performed over the next 10 to 20 years in the inactive solid-waste storage areas, at liquid-waste disposal sites, along portions of the White Oak Creek watershed and White Oak Lake, at surplus contaminated laboratory research facilities (e.g., research reactors and isotope processing facilities), and at the various on-site surface impoundments for liquid-waste collection. Efforts to characterize the sites are under way at many of these locations, including installation of a comprehensive site groundwater monitoring network to guide the future remedial actions.

In addition to providing direct support to the operation of facilities for the disposal of ORNL's waste, the research staff participates in developing technology to better manage all types of waste. Examples of future directions for research and development by ORNL in this area include improved methods of shallow-land burial, compacting and stabilizing the radioactive wastes prior to disposal, designing trenches or storage modules, and direct monitoring of disposal-unit releases.

ORNL's Drop Test Facility (left) helps researchers address questions about whether a transportation cask could be damaged enough to release radioactivity as a result of the impact of a fall or a puncture in a truck or train accident. In August 1984 ORNL dropped a TRUPACT cask designed to contain transuranium waste from a height of 9 m onto an unyielding surface (right) and later another test cask from a height of 2 m onto a 15-cm spike. The packages survived the tests and met U.S. Nuclear Regulatory Commission standards.

Repositories for spent nuclear fuel or contaminated materials will be needed in the United States. ORNL has been conducting research related to the transportation of radioactive material to repositories and the best sites for repositories.

ORNL transportation studies have predicted which highway and rail routes would most likely be used in moving spent fuel from nuclear power plants to candidate repositories. For example, ORNL's studies of the proposed Monitored Retrievable Storage (MRS) Facility show that over 60% of the estimated 850 truck and train shipments of spent fuel per year would come from the north or northeast if the MRS is located in Oak Ridge.

ORNL has also used its Drop Test Facility to address concerns about the safety of transporting spent fuel. A common question is, Could a transportation cask be damaged enough to release radioactivity as a result of the impact of a fall or a puncture in a truck or train accident? In August 1984 ORNL dropped a TRUPACT cask (designed to contain transuranium waste) from a height of 9 m onto an unyielding surface to test impact resistance and later another test cask from a height of 2 m onto a 15-cm spike to test puncture resistance. The casks survived the tests and met U.S. Nuclear Regulatory Commission standards for impact and puncture resistance.

Which type of sedimentary rock has the best potential for hosting radioactive waste repositories that may be built in the near future? ORNL researchers found that the best rock is shale, followed by sandstone, carbonate rock (like limestone), anhydrock, and chalk. Because of shale's great abundance and excellent hydrological and geochemical properties, ORNL recommended that the Department of Energy examine areas underlain by shale for possible sites for geologic repositories.

Other ORNL research efforts include development of cement-based hosts for disposing of radioactive wastes and an integrated data base that provides consistent data on the inventories, characteristics, and projections of all types of radioactive waste at various domestic sites.

In short, ORNL's nuclear waste programs embrace projects that not only will benefit the Laboratory's environment but also will influence the future of nuclear waste disposal throughout the nation.

Lester C. Oakes (center) is associate director of ORNL's Instrumentation and Controls (I&C) Division and head of the division's Reactor Systems Section. A native of Knoxville, he holds a master's degree in electrical engineering from the University of Tennessee. After a stint at Fairchild Engine & Aircraft Company, he came to ORNL in 1951 to begin a career devoted to the instrumentation and control of nuclear reactors. In 1979 he was assigned to the Electric Power Research Institute for about a year to assist in the evaluation of the reactor accident at the Three Mile Island nuclear power plant. Oakes is a fellow of the Institute for Electrical and Electronic Engineers.

Roger A. Kisner (right) is a principal investigator for an I&C Division program dealing with improving the control and protection of nuclear power plants. A native of Washington, D.C., he holds a master's degree in nuclear engineering from Virginia Polytechnic Institute and State University of Blacksburg. He has worked as a product development engineer and is a registered electrical engineer. He came to Oak Ridge in 1976 to work at the Oak Ridge Gaseous Diffusion Plant and then became a project manager at the Department of Energy's Office of Waste Isolation. In June 1978 he joined the I&C Division to begin research on human-machine interactions, automation, and control of systems. Kisner is a member of the Oak Ridge Associated Universities Traveling Lecturer Program.

Pedro J. Otaduy (left), a staff member of the I&C Division since December 1982, has been working on developing an intelligent advisor for ORNL's High Flux Isotope Reator and applying artificial intelligence to advanced control concepts for nuclear reactors. A native of Mondragon in the Spanish Basque Country, he came to the United States in 1973 as a Fulbright student at the University of Florida at Gainesville. He first worked at ORNL in 1975 as a graduate research participant. After earning a Ph.D. degree in nuclear engineering from the University of Florida and working as a postdoctoral research associate at ORNL, Otaduy was awarded a Wigner Fellowship by the Laboratory in late 1980. As a Wigner Fellow, he worked on an assessment of the stability of boiling-water reactors. His other awards include Certificates of Appreciation from DOE and ORNL for his "contributions to the resolution of the Three Mile Island accident" and from the American Nuclear Society in "recognition of his special services."

Here the three men discuss applications of artificial intelligence to nuclear reactor operation at the High Flux Isotope Reactor control panel.

Automating Large-Scale Reactor Systems

By LESTER C. OAKES, ROGER A. KISNER, and PEDRO J. OTADUY

To the nuclear industry, the role of the operator in controlling a nuclear reactor has long been regarded as essential, just as the space industry has long insisted on the presence of one or more astronauts with the "right stuff" to control space vehicles in orbit or on the way to the moon. However, the complexity of devices like space vehicles and reactors requires computers, sensing instruments, and other automated support systems to guide the operator in making midcourse corrections and in dealing quickly and correctly with emergencies.

Recent events related to the complexity of nuclear plants have made the reactor operator's role more ambiguous. In some instances, reactor operators have indeed saved nuclear power plants in trouble; an example is the Tennessee Valley Authority's Browns Ferry plant, where a 1975 fire destroyed the electrical cables in the control systems but did not lead to reactor damage. In the 1979 Three Mile Island (TMI) accident, on the other

Reliable automatic systems to monitor, control, and respond to moment-by-moment operations of nuclear power plants and artificial intelligence systems to help operators make correct technical decisions in a hurry could redefine the role of reactor operators by freeing them to do what humans do best—system supervision, planning, and management.

The tools and methods used for designing large-scale control systems for nuclear reactors are changing rapidly. Computer-aided engineering packages are becoming available for designing, analyzing, and simulating control systems. One such software package is in use at ORNL's Instrumentation and Controls Division. Here, ORNL engineers Roger Kisner and Jerry Bentz use Matrix$_X$, an interactive environment for graphical building and editing of linear and nonlinear systems.

hand, reactor operators made crucial mistakes such as shutting off the emergency core-cooling system and opening valves at the wrong time. Those errors in judgment turned an abnormal occurrence (a stuck relief valve) into a serious small-break loss-of-coolant accident—perhaps the straw that broke the nuclear industry's back.

The TMI emergency suggested that operators need reliable automatic systems to monitor, control, and respond to moment-by-moment operations and to help them make correct technical decisions in a hurry. Such systems could eventually be "intelligent" enough to redefine the role of the operators, freeing them to do what humans do best—system supervision, planning, and management.

Long before the TMI accident, Oak Ridge National Laboratory staff members in the Instrumentation and Controls (I&C) Division began advocating the need for extensive automation of control and safety systems in nuclear reactors. This philosophy had been put into practice in the research reactors that were designed or built at ORNL. Each succeeding reactor, starting with ORNL's Bulk Shielding Reactor (put into operation in 1952), has relied increasingly on automation. Although the Laboratory's "newest" reactor, the High Flux Isotope Reactor (HFIR), was completed 20 years ago, the HFIR control system still represents the state of the art in automation of nuclear reactors in the United States and most of the world.

The objective of the ORNL automation program has been to design for the best match between the operator and machine. It has never been, nor is it now, our aim to remove the operator from the control loop completely. Operators can do some tasks better than instruments. Also, some sequences of action can be handled easily by an operator but would be quite costly to do automatically. Traditionally, a most compelling rationale for keeping the operator in the loop has been the belief that it is nearly impossible to anticipate all normal conditions, and even harder, to anticipate all abnormal conditions that may occur during operation of a plant. The operator's job is to handle those events that cannot reasonably be anticipated and accommodated by the control systems.

Unfortunately, this rationale has not completely lived up to expectations. It assumes that the operator, using available sensory information, can rationally evaluate a strange new event in a short time under stressful conditions. Laboratory tests show that humans perform at a much lower reliability level than well-designed mechanical components and systems. At best, humans make one error for every 100 actions under normal conditions; this rate increases to one error per 10 actions under stressful conditions.

This human inability to perform with high reliability under stress has already affected the design of reactor systems for responding to accident conditions. For example, in the Federal Republic of Germany when an accident occurs, the reactor is put into an automated mode for 30 minutes; during that time the operator is essentially locked out of the system.

In the United States, an American Nuclear Standards Institute (ANSI) committee recommended in 1978 that no operator action be permitted for the first 20 minutes. The committee members recognized that poor human performance under stress and institutional constraints that force the operator to follow a prescribed set of procedures during emergencies combine to effect mistakes in judgment. The ANSI committee believed that an operator is likely to take the wrong action during the first few minutes of an unanticipated event.

The current level of automation in U.S. reactors is not far from that of 1962 when the HFIR was designed. Since then new technologies have emerged that could have a dramatic impact on the next move toward more advanced automation. First, digital control technology uses sophisticated data management and high-speed calculational capability to rapidly assess a wide variety of plant data. This capability allows a larger number of input parameters to be incorporated into the control algorithms, thus extending the range of preprogrammed actions. ORNL is applying today's digital control technology to designs of a new generation of advanced reactor controls.

Second, great progress has been made in both the methodology and machinery for artificial intelligence (AI). AI is a computer science devoted to simulating human precepts and reasoning processes. AI "expert systems" can incorporate into the control system the expertise of the best reactor operators; these expert systems respond to normal and abnormal events using operator experience-based knowledge. AI is expected to help replace some reactor operator activities by taking appropriate actions whenever it can do so with greater accuracy and speed than humans. ORNL has programs under way in both advanced automation of reactor controls and artificial intelligence, including developing the Expert Monitor and Expert Advisor. The remainder of this article will discuss these developments in greater detail.

Advanced Automation of Reactor Controls

A nuclear power plant is a complex mixture of equipment and systems. For example, a recently constructed light-water nuclear plant has more than 2000 annunciator lights; 10,000 valves, 5 cm (2 in.) in diameter or smaller; and 1.8 million m (6 million ft) of power and signal cable.

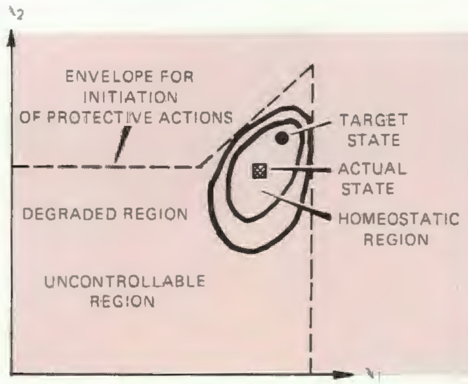
The plant's equipment and systems are classified according to their function: prime systems contribute directly to the production of electric power; support systems provide necessary functions and services to prime systems; and utility systems supply support systems with commonly used bulk materials. To automate a nuclear power plant, the prime, support, and utility systems must be controlled and coordinated to work together.

In the future, control engineers will try to develop systems that elevate the role of plant operators to that of system managers. In this role, the operating crew plans activities important to the long-term operation of the power plant, including refueling, maintenance, and repair. Currently, the operator handles the moment-by-moment actions of local control loops as well as higher-level system supervision.

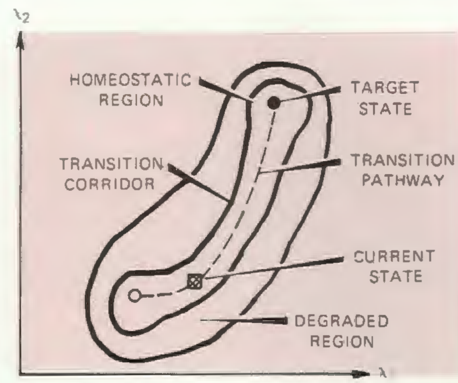
Humans are better at planning and scheduling than performing repetitive, tedious tasks; however, the operators must retain ultimate responsibility for the behavior of the plant.

Intelligent Automatic Control: Disciplines, Traits, and Goals

New control engineering disciplines apply the higher intelligence of digital systems in developing intelligent advanced control for a nuclear power plant. These disciplines include heuristic control of systems (i.e., systems that use experience to increase intelligence), wide-range control of nonlinear processes, learning capability, control with degraded equipment, and dynamic control for load-following capability (i.e., the ability of the nuclear power plant to increase or decrease power production in response to changing demand).



STEADY STATE CONDITIONS



TRANSIENT CONDITIONS

Control regions in state space under steady-state conditions (Fig. 1) and transient conditions (Fig. 2). A state vector projected into this space of regions is made up of a mixture of both continuous variables and discontinuous parameters. A discontinuous parameter can assume only discrete values (in many cases it may simply indicate whether a pump or stop valve is on or off). The result is a point in space that moves with the changing state of the plant. Figures 1 and 2 show the control regions for a simple system of two state variables.) These multidimensional regions are not fixed in space but rather are related to the target state (Fig. 1, steady-state operation) or to both the target state and the pathway of transition (Fig. 2, a system moving from initial to target state). Thus, not only is the vector moving as it follows the dynamics of the plant, but also the regions are being readjusted as margins to specific limits change and the availability and operability of plant equipment change. The boundaries separating the contiguous regions are flexible; their relative positions depend on known plant conditions. Real-time calculations continuously determine the shape and coverage of the regions. These calculations must be based on an a priori quantitative knowledge of the behavior of plant components, their failure modes, and the extent and range of maneuverability that the control system has over them. Creation of the regions also must be based on identification of the immediately available capabilities of the control and protection systems. The movement of a system's vector into the next bordering region is an indication that significant changes have occurred or are beginning to occur in the plant. This indicator denotes the need for a change in the general strategy being applied to the control of the affected system and, hence, a change in the specific rules and procedures being used. This change of strategy may require not only proportional changes in setpoints and limits but also abrupt rerouting of process flows and other reconfigurations of systems and components.

The intelligent automated control system of the future must have the following characteristics:

- Fault tolerance so that effective control of the plant is retained under various stages of control equipment degradation
- Robustness to handle a complete range of plant operating models
- Real-time process monitoring performance to track events and diagnose problems as they occur in order to affect the event's outcome
- Ability to look ahead—that is, to project the near-future plant status
- Modular subsystems, where each intelligent module possesses (1) the ability to learn from experience and adapt to new situations, and (2) the ability to explain its function and the rationale behind its actions
- Capability to change as operating conditions change, detect new conditions, overlay the new goals of the plant, and adopt new strategies for meeting those goals.

A control system with these capabilities is goal oriented; it goes beyond maintaining prescribed values and following numerical rules for plant conditions, focusing instead on helping operators solve problems as (or before) they arise.

The general goals of automating a nuclear plant can be arranged as time-oriented layers. Each of the layers deals with the amount of time or frequency of time spent on meeting these goals; the model used by the control system at each layer (or amount of detail considered) is also different. The top layer has the least detail. The goals, in order of increasing detail and immediacy, are to

- extend reactor core life as long as possible to decrease down time and improve fuel conversion,
- minimize wear on plant components to increase their service life,
- protect equipment, facilities, and instrumentation from immediate damage,
- provide sufficient turbine-generator output power,
- keep plant parameters within design specifications and away from safety trips,
- minimize the control actions required to accomplish the control objectives, and
- maintain the stability of the process.

These goals become the operational objectives of the various control modules in the plant control system hierarchy. Traditional feedback-control cannot meet these complex goals; however, by merging artificial intelligence technology with the control system, operator knowledge and skill are added to system software. This merger should lead to improved diagnostic and decision-making capability as well as help operators to understand some internal processes of the control system. The ultimate goals of operating a power plant are to produce electric power economically while protecting the plant site, plant personnel, and the environment.

Advanced Control Activities

At ORNL Roger Kisner and John Anderson have begun preliminary work on a method for implementing condition-dependent

David Wehe makes a point that provokes a thoughtful discussion among his listeners. Seated are, from left, Frank Clark, Pedro Otaduy, Jim Mullens, Ray Brittain, and Glen Arnold.

control strategies by means of a hierarchical control system (i.e., each module is capable of sending and receiving data, yet is centrally controlled). This hierarchical structure is composed of levels, or layers, of control modules in which a module can communicate with both superordinate and subordinate modules in a sort of "machine bureaucracy."

Condition-dependent control involves dividing the state space for the controlled system into contiguous control regions: homeostatic, degraded, and uncontrollable. Each region has appropriate operating goals and strategies for meeting those goals.

ORNL researchers have taken a phased approach to control system design because designing an automated system for a nuclear power plant is complex. The progression can be thought of as a series of logical (not necessarily chronological) phases in which each phase adds another layer of intelligence to the control system.

The resulting intelligent, automated control system must have several characteristics. It must be (1) endowed with distributed intelligence throughout the subsystems composing it, (2) hierarchical in its command and data flow, (3) able to learn and adapt to new situations, (4) fully functional under dynamic conditions, and (5) completely operational in real time. Reliable control systems possessing these characteristics must first be developed for small systems, such as the HFIR, in order to build confidence in the methods, and then, after refinement and testing, be applied to large-scale systems. Other fields besides nuclear power can also benefit from this development and demonstration of advanced and automatic control technology.

Integrating the Human with a Software System

Increased automation is expected to produce a dramatic change in the role of the nuclear power plant operator. This change is expected to be for the better: automation may provide the best capability for mastering the complexity of plant control, and it may permit the design of control systems that are at the same time safer, more efficient, and better suited to the characteristics of human operators.

Automation can achieve its full potential only when functions are properly divided between humans and software. Although it seems reasonable to approach the design of a large-scale system by first defining the desired mixture of human and software participation in plant control, the actual mixture depends a great deal on the level of computer and AI technology available at the time of system design.

Some of the control tasks that could be performed by software may be allocated to the human to ensure that the operator has complete, unfragmented tasks that may be required for job satisfaction. It is also important that the operator has software to provide cognitive support for decision making. An effective relationship among the operating crew, system software, and the plant components may be achieved by placing the operators at the top of the hierarchy and assigning software systems to collect and analyze most of the data and control decision-making and execution.

Several years ago plant operators attended a meeting to discuss designing the control room for a new nuclear power plant (which, like many others, was canceled). As with so many such canceled plants, its control room was planned to be fully computerized. After enduring several hours of enthusiastic vendor presentations, one of the operators rose from his seat, strode to the chalkboard, and silently wrote in large letters:

COMPUTER PROGRAMMERS ARE NOT OPERATORS; OPERATORS ARE NOT COMPUTER PROGRAMMERS.

In one sense, that man was right, at least in terms of what is normally meant today by operators and computer programmers. But in another sense, he was wrong. In future systems, operators will never have to write programs in anything approaching BASIC or the like, but they most certainly will have to learn to interact with software systems (instruct computers in specially designed high-level languages and understand what computers have to say to them). Operators in the future will have to learn more about computers than today's operators. (This need may result in changes in operators' educational requirements; today reactor operators in the United States are not required to have a college degree.)

Computers will not replace operators in the foreseeable future, but they will make profound changes in the ways operators think and act. These changes may be similar to those that have occurred in the roles of operators and computers in the control of aircraft and the remote control of robotic manipulators for space, deep-ocean, and manufacturing applications. In these cases the human operator has moved from being a direct, in-the-loop controller to being a "supervisory controller." That is, the operator controls the vehicle or remote manipulator through the intermediary of computer software. The operator intermittently provides high-level commands to software and receives complex integrated information from it to establish subgoals and monitor the actions of the computer in implementing them automatically. The computer executes its instructions through its own external sensors and effectors, returning to its superior when it has accomplished a subgoal (e.g., achieved a specified altitude or landed the aircraft, or moved a robot arm to a new location and grasped an object) or when it has run into unexpected trouble and needs help.

Artificial Intelligence

The I&C Division is looking at ways to use artificial intelligence tools to assist nuclear reactor operators. AI would introduce human-like qualities, such as reasoning, learning, speaking, and seeing, and would apply expert "rules-of-thumb" to solve problems too demanding for classical analytic methods.

Ray Brittain (left) and Frank Clark work on developing AI programs for monitoring reactor operation.

A reactor operator must monitor, diagnose, and control a large-scale power plant—a job similar to that of a commercial pilot. Both reactor operator and pilot are trained to handle extremely unlikely situations, yet they spend most of their time attending to routine tasks and data. However, unlike the commercial pilot, reactor operators have not been provided the same amount of technical innovation to assist them. Some commercial airplanes, for example, have "stick pushers" that will actually take control of the aircraft in an emergency situation. At ORNL, we are looking at ways to provide "smarter" and "quicker" tools to assist the reactor operators in their jobs—and current AI techniques offer such a possibility.

One application of AI is an expert system that transfers the knowledge of a recognized expert in a field into a computer's knowledge base and then uses it to solve real problems. This approach holds the promise of allowing the computer to perform like the expert, and effectively increases the probability of success for the average user. This technique is particularly appropriate where a known relationship exists between the controllable variables (such as control-rod position) and a goal (such as power generation). In this area of AI, the I&C Division has found promising applications to assist the operator.

In order to become familiar with expert systems, four researchers in I&C have focused on reactor controls at the HFIR. These researchers are Pedro Otaduy, Jim Mullens, Ned Clapp, and Dave Wehe. Otaduy spearheaded the development of the Expert Intelligent Control Advisor, using discretionary funds from the Laboratory director. The HFIR Advisor will provide information to the operator about whether the HFIR is operating normally or abnormally and will suggest corrective actions. With funds from the Nuclear Regulatory

Working in the HFIR control room are, from front to back clockwise, Charles Murphy, Ray Brittain, Pedro Otaduy, David Wehe, and Jim Mullens.

Commission, Mullens has led the development of the Expert Monitor, which will diagnose reactor problems, much as an electrocardiogram diagnoses heart disorders. This intelligent diagnostic advisor will continually examine noise signals from the reactor during operation and compare them to normal signal patterns to determine whether reactor operation is abnormal. These AI developments complement the previously mentioned work on developing advanced reactor controls.

The HFIR, a 100-MW research reactor, has many characteristics of commercial pressurized water reactors (PWRs) because of its pressurized primary system and multiple primary and secondary coolant legs. As with a commercial plant, operational emphasis at the HFIR is placed on maximizing fuel use and plant availability, while minimizing safety risks, radiation exposure, and production of low-level wastes. Therefore, developing an expert system to automate the HFIR's 24-day fuel cycle and developing and testing real-time AI applications can benefit the commercial nuclear industry.

ORNL's Expert Advisor

The HFIR Expert Intelligent Control Advisor incorporates the expertise of HFIR's excellent reactor operators, who keep HFIR in operation 90% of the time (compared with an operating time of less than 65% for the average commercial nuclear power plant in the United States). The project focuses on the development of an ever-alert and cooperative expert companion to the reactor operators. It will relieve the operators of routine tasks, request their attention when abnormalities arise, provide diagnostic aid, and give information on project actions or effects as needed or on demand.

One of ORNL's goals in applying AI to reactor control systems is to open up the traditional black box controller—that is, let the user query the control system on the reasoning behind its action. For instance, the HFIR advisor will be expected to respond intelligently to operator queries such as "Why do you say control rod should be inserted two centimeters?"

ORNL's exploratory work on the suitability of AI tools and techniques for nuclear reactor control and operation has included the development of the Expert Advisor on a model of the HFIR in I&C's hybrid computing facility and use of the Expert Monitor on a water loop applying noise-analysis methodology.

ORNL's Expert Monitor

The prototype HFIR Expert Monitor, written in the expert systems languages OPS5 and LISP, can monitor 12 analog signals generated by an analog simulation of the HFIR, graphically display the basic components of the plant and process signal values, validate and interpret those signals, and explain what physical processes are occurring and why. The main goal of the system is to track energy and mass inventories to ensure that system changes are carried out.

For the prototype of the noise-based automated monitoring system, ORNL built a bench-top flow loop that resembles a PWR system in that it contains physical analogs of a pressurizer, a reactor vessel, and a pump. The monitoring system can measure pressure at three locations and calculate their frequency spectra, which characterize the loop's behavior during the measurement. These spectra contain features that a human monitor could identify as symptoms of normal and abnormal operation of the flow loop. In a recent test, the "rules" of this identification process were given to the automated monitor, which also detected several problems in the flow loop. These problems included a clogged sensing line in a pressure sensor, air in the same sensing line, and air in the "reactor vessel."

Upon detecting a problem, the system made a numerical estimate of its severity by matching a differential equation model of the loop to its observed behavior (spectra). This estimate required a nonlinear least-squares fit of the model's predictions to the observed spectra. A learning technique was developed at ORNL to perform this fit quickly using a minicomputer. Through this mechanism, the numerical values for the observed problem could be obtained.

Rule-Based Expert Systems

In one simple form, a rule-based expert system can be thought of as

Design Tools and Artificial Intelligence Hardware for Reactors

The tools and methods used for designing large systems are changing rapidly. For example, the once standard bottom-up design technique (e.g., selecting components before planning the overall system) has become an unacceptable way to design a large, complex project.

The design environment, too, has changed with the complexity of the design process. In the past, design teams usually worked in one location; now design team members may be scattered across the nation. The mobility of engineers adds yet another design problem: the design and construction period for a nuclear power plant corresponds to roughly twice the average time that an engineer is employed by one company. Thus, the control engineer may never be able to find the person responsible for technical decisions made early in the design process.

Other factors forcing the need for and development of improved design and analysis tools are the increased complexity of plant control systems; the requirement for increased engineering productivity; the impetus to optimize the economics of a system; and the need to minimize design errors and catch the remaining errors as early as possible.

Tools will be needed to support the control engineer in the capacity of system integrator. One high-level tool that will come in handy is a data base–supported design system that can put all other necessary design and analysis tools into the engineer's hands and enable design team members to interact and to exchange design data and material. A few data bases are being developed; however, a large-scale data base, a data base manager, and an advanced analysis and design workstation have not yet been successfully coordinated.

Computer-aided engineering packages such as Matrix_X are becoming available for the development of complex control systems. Matrix_X (by Integrated Systems, Inc.) and programs like it provide an interactive environment for editing linear and nonlinear systems and for designing, analyzing, and simulating such systems.

Besides control systems to provide control schemes using heuristic rules or procedural steps, AI can also be used for filtering alarms and detecting failures in reactors. During alarm status, the operator is overloaded with information, making it difficult to decide which steps should be taken in response to the alarm. AI programs such as those developed at ORNL for HFIR can help the operator interpret what happened and how to resolve the situation as well as monitor the entire reactor to detect failures so that they can be corrected before causing a major problem.

The development of significant AI programs is usually performed on sophisticated computers tailored to run these unconventional languages such as OPS5 and LISP. I&C has developed an unusual network of such hardware. Most notable is the hybrid computer. The analog part of this computer can realistically simulate a reactor such as the HFIR and feed true analog signals into the digital computer. This capability allows testing of the Expert Advisor by subjecting it to a variety of unusual conditions, such as noisy, intermittent, or missing signals from plant sensors. The computer networks allow ORNL researchers to share their individual AI developments and help ensure that these software pieces will fit consistently together.

Convinced that this approach was viable and potentially useful to the nuclear industry, the AI group began a program of remotely monitoring the HFIR. The group used a PDP-11 minicomputer at the reactor site to continuously log several primary reactor signals. Over several months, the computer built its own data base of "normality" for later reference. Because of this "flight recorder," programs now have the data allowing them to look back to see whether a given plant state is "typical" for a particular plant configuration.

During these phases, the AI group talked frequently with expert reactor operators because in order to make diagnostic and control decisions about the plant, they had to assimilate large amounts of plant information. To simulate the human operators' thought processes, the Expert Monitor must also have access to the same information. After careful deliberation, the AI group selected about 60 additional plant signals and fed them into the front-end, signal-monitoring computer. Although it has only a subset of the information presented to the operator, the Expert Monitor "knows" enough to "sense" the major parts of the reactor. And information about parts of the plant available to the computer can sometimes be inferred through mass-energy balances.

The Expert Monitor continues to increase its ability to recognize various phases of normal and abnormal plant operation. In particular, ORNL researchers are developing a real-time system with capabilities to change priorities, recognize plant state and mode of operation, encode emergency and abnormal occurrence procedures, and learn from operators.

Another major area of investigation is an intelligent man-machine interface. An intelligent interface assimilates redundant and consistent information, thus reducing the sensory overload that operators experience. Instead of looking at three redundant indications of the same measurement, the operator sees only a single piece of information. Furthermore, the interface automatically displays information that is suspect or that deserves the operator's attention. This task is accomplished by highlighting the suspicious areas and by "pop-up" windows in corners of the display screen.

Operating the Nuclear Plant of the Future

The operator in future nuclear plants will be the "master" of a capable, cooperative, alert companion-controller of the computer persuasion. Together, operator and computer will carry out the task of operating a nuclear power plant safely and profitably.

In future plants, intelligent sensors will feed digitized process data to the control system through microwaves and fiber-optic cables. Data generated by sensors will be internally validated by microcomputers incorporated in them. The sensors will complement signal readings with information on statistical parameters that describe the signal's fluctuations and trends. In addition, sensor design, performance, and statistics information will be made available by the sensor itself to the control system, upon request.

Equipment and systems will also be intelligent. For instance, a pump will check itself and protect itself from damage by using its built-in microcomputer to ascertain that data received from its built-in sensors are correct.

The intelligent control system will maneuver the plant along safe optimal paths to meet goals set by the operator. The system will deliver to the centrally located operator all information desired including plant design, operational status, performance, and maintenance. The operator can query the control system about its line of reasoning and about possible actions or malfunctions.

To make the intelligent controller work, a network of redundant multiprocessor computers may be required. Multiprocessor computers consisting of 256 processors linked to each other in a parallel architecture are already within technological and financial reach. Parallel computers will permit the operator to interact simultaneously with the plant monitor and controller while receiving advice from expert systems and mathematical models of plant processes running in parallel at faster-than-real-time speeds. This feat would be accomplished by allocating subsets of processors to specific specialized tasks, such as running dynamic models for plant systems for varied time scales, implementing expert systems, and managing data bases. One or more processors dedicated to a task would communicate its findings as well as its information needs to other processors dedicated to other tasks as they run concurrently.

a three-part product: a knowledge base consisting of a group of rules, a time-dependent data base that describes the current state of the physical system, and an inference engine (a program that determines the appropriate knowledge to apply to the data). As a simplified example, consider a knowledge base containing the following information :

- neutron flux decreasing
- core coolant outlet temperature decreasing
- core coolant mass flow rate constant
- goal is to maintain power level.

With these data, the system might logically infer that it should withdraw the control rod slightly (to increase fissions) and explain to the operator why this action should be taken. If the operator contradicts the system, the program queries the operator for the correct knowledge to use next time. Thus the program learns from the operator and becomes smarter over time.

On the other hand, the operator might ask the AI expert system whether he should withdraw the control rods given the current data. This interaction is known as backward-inferencing— that is, one proposes an action and the expert checks whether the knowledge and data supports the action. Good expert systems use both forward and backward reasoning to speed their problem-solving.

These simple examples demonstrate the basic idea of a rule-based expert system. Rule-based expert systems have proven rather successful in a number of fields, including medical diagnosis, circuit design, prospecting, financial management, and equipment maintenance. Such a system is used in the Expert Intelligent Control Advisor being developed for the HFIR.

Using advanced reactor controls and AI techniques for monitoring the reactor and advising the operator will expand the current concept of control to include the total performance of the reactor. The ability to collect information about the response of the system under different conditions will build a data base that can be used in the future to help control unusual situations and to improve the understanding of the plant. This improved understanding can aid both the control and diagnostics of the reactor. In short, AI techniques can provide the average reactor operator with an advisor that incorporates the knowledge of design engineers and the world's best reactor operators to help the operator in any unusual situation. The HFIR Expert Intelligent Advisor and Expert Monitor projects and the advanced reactor control project at ORNL will contribute greatly to giving tomorrow's commercial reactor operator the "right stuff." ornl

BOOKS

***The Nuclear Connection: A Reassessment of Nuclear Power and Nuclear Proliferation**, eds. Alvin Weinberg, Marcelo Alonso, and Jack Barkenbus, A Washington Institute Book, Paragon House Publishers, New York, 1985 (286 pages plus index). Reviewed by Donald B. Trauger, Central Management Offices.*

Former ORNL Director Alvin Weinberg and coeditors Marcelo Alonso and Jack Barkenbus have compiled a volume about a vitally important issue in our troubled world. Proliferation of nuclear weapons has disturbed nuclear proponents and opponents alike since the early days of a perceived U.S. monopoly in nuclear technology. The proliferation picture has seldom been presented in so clear and evenhanded a manner as in this book.

The title suggests that the eight contributing authors* see a potential relationship between peacetime nuclear energy and weapons of war. Actually, the connection is not clear, as the jacket design suggests; the word "Connection" is depicted in broken type, graphically reflecting the true picture. Although nuclear energy and weapons are related, experience and logic suggest that the course of weapons development has been, and will continue to be, direct rather than through nuclear-power materials and technology.

Cartoonists have often depicted nuclear power plants as exploding (for dramatic effect or to promote antinuclear causes), but such explosions are now widely understood to be impossible. The connection (or lack thereof) between nuclear energy production and nuclear weapons is complex and subtle, not direct. This book explores the potential avenues by which the connection is traced and, in general, rejects these as erroneous.

One obvious method of obtaining weapons material from energy-production systems, for example, is to extract plutonium from spent fuel from a nuclear power reactor and use it to make an atomic bomb. However, the methods chosen thus far by the nuclear weapons countries (the United States, the Soviet Union, China, France, and Great Britain) for obtaining fissionable material have included (1) obtaining plutonium by reprocessing spent fuel from reactors dedicated to weapons production and (2) producing highly enriched uranium by gaseous diffusion or centrifuges. The book extensively and effectively examines the proliferation potential of these methods. The authors project that alternatives to using energy production systems to produce nuclear weapons material will continue to prevail.

For history buffs, *The Nuclear Connection* provides an accurate, capsulized account of many sequences of events that led to the production of nuclear energy. I was particularly interested in Karl Cohen's review of the uranium enrichment process. As one who participated in the first 12 years of the development of that process, I can attest to the accuracy of the chapter, and I relived some of the excitement of those times as I read it.

Plans, programs, and international agreements to prevent the spread of nuclear weapons are reviewed in the book beginning

* Chapters and contributing authors are (1) "Prospects for Commercial Nuclear Power and Proliferation" by Peter Auer, Marcelo Alonso, and Jack N. Barkenbus with commentaries by Juan Eibenschultz and David J. Rose; (2) "The Front End of the Fuel Cycle" by Karl P. Cohen with commentaries by Manson Benedict and Rudolf Rometsch; (3) "Backing Off the Back End" by Richard K. Lester with commentaries by James Bedore and Albert Carnesale; (4) "National Policy Issues" by David Fischer with commentaries by C. P. Zaleski and O. Quihillalt; (5) "Nonproliferation Regime: Safeguards, Controls, and Sanctions" by Lawrence Scheinman with commentaries by Warren H. Donnelly and William Epstein; and (6) "Nuclear Energy and Proliferation: A Longer Perspective" by Alvin M. Weinberg with commentaries by Bertrand Goldschmidt and Herbert Kouts.

with the Baruch Plan of 1946. The book also covers modern concerns over the weapons capability of countries such as Argentina and Pakistan. Interim agreements, from the early bilateral treaties to the SALT-II controversy involving the United States and the Soviet Union, are discussed in detail. The Nuclear Non-Proliferation Treaty of 1968 deservedly receives extensive review. The authors conclude that the international agreements and the agencies that provide control with inspection (such as the International Atomic Energy Agency) are serving well. Even so, they recognize the need for improvement.

In presenting arguments, the authors carefully provide current, accurate information about many aspects of nuclear energy production. Projections of energy demand and sources of production are treated; data about installed nuclear and electric capacity in developed and developing countries are presented; costs of energy production, including those for enrichment, nuclear reactors, fuel reprocessing, and waste disposal, are given; and the status of various countries with respect to nuclear capability and production is reviewed. Thus, the book provides a handy refresher course and is useful as a reference.

A valuable feature of *The Nuclear Connection* is its treatment of potential technical or commercial solutions for preventing proliferation. Foremost among suggested fixes is the proposal that each nation supplying enriched uranium or other fuel to another nation for nuclear power require the return of the fuel at the end of its useful life. Initially, the returned fuel would be stored; eventually, it could be reprocessed for fabricating new fuel. This measure should be attractive to many countries receiving fuel for nuclear power because, by returning spent fuel, they avoid the problem of disposing of radioactive waste.

The Soviet Union, in fact, requires the return of fuel supplied to its satellites or other countries and thus has a diversion-proof system in place. This plan would be much more difficult to implement in the Western world, where competition between countries exists and where the kind of authority accepted in the Russian sphere may be unacceptable. Even so, the option has an attractive nonproliferation potential that several authors enthusiastically support.

Accepting proliferation controls is increasingly difficult for non-weapons countries because of their concern about the increasing weapon stockpiles of the two major powers—the United States and the Soviet Union. The politically adverse effect of this "vertical" proliferation on "horizontal" proliferation is discussed. Recent news items, particularly the recent Bellerive Conference on this subject in Geneva, Switzerland, also suggest that this issue is important. Vertical proliferation looms as dangerous now as horizontal proliferation.

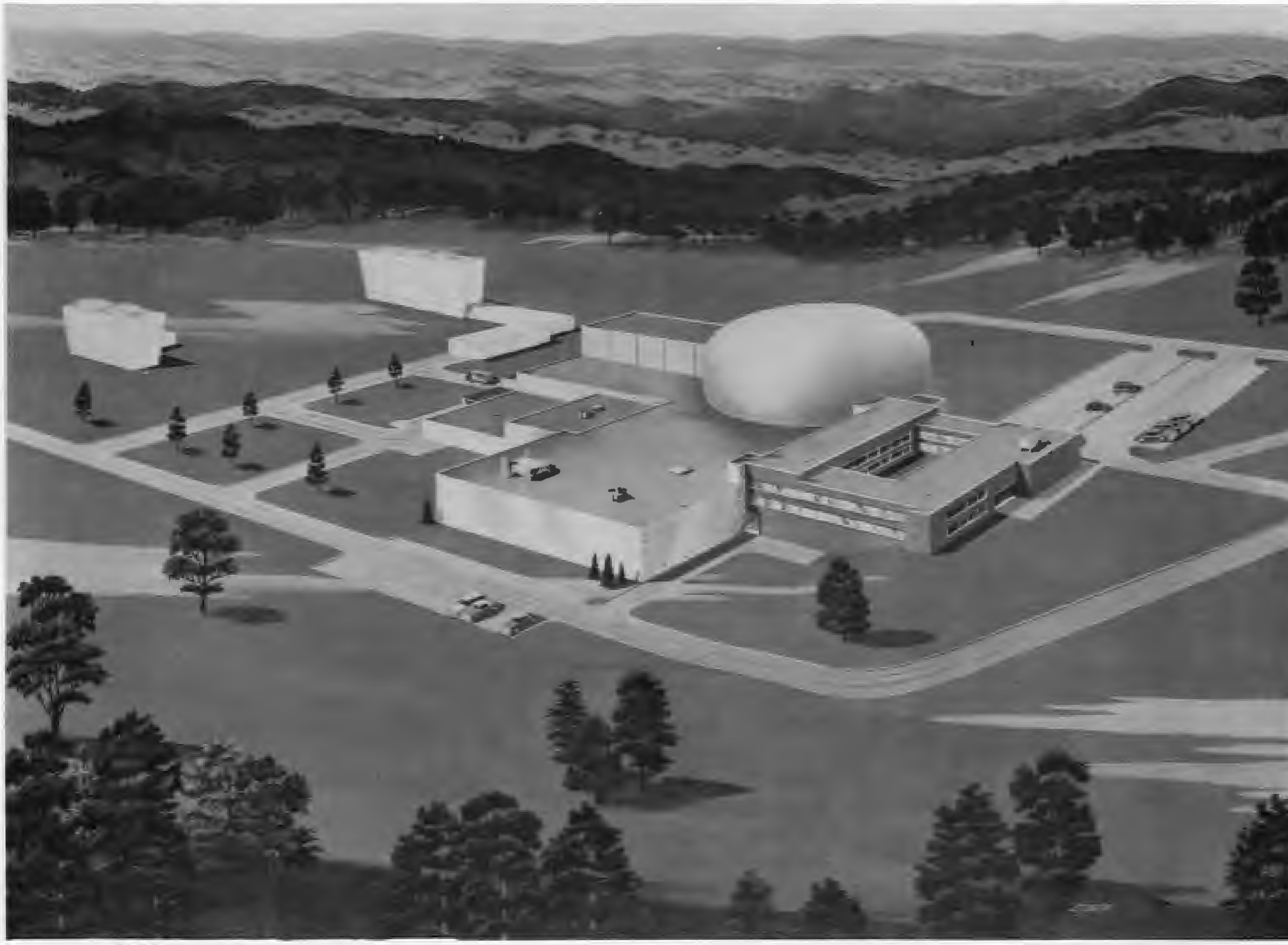
The presentation of material in *The Nuclear Connection* is organized into six separately authored chapters, each accompanied by two commentaries.* The commentary is generally useful in placing each chapter in perspective. It also provides many of the opinions that a reviewer might normally offer. A not unexpected result of the multiple authorship is a somewhat disconnected and, in some cases, repetitious treatment of subjects. In spite of this, the book is well coordinated, and the multiplicity of viewpoints makes for interesting reading.

Experts and educated laypeople alike will find *The Nuclear Connection* readable and highly informative, both about nuclear proliferation and about a large segment of the overall nuclear industry and technology. For those interested in particular aspects of nuclear energy, the chapters can stand alone. However, I highly recommend reading the entire book.

EDITOR'S NOTE: **The Second Nuclear Era: A New Start for Nuclear Power,** by Alvin M. Weinberg, Irving Spiewak, Jack N. Barkenbus, Robert S. Livingston, and Doan Phung, was published in late 1985 by Praeger Publishers, New York. The book addresses the question of how nuclear power can be made a more viable option for the generation of electricity. The contributors have worked or are working at the Institute for Energy Analysis at Oak Ridge Associated Universities. Four of them (Weinberg, Spiewak, Livingston, and technical editor Russ Manning) are former ORNL employees.

In the book the authors conclude that improvements following the 1979 accident at the Three Mile Island nuclear power plant have made current nuclear power reactors safer. However, they believe that a "second nuclear era" would be more acceptable to the public and utilities if safety were guaranteed through the use of "inherently safe" reactors.

They also suggest that nuclear power can be improved by standardizing plant design, concentrating reactors at a few sites, regulating reactors in a flexible and reasoned way, consolidating utilities and reactor construction firms, reducing construction costs for new reactors, improving performance of existing reactors, and ensuring secure disposal of radioactive waste. ornl



Artist's impression of the Center for Neutron Research (CNR).

Building a Better Research Reactor:

The Proposed Center for Neutron Research

By COLIN D. WEST

The United States was once the world's leader in neutron-scattering experiments, which are an important source of information about the basic structure of materials, because it had the reactor with the highest neutron concentration per unit area per second—the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. That lead has shifted to France in the past decade, but a new facility now being designed for ORNL will recapture it.

Early this year President Reagan requested $2.5 million for FY 1987 for research and development related to the proposed Center for Neutron Research (CNR), a new, national experimental facility that can provide an unparalleled steady-state source of neutrons and unmatched research space and equipment. The CNR, which will be a successor to the HFIR, will be open for use by scientists from universities, industry, and federal laboratories. It will be equipped with advanced instruments for neutron scattering and nuclear physics research, isotopes

Colin West is a group leader in ORNL's Engineering Technology Division, where he is responsible for irradiation experiments and for the direction of reactor design and R&D work related to the proposed Center for Neutron Research. This work is carried out in several divisions of the Laboratory. West was born in the United Kingdom and is now a U.S. citizen. He holds a Ph.D. degree in physics from the University of Liverpool. Before joining the ORNL staff in 1977, he worked for the United Kingdom Atomic Energy Authority. His research interests include irradiation experiments, reactor design, and Stirling engines. He has received two awards from Martin Marietta Energy Systems, Inc., for having several patents and for contributing to the upgrade of the irradiation facilities of ORNL's High Flux Isotope Reactor

production facilities, and facilities for studying the behavior of materials in very high radiation fields.

The CNR will be built around a new research reactor of unprecedented flux—that is, it will produce the most intense continuous beams of neutrons in the world. ORNL's goal is to reach a thermal neutron flux for beam experiments of 5 to 10 $\times 10^{19}$ neutrons $m^{-2} \cdot s^{-1}$. By comparison, the Institut Laue Langevin (ILL) reactor in Grenoble, France, currently the world's leading center for neutron-scattering experiments, has an unperturbed flux (that is, a nominal flux in the absence of any experimental facilities that might absorb neutrons) of 1.5×10^{19} $m^{-2} \cdot s^{-1}$. By combining the higher source flux with improved experimental facilities, the CNR will surpass the useful neutron flux capability of the ILL reactor by a factor of 5 to 10, and it will exceed the current U.S. high flux reactors—the HFIR and the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory—by a factor of 10 to 20. The CNR will also have 3 times as many scattering instruments than either the HFIR or the HFBR; thus, the CNR's scientific output should be at least 30 times as high as either of the facilities.

President Reagan has requested funds to support research and development related to ORNL's proposed Center for Neutron Research, which will succeed the High Flux Isotope Reactor as an improved steady-state source of neutrons for neutron scattering research, for isotope production, and for understanding the effects of radiation on materials. The CNR, which ORNL proposed and designed, will be available to scientists from universities, industry, and other federal laboratories.

For the production of transuranium isotopes for research, the new reactor will be superior to the world's current best facility—the HFIR. The CNR will also produce greater quantities of certain important isotopes used in medicine, and it will permit a faster simulation of long-term irradiation effects on the properties of engineering materials and nuclear fuels, making it a world leader in studies of the effects of radiation on materials.

The main motivation for building the Center, however, is to provide the best reactor possible for neutron-scattering experiments. The CNR's open-user policy will attract many scientists from universities and industry: in fact, we anticipate use by 700 to 1000 researchers each year for experiments in solid-state physics, chemistry, metallurgy, ceramics, polymers, colloids, biology, and nuclear physics.

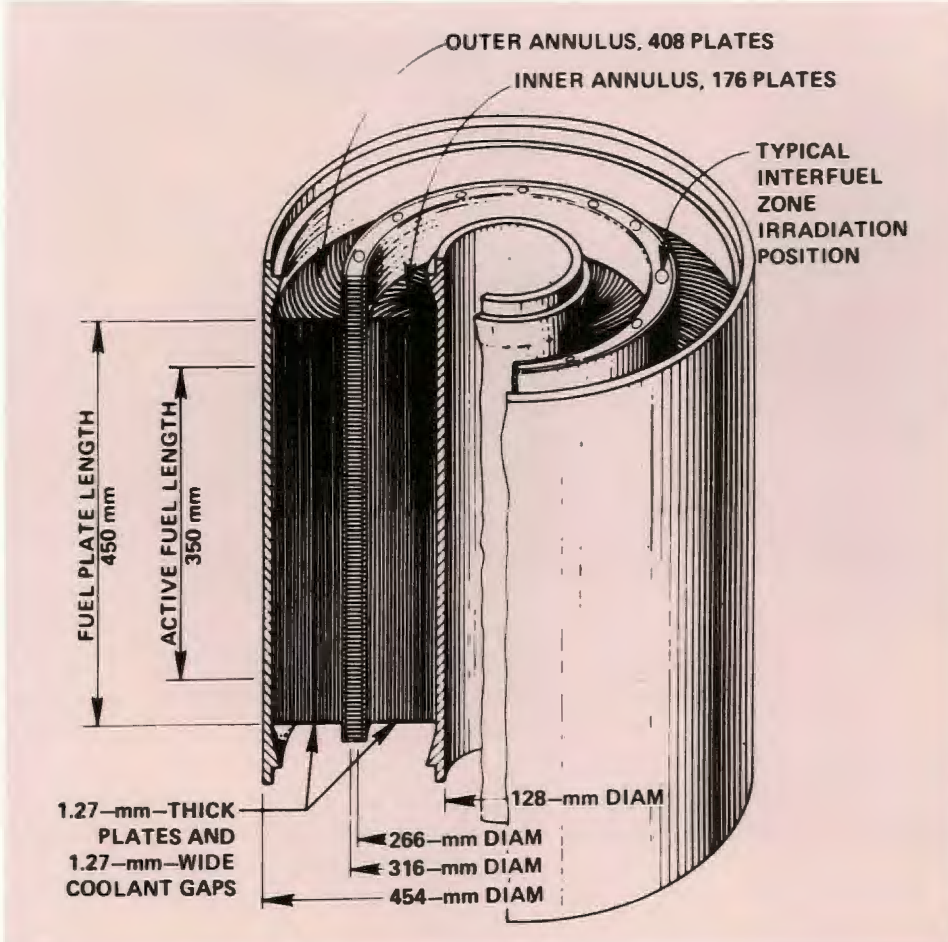
The Reactor

After a survey of different reactor concepts (including liquid-metal, molten-salt, gas, and water-cooled types), we have concluded that a heavy-water moderated reactor is the best choice for high thermal flux, minimum technical risk, and reliability of operation. The CNR reactor will use heavy (deuterated) water to cool the nuclear fuel core, slow down neutrons, and reflect them back into the core; by contrast, the HFIR uses ordinary water as the moderator and coolant and beryllium as the neutron reflector. The CNR will use uranium silicide rather than the HFIR's uranium oxide for its fuel.

By basing the CNR reactor as much as possible on existing technology, we shall minimize development costs. Our goal in this program is not to do research required for developing a radically new reactor design, but simply to build an unequalled research reactor for experiments on interesting materials.

The challenge, then, is to achieve a substantial flux increase with reasonable extensions of existing technology and to identify the areas of research that can be expected, with reasonable confidence, to show the biggest improvements in reactor performance. The minimum goal is to produce a thermal flux in the reflector of more than 5×10^{19} neutrons $m^{-2} \cdot s^{-1}$; if technically feasible, as our initial calculations suggest, we will push the design toward 10^{20} neutrons $m^{-2} \cdot s^{-1}$. To help ensure that the reactor is actually operating and available for a high proportion of the time, the design goal for the minimum core lifetime—the length of time the reactor can operate without refueling—has been set at two weeks.

The basic requirements of the reactor core design are a high power level (so that very many fissions will occur, producing many

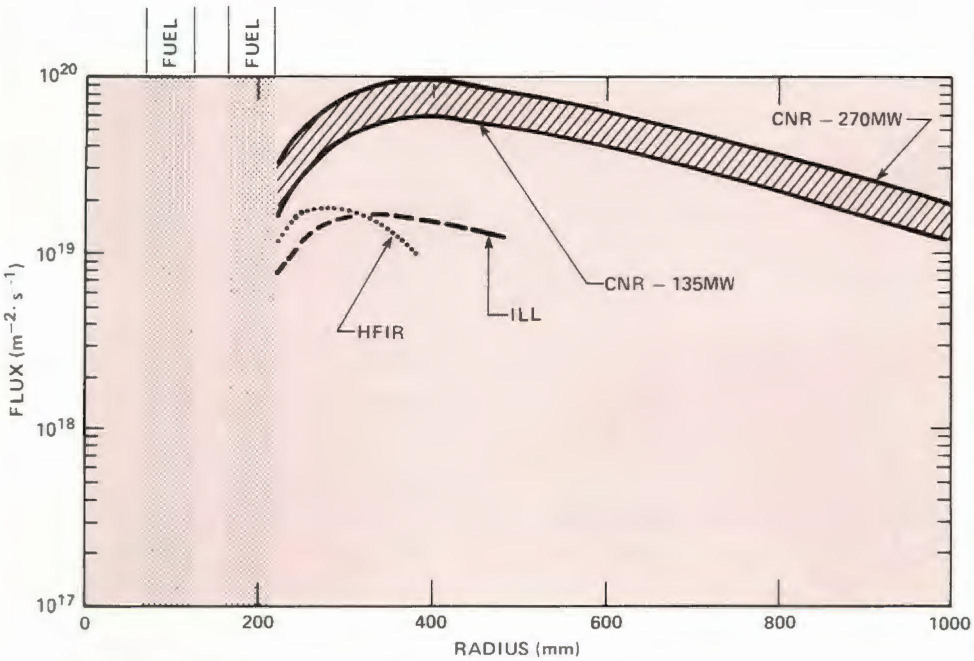


Reference core for the CNR.

neutrons) and a very compact core with a small surface area (so that the neutron flux, which is the number of neutrons passing through a sphere of unit cross-sectional area per second, is high). In fact, for cores of basically similar composition and geometry, the thermal flux in the reflector must be roughly proportional to the reactor power and inversely proportional to the surface area of the core. The surface area of the core increases as the two-thirds power of its volume, and the power density is equal to the power divided by the volume. As a result, the peak flux varies with the cube root of the reactor power and as power density to the two-thirds. This argument, which is the physical explanation of a correlation derived by ORNL's Felix Difillipo from many calculations, indicates the importance of a high power level and, especially, of a high power density.

The core is surrounded by a reflector of heavy water whose light atoms slow down the fast neutrons escaping from the core. Some of the neutrons are reflected back into the fuel region, and the combination of slowing down and reflection builds up a large peak in the population of thermal neutrons some distance outside the core. Beam tubes that transport the neutrons to experiments placed outside the reactor are inserted into the reflector close to this thermal peak.

Many preliminary calculations, based on a simplified model of the



Reference cores and thermal flux distribution for the Institut Laue Langevin (ILL) in France and the High Flux Isotope Reactor (HFIR) at ORNL.

reactor, have been performed, mainly by Difilippo and his colleagues in ORNL's Engineering Physics and Mathematics Division and by Trent Primm in the Engineering Technology Division, to evaluate different core designs. Currently, we favor a cylindrical core geometry with two annular fuel sections similar to the HFIR fuel elements.

The proposed fuel for the CNR is uranium silicide with the same aluminum alloy cladding material used on the HFIR fuel. George Copeland and John Griess of ORNL's Metals and Ceramics Division, who are experts on fuel composition and cladding behavior, have provided guidance on the choice of fuel composition and conformation. According to the calculations, a neutron flux requirement of at least $5 \times 10^{19}\ m^{-2} \cdot s^{-1}$ can be met with a reactor power of about 135 MW and an average power density of 3.8 MW/L. Wally Gambill of ORNL's Chemical Technology Division has shown that this power density is a reasonable target for the kind of aluminum fuel cladding used in the HFIR. Gambill calculates that the average power density could be increased to about 8 MW/L in the CNR if we can overcome the tendency of the aluminum cladding to grow a low-conductivity oxide layer. Because of its low thermal conductivity, this oxide layer can cause the fuel to overheat if the reactor core has too high a power density. Griess and others are conducting initial experiments to determine if oxide buildup can be reduced by surface treatment. Other options are changes in coolant chemistry or improvements in the coolant flow.

At the higher power density, it would be possible to attain an unperturbed thermal flux peak in the reflector of 10^{20} neutrons $m^{-2} \cdot s^{-1}$, nearly 7 times the ILL flux. We hope that research at ORNL and elsewhere will lead to important improvements in the reactor core design before the final CNR design is complete.

Calculated radial thermal flux distributions for a candidate CNR core, which we call the reference core, are compared with the flux distributions for the HFIR and ILL reactors. The calculation for a 270-MW CNR assumes that buildup of oxide scale on the aluminum cladding during the core lifetime is greatly reduced compared with current experience. Even if we cannot reduce the oxide growth rate, however, the CNR design offers significant advantages in both the magnitude of the peak thermal flux and the volume of the high flux region.

Neutron-Scattering Facilities

The reactor would be housed in a cylindrical, concrete and steel containment building large enough to provide space for neutron-beam experiments at two different levels in both the reactor building and in a large guide hall adjacent to the building. Through workshops he has organized, Ralph Moon of ORNL's Solid State Division has enlisted the aid of prominent members of the neutron-scattering scientific community in planning the experimental equipment and facilities needed by the Center. Besides the beam tubes for thermal neutrons, at least eight beams of cold neutrons will be delivered to the guide hall through totally reflecting neutron guides. Six more inclined beams will be delivered to the second floor of the reactor building. The reactor equipment and the control room will be housed in a separate building and on the top floor of the reactor building, with access restricted for security. A building with offices for permanent staff and visiting scientists, laboratory space, and machine shops will complete the complex.

Current plans call for two cold sources of liquid deuterium in the reflector. At the low temperature of liquid deuterium (25 K), the neutrons will be slowed down still further, making possible many important experiments that cannot otherwise be performed effectively. The heat load imposed on the liquid deuterium by radiation from the nearby core will be minimized by using carefully selected structural materials and, if necessary, by gamma shielding. The ORNL team hopes to locate the cold sources in a region where the thermal flux is about 2 to 3×10^{19} neutrons $m^{-2} \cdot s^{-1}$; this would provide a source flux of cold neutrons about six times that of the ILL. We also plan to incorporate a hot source—probably a block of graphite located in the reflector and heated to 2000 K—near the core to provide neutrons of a higher energy than found in the reflector itself.

Neutron Scattering

Neutron scattering research has grown dramatically throughout the world over the last decade. Growth has occurred both in the number of practitioners and in the number of scientific disciplines in which neutron scattering has been productively applied. This spurt was triggered by the Institut Laue-Langevin (ILL) in Grenoble, France, where intense neutron beams from ILL's research reactor, innovative instrumentation, and institutional policies have combined to create great interest in, and demand for, neutron scattering facilities.

The growth of neutron scattering stems from certain fundamental properties of the neutron which give it some unique advantages over other commonly used scattering probes, such as X rays and electrons. For structural studies, where the goal is to determine the relative position of atoms within the sample, a probe with a wavelength comparable to interatomic distances is desired. Clearly all three probes, each of which may have the appropriate wavelength, can be used for structural determinations. Therefore, the selection of the most appropriate probe rests on factors other than wavelength.

For dynamical studies, where the goal is to determine the relative motion of atoms within the sample, it is desirable to have a probe with energy comparable to the energy of motion of the sample's atoms. Because the thermally activated motions of atoms have energies generally less than 100 meV—the energy range of most neutrons from the cores of research reactors—the neutron offers a great natural advantage for studies of the dynamics of condensed matter (solids and liquids).

The slow velocity of thermal neutrons permits easily measured flight times of a few milliseconds at distances of a few meters. Time-of-flight techniques are therefore an important part of neutron scattering experiments.

The selection of a probe is also influenced by its scattering amplitude—a measure of the strength of the interaction between the probe and target atom. Neutron scattering amplitudes offer at least two advantages over those of X rays and electrons.

First, because neutrons interact weakly, multiple scattering effects occur less among neutrons than among X rays and electrons, and probabilities (cross sections) for scattering neutrons in a particular direction are more easily determined.

Second, the nuclear scattering amplitudes for neutrons do not vary systematically across the periodic table as do the corresponding amplitudes for X rays and electrons; instead, they vary markedly for different target materials. This property allows the neutron to "see" light atoms in the presence of heavy atoms and to distinguish between neighboring atoms in the periodic table. Even more significant in the case of neutrons, a strong variation in scattering amplitude exists among isotopes of the same element. An important example in neutron scattering is hydrogen and its isotope deuterium, which have strongly different scattering amplitudes, leading to many applications in biology and polymer science.

Another property of the neutron that has led to a better understanding of materials is the neutron's magnetic moment. This attribute results in a magnetic interaction with atomic magnetic moments, which reflect the strength of the magnetic fields produced by the atoms' circulating electrons. The magnetic scattering of neutrons has truly revolutionized the understanding of magnetic materials. Many complex magnetic structures have been determined, and magnetic scattering has tested theories of phase transitions (e.g., the onset of magnetic order).

The penetration of neutrons into materials such as aluminum suggests that neutron scattering is more useful for probing the bulk of a solid than the surface. Surface preparation, therefore, is not normally a concern. With neutron scattering, residual stresses can be probed to depths of several centimeters, and the entire population of defects in a sample can be measured simultaneously. Another important consequence of the penetrating power of neutrons is the ease of bringing a beam in and out of cryostats, furnaces, and pressure cells so that the sample temperature and pressure inside can be readily controlled using common structural materials.

The disadvantages of using neutrons are their relative scarcity and high cost, compared with X rays and electrons. These factors dictate that neutrons be used only for those problems where their unique properties give them clear advantages over other probes and that facilities be shared among qualified users. Even with this constraint, wide fields of research in many scientific disciplines remain open for neutron scattering.—*Ralph M. Moon, Solid State Division.*

The CNR will employ two approaches to increase the intensity of the beams at the experimental target: (1) increasing the height, but not the width, of the beam tube entrance and (2) using monochromators (devices for selecting neutrons of certain wavelengths) that focus in a vertical plane. With very little loss in resolution, these techniques can significantly improve the flux for some experiments. The CNR will employ both of these approaches to achieve additional gains over existing reactors in neutron flux at the sample position.

To obtain advice on selecting instruments for the CNR, Moon organized in Oak Ridge a workshop involving scientists from many

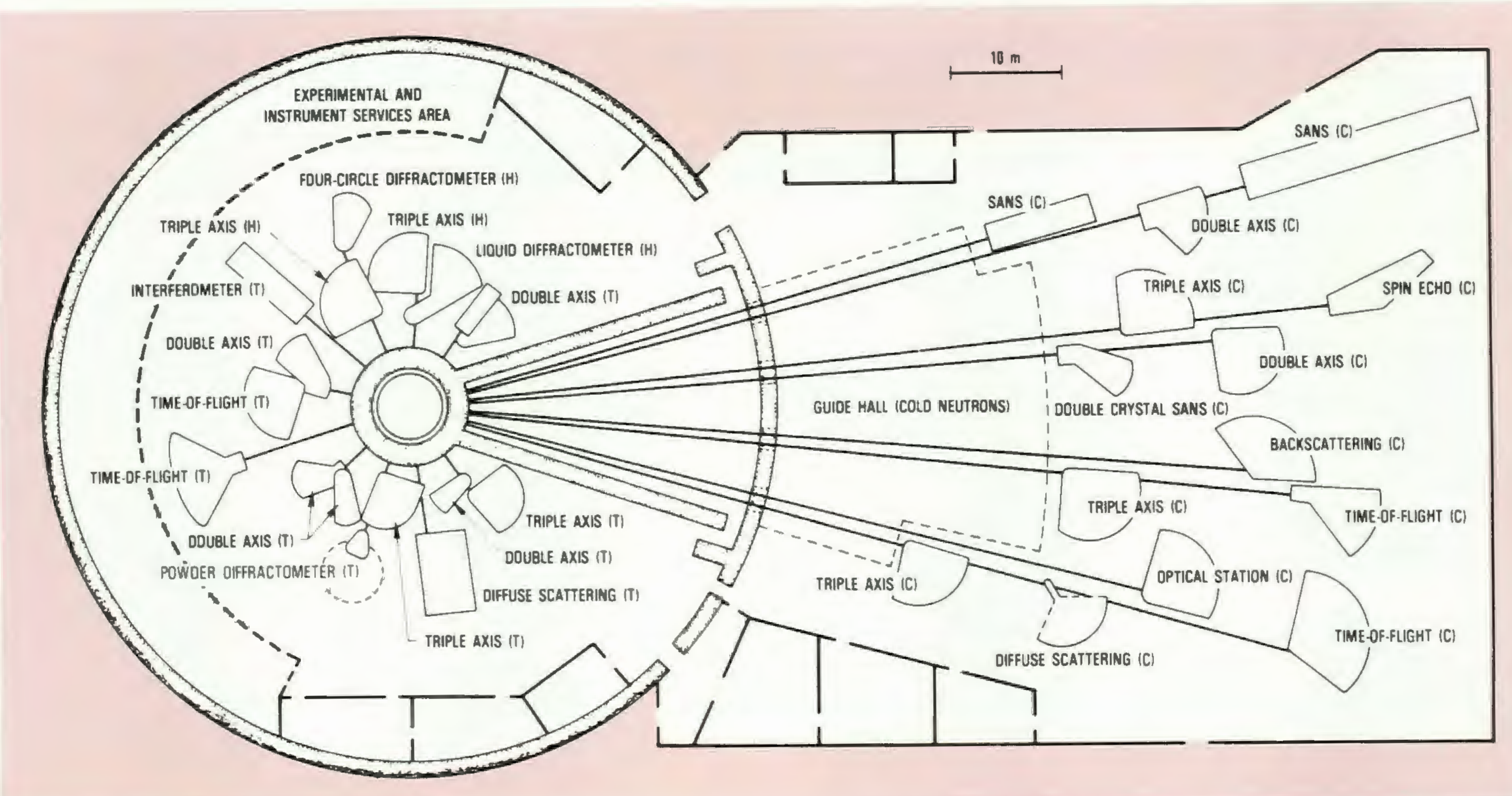
Table 1. Irradiation positions and characteristics for CNR core—comparison with HFIR

	Flux (10^{19} $m^{-2} \cdot s^{-1}$)			Spectrum (ratio)	
	Fast	Epithermal	Thermal	Fast/thermal	Epithermal/thermal
CNR reference core (135 MW)					
Interfuel zone	3.8	0.4	0.08	50	5.4
Epithermal peak region	0.9	1.5	3.0	0.3	0.5
Outer reflector thermal	—	—	1.7	—	—
HFIR					
Target region	1.4	0.6	3.0	0.5	0.2
Removable beryllium	0.5	0.4	1.7	0.3	0.2
VXF[a]	—	0.1	1.0	—	0.1

[a]Small inner vertical experimental facility.

Table 2. Major research areas—a 3- to 4-year national program

Research area	Cost ($ million)	Major ORNL participants
Fuel, cladding, and control rod materials and fabrication	8.1	Metals and Ceramics Division
Core analysis (neutronics and thermal hydraulics)	9.1	Engineering Physics and Mathematics, Chemical Technology, and Engineering Technology divisions
Neutron collection (beam tubes and sources)	7.5	Engineering Physics and Mathematics, Metals and Ceramics, Solid State, and Engineering Technology divisions
Balance of plant	3.1	Engineering Technology Division
Other	1.9	Instrumentation and Controls, Energy, and Engineering Technology divisions
Contingency	5.8	
Total	35.5	



A schematic of the main experimental floor at the CNR showing possible locations for the instruments. In all, about 30 instruments costing a total of $30 million are planned for the CNR.

different disciplines. Study groups in solid-state physics, chemistry, materials science, polymer science, biology, neutron optics, and nuclear physics made recommendations on the types of instruments considered essential to advancing the science in their particular fields. In all, about 30 instruments costing a total of $30 million are planned for the CNR.

Materials Irradiation Facilities

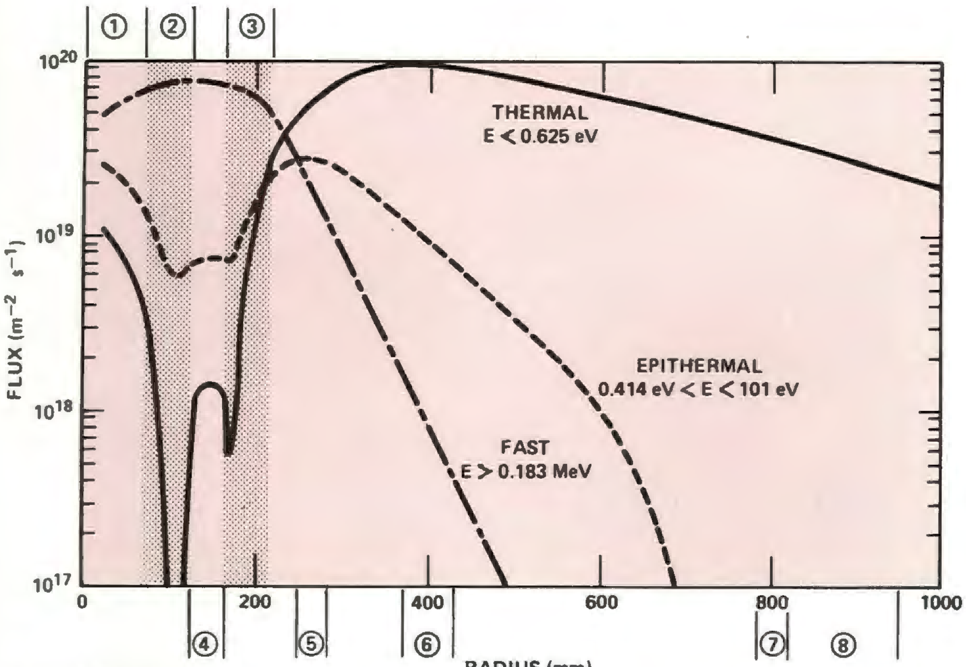
Most experimenters who study the effects of radiation on materials want a high flux that is very rich in fast neutrons because it is the fast neutrons that cause most of the property changes observed in irradiated materials. Such a "hard spectrum" occurs close to the fuel of the reactor because in that region the fast neutrons produced by the fission process have not had time to be slowed down, or thermalized, by the heavy-water moderator. Our current CNR design provides for irradiation positions between the two annular fuel elements. A ring of aluminum (about 25 mm thick) separating the two elements will contain several axial holes about 18 mm in diameter. These holes will accept experimental capsules of the same size as the ones now irradiated in the HFIR target region, but they will be subjected to a flux three to five times higher.

Larger experiments may be accommodated in the reflector outside the fuel where the spectrum is as hard as in the HFIR's equivalent positions (the removable beryllium irradiation facilities) but where the flux is higher.

Some experiments involving irradiation of fuels require a lower flux, which is more representative of operating conditions in power reactors; these will presumably be placed far out in the reflector, away from the core and its fast neutrons.

Isotope Production

For isotope production, a high flux of neutrons with energies in the thermal range, or slightly higher in what is called the epithermal range, is required. Two excellent places for the production of transuranium elements (such as californium, a neutron source used to treat advanced cancers) will be the zone between the fuel elements and also a region just outside the fuel where the fast neutrons from fissioning uranium in the core have mostly slowed down to the epithermal range, but are not yet fully thermalized. Those two positions, and others even farther out in the reflector where the epithermal neutrons have come down to still lower energies, will be the facilities of choice for the production of many other isotopes. (For more information on isotope



1. INNER REFLECTOR
2. FUEL
3. FUEL
4. INTERFUEL IRRADIATION POSITIONS
5. EPITHERMAL PEAK IRRADIATION POSITIONS
6. BEAM TUBE ENTRANCE
7. OUTER REFLECTOR THERMAL IRRADIATION POSITIONS
8. COLD SOURCE LOCATION (270–MW CORE)

The CNR's radial flux distribution and spectrum.

production at ORNL, see the article on page 74).

The facilities for transuranium production will be designed, if possible, to accept the standard target rods now used at the HFIR. This approach will allow the equipment and techniques already developed for preparation and processing at the Transuranium Processing Plant to be used without modification.

The capture of neutrons by the target material in isotope production, or by materials irradiation samples, will naturally affect the neutron flux and spectrum available for other uses, including the beam tubes, hot source, and cold sources. All of our calculations so far have considered the so-called "unperturbed" flux—that is, the flux that would be observed in the absence of any experiments or experimental equipment in the reactor. The same convention has been observed for other reactors; thus, the flux figures quoted for ILL, for example, are also idealized, unperturbed ones. The next step in our design work will involve taking account of the perturbations; it is known that the real, available flux at ILL is about 20% lower than the theoretical unperturbed value, so the effect is quite significant.

Research Program

As indicated earlier, the power, and, therefore, the flux obtainable from a reactor of a given size is limited by the fuel and its cladding. To increase the fuel loading, the ORNL team proposes using ^{235}U fuel, in the form of a silicide (U_3Si_2) that has a higher density than the oxide form used in the HFIR and, consequently, allows more uranium to be contained in a fuel plate of a given size. Fortunately, just such highly loaded fuels have already been developed for quite other purposes in a program based at Argonne National Laboratory. ORNL has made contributions to this Reduced Enrichment for Research and Test Reactors Program, and silicide fuels are now in use at the Oak Ridge Research Reactor as part of the extensive test program.

Basic information and fabrication techniques are, therefore, already known, although for the CNR program much work remains, including investigation of the irradiation properties of highly enriched uranium silicides. The exciting possibility of much higher performance if the oxide formation can be suppressed in the aluminum fuel cladding is another area of promising research for the CNR. Improving the thermal hydraulic design and the detailed fuel distribution within the core can also lead safely to a higher flux. Improving the cold source (compared with present designs) and the beam tubes and guides will increase the fraction of neutrons that reach the experimental samples.

Of course, work is also needed in other areas, such as structural analysis, safety-related issues, environmental effects, and controls and instrumentation to establish the basic feasibility and safety of the design. Our proposed R&D program would be completed over 3 to 5 years, depending on funding levels. Much of the R&D will be performed under subcontract by universities, other laboratories, and industry, who have the necessary expertise or facilities. We hope that funding from the U.S. Department of Energy for the program will begin later in FY 1986 and in FY 1987. The work done so far has been supported by the Director's discretionary fund, a mark of the importance that the Laboratory attaches to this project.

Research and Development Opportunities

Area	Goal	Potential benefits
Oxide formation	Reduce oxide formation rate by 80%	35–80% increase in peak reflector thermal flux compared with HFIR fuel
Fuel density grading	Fabricate fuel with continuous gradient areal loading both of radially and axially	20–40% increase in peak reflector thermal flux compared with HFIR fuel grading
Fuel composition	Increase mass of fuel Increase thermal conductivity of dispersion by use of silicide fuel	Lengthen fuel cycle by 25–75% compared with HFIR fuel Increase peak reflector thermal flux by 0–10%
Fuel inspection technique	Reduced variability in areal fuel loading of cores accepted for use	20–40% increase in peak reflector thermal flux compared with HFIR fuel inspection methods
Thermal hydraulics	Improve coolant velocity Provide greater cooling capacity (250 MW)	Increase peak reflector thermal flux by 75–115% compared with HFIR coolant conditions and power
Core physics	Optimize core, reflector, and control rod geometry for beam tube work	50–100% increase in peak reflector thermal flux compared with HFIR
Instrumentation and controls	Set scram point closer to operating point	0–15% increase in peak reflector thermal flux compared with HFIR system
Beam tube and guide tube design	Improve beam tube geometry Improve guide tube coatings and geometry	50–100% increase in useful flux at the beam target compared with ILL
Cold source	Reduce thermal load and void formation Improve coupling between cold source and guide tubes	Necessary for cold source to be usable in much higher thermal flux region than ILL 25–75% increase in transmission compared with current sources

Costs

Thanks to excellent support from the Engineering Division of Energy Systems, under the leadership of John Murray, Fred Peretz, and Tom Pickel, we have a feasibility study with cost and schedule estimates for the construction of the Center. The artist's impression of the Center, showing the containment building, guide hall, office buildings, control room, and cooling towers, was prepared as part of their work. Based on a 200-MW plant, their preliminary estimate for final design and construction is $280 million, including all experimental facilities and neutron-scattering instruments. Because of uncertainty, cost estimates were also prepared for a 100-MW facility ($240 million) and a 400-MW facility ($340 million). Design, safety and environmental analysis, and construction of the CNR will take 8 to 10 years.

In estimating the operating costs for the CNR, we have relied on our operating experience with the HFIR. The greatest uncertainty is in the annual fuel cost, which is difficult to estimate before the core design has been fixed. This cost is dominated by the fabrication expense. We have actually made two sets of estimates, one based on fabrication cost per core equal to the HFIR case and the other based on doubling this fabrication cost to allow for possible surface modification of the fuel cladding. Our estimates, which assume that the reactor will be designed for a 15-day core lifetime and that two days must be allowed for refueling, range from $21.5 million to $30.8 million. For comparison, the current operating cost of the HFIR is $8.5 million per year, plus $3 million per year for neutron scattering. ORNL's cost for neutron scattering at the CNR is estimated to be $10 million per year. This increased amount will support an adequate staff (60 scientists and 30 technicians) to provide good interaction with users and to carry out their own research programs.

Summary

The United States could regain its leadership in neutron-scattering experiments, increase its capability for producing isotopes, and have the world's most powerful facility to study the effects of radiation on materials by building the Center for Neutron Research. ornl

Effects of Irradiating Engineering Materials

Testing structural materials that can be used in a high-radiation environment, as well as fuels or breeding materials for a variety of nuclear reactors, is a substantial and long-term effort at ORNL and at other laboratories in the United States and Europe. The name "engineering materials irradiation" is given to such work, distinguishing it from the more basic investigations of irradiation effects carried out by, for example, solid-state physicists and biologists.

Fast neutrons cause damage to materials primarily by striking the atoms of a solid, displacing them from their regular positions in the crystalline lattice. The resulting atomic defects slowly aggregate in the lattice, forming larger, microscopic defects consisting of platelets of atoms (dislocation loops) and tiny cavities. Slow neutrons cause damage primarily by transmutations; new atomic species are created, a process that is frequently accompanied by the formation of helium atoms. These helium atoms help to stabilize the microscopic cavities and often form small helium bubbles within the solid. The formation of these various microcopic defects alters the physical and mechanical properties of the material. Dimensional changes may occur as the result of irradiation creep or swelling caused by internal cavity formation. The material's strength frequently increases, but its ductility and resistance to crack propagation often decline.

The scale of irradiation effects is generally unappreciated by those not directly involved in this field of study. The atomic displacements are not simply a few atoms knocked out of place; in the first-wall material of a fusion reactor vessel, for example, it is expected that each atom of the structure will have been struck by fast neutrons and displaced to a new position not just once, but 100 times, during the life of the reactor.

For structural materials, usually steel or graphite, the experimenter's goal is to determine the extent of radiation-induced change in mechanical properties, such as tensile strength and fracture toughness. Most of these properties must be determined by measurements on the (radioactive) specimens in postirradiation examination (PIE). In addition, dimensional changes are usually measured during PIE or by neutron radiography. Creep, which is also affected by neutron irradiation, has been measured on specimens while they are in the reactor, but is more usually evaluated during PIE.

In fuels testing, the usual goal is to determine the integrity of fuel cladding, the release and transport of fission products, and the mechanical changes in the fuel. Often, an inert gas is swept over the fuel specimens during irradiation; the sweep gas is then analyzed for gaseous fission products. The same technique has been applied to investigations of tritium breeder materials for fusion reactors.

At ORNL most materials irradiation experiments have been carried out in the High Flux Isotope Reactor and Oak Ridge Research Reactor. If the Center for Neutron Research is built, these experiments could be carried out at a higher flux, thus providing valuable information about long-term radiation damage in reactor materials in a shorter time.—*Arthur Rowcliffe, Metals and Ceramics Division.*

Contributors to the CNR Project

Although the CNR is only a small project so far, a large number of people have contributed to the proposal. Colin West is the director for the design and R&D work. Ralph Moon is responsible for specifying the neutron beam research facilities that are needed and for interacting with potential users.

The heart of the technical team consists of George Copeland, Metals and Ceramics (M&C) Division; Felix Difilippo, Engineering Physics and Mathematics Division; Ken Farrell, M&C Division; Wally Gambill, Chemical Technology Division; John Griess, M&C Division; Trent Primm, Engineering Technology Division; and Ilana Siman-Tov, Engineering Technology Division.

Members of the Energy Systems Engineering Division who have contributed to the CNR project are Charlie Collins, Lynn Degenhardt, Fred Kalb, Charlie Kirb, John Murray, Fred Peretz, Ron Phillips, Tom Pickel, Rolf Rosenvinge, Jim Schubert, and Nick Tronolone.

Other ORNL employees or former employees who have been involved (some of whom will likely be involved again when the CNR research program starts up) are John Anderson, Syd Ball, Dave Bartine, Dick Cheverton, Bob Childs, Tom Cole, Jack Cunningham, Rich Gwaltney, Bob Holcomb, Marshall Sims, Regina Stinnett, Dave Thomas, Dave Vondy, and Brian Worley.

For 40 years ORNL has been producing radioisotopes for research, industry, and medicine—perhaps its most significant contribution in the nuclear field to the outside world. Applications of ORNL's best-selling radioisotopes and a history of its radioisotope program are presented.

R. S. Pressly weighs an aliquot of barium carbonate for the first radioisotope shipment from Clinton Laboratories (now ORNL) in August 1946. The shipment contained one millicurie of carbon-14. The center photograph shows Lab employees gathered at the Graphite Reactor to celebrate the first shipment of a reactor-produced isotope to the private sector. At right is carbon-14 production equipment.

Radioisotopes from ORNL:

40 Years of Customer Satisfaction

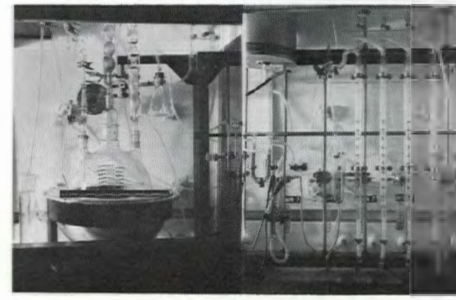
By CAROLYN KRAUSE

On August 2, 1946, a small amount of the radioisotope carbon-14, which was produced at the Graphite Reactor in Oak Ridge, was delivered to the Barnard Free Skin and Cancer Hospital in St. Louis, Missouri, for use in nuclear medicine. It was the first reactor-produced radioisotope shipped to the private sector.

Since then Oak Ridge National Laboratory has produced, packaged, and delivered numerous radioisotopes for use in industry, agriculture, research, space, and, most important, nuclear medicine. Undoubtedly, one of ORNL's most significant contributions in the nuclear field to the outside world, besides the development of nuclear power, is its production of radioisotopes. This contribution includes transferring the technology of radioisotope production to the private sector and continuing to supply it with enriched stable isotopes from which many pure radioisotopes can be obtained.

Today, using electromagnetic separators (calutrons), particle accelerators, and research reactors, ORNL produces more than 250 stable and radioactive forms of virtually all the known elements. The Laboratory makes these isotopes available in high-purity form to suppliers of pharmaceuticals and other products. In 1984 ORNL sold more than $15 million worth of stable and radioactive isotopes.

One of the most important radioisotopes used in medicine in the Western world is thallium-201, which is employed in over a half-million heart scans a year. Thallium-201 itself is not produced



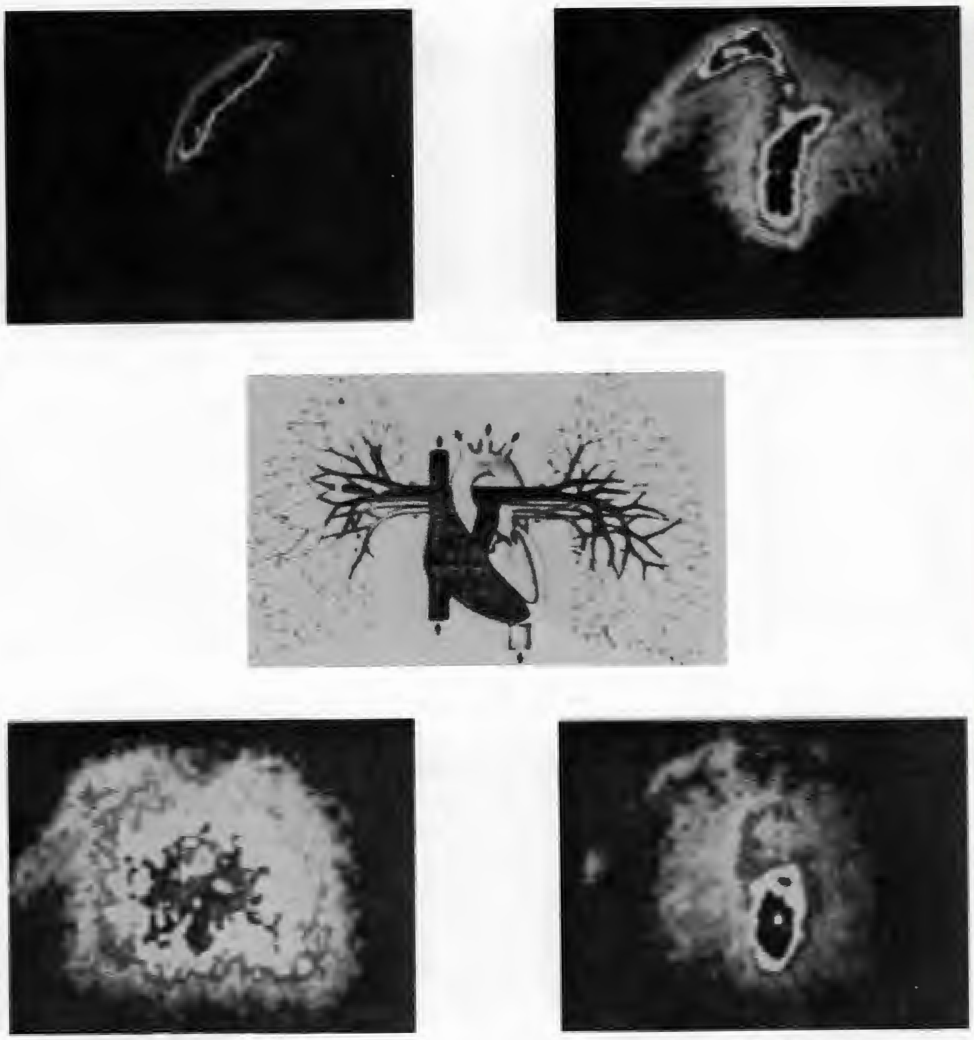
at ORNL, but the source material is enriched thallium-203, a stable isotope whose principal source in the free world is ORNL. Thallium-203 is produced in the calutrons to increase the yield and isotopic purity of the final product. The stable thallium-203 is converted by American, European, and Japanese cyclotrons into radioactive thallium-201, which is used to image the heart to determine if a heart attack is imminent, if one has occurred, or if therapy is effective.

Radioisotopes produced at ORNL today usually come directly from the High Flux Isotope Reactor (HFIR) or are decay products of elements made at HFIR. ORNL also packages radioisotopes in clever ways to meet customer needs. Here are some examples.

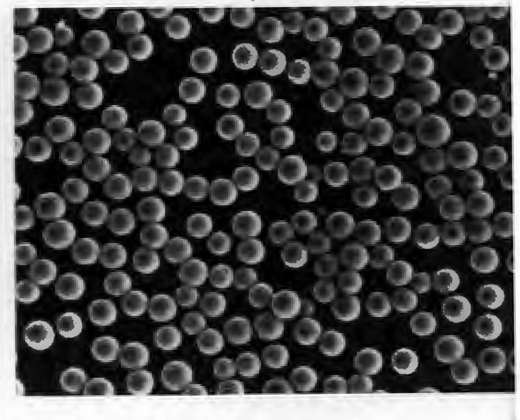
• **Osmium-191 for producing a heart-imaging agent.** Produced at HFIR, this radioisotope quickly decays to the short-lived daughter product iridium-191*m*, which emits a very low dose of gamma radiation and, thus, is particularly safe for detecting congenital heart defects in children. Researchers in the Nuclear Medicine Group, led by Russ Knapp of ORNL's Health and Safety Research Division, have developed an improved bedside generator that is safer and more efficient than the conventional version. Using a special absorbent that binds the osmium isotope but not the iridium imaging agent, the ORNL device increases the yield of pure iridium-191*m* from osmium-191 from 10% to 40%. In addition, it prevents for a longer time the contamination of the short-lived iridium agent with the longer-lived and highly radioactive osmium. The ORNL generator has been tested successfully in 100 patients in Belgium, and clinical studies of the generator are under way in the Federal Republic of Germany. The generator is expected to be approved for clinical use in the United States later this year.

• **Gadolinium-153 for measuring bone mineral loss.** A rare-earth radioisotope produced by irradiating europium with neutrons in HFIR, gadolinium-153 is used in scanning bones for mineral loss. Bone mineral loss, or osteoporosis, affects at least 10 million Americans—mainly, postmenopausal women and the elderly. Some 50,000 people die each year because of complications from broken hips, which can result from minor falls when calcium loss is severe and bones become progressively brittle. Fortunately, bone demineralization can now be effectively treated by giving patients calcium supplements and sodium fluoride. Because of the increased availability of these treatments, demand for gadolinium-153 has doubled in the past three years. Bone mineral loss or gain (as a result of therapy) can be inferred by measurements of bone density derived by comparing differences in the absorption of gadolinium-153's two radiations—a gamma ray and an X ray. Gadolinium-153 is currently the best-selling medically related radioisotope produced at ORNL. In 1984 ORNL distributed $500,000 worth of gadolinium-153 pellets to manufacturers of bone scanners.

• **Yttrium-90 for liver cancer treatment.** This decay product of strontium-90 (from spent nuclear fuel) can serve as an anticancer agent because its localized dose of powerful radiation will destroy tumor cells. It is safer than other isotopes because it has an extremely short half-life (63.4 h) and emits no gamma radiation. Clinical researchers are investigating its effectiveness in treating liver cancer and are



Angiograms using radioactive iridium-191m show how blood moves in the heart muscle (center) of a human patient. The illustration shows radioactivity in a bolus of blood in the major vein, or superior vena cava (upper left); right ventricle (upper right); lung field (lower left); and left ventricle (lower right). Such angiograms can be used to detect blood flow obstruction in the human heart. (Courtesy of Belgian collaborators.)



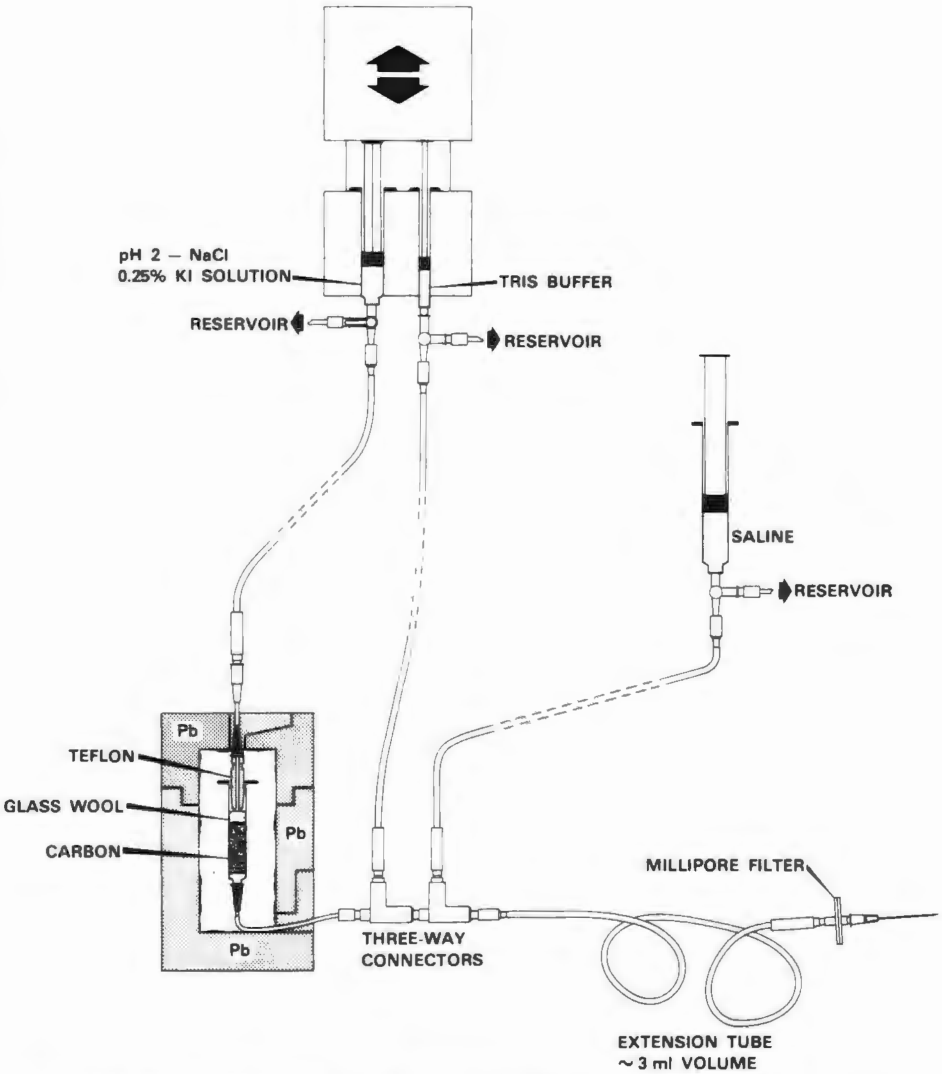
ORNL makes resin microspheres containing yttrium-90. The radioisotope is absorbed into microspheres having a diameter of 27 μm each. The microspheres are heated in an inert atmosphere, thus reducing their diameter by one third. The smaller size allows the yttrium-90 to be trapped in capillaries of cancerous livers where the powerful, short-range radiation destroys nearby cancer cells.

planning on testing it as a treatment for breast, colon, prostate, and skin cancers. So far poor results have been obtained from treating cancerous livers with chemotherapy, and surgeons have found it difficult to remove malignant tumors from liver tissue; researchers are therefore investigating whether radiopharmaceuticals in various forms can achieve better results.

The Medical Research Foundation (MRF) in Atlanta has demonstrated in laboratory mice that purified yttrium, which is soluble in blood, is safely contained in carbonized microspheres, produced at ORNL under the leadership of James Wike of the Operations Division. The microspheres are made small enough to enter blood vessels supplying a liver tumor but large enough to become lodged within the tumor's blood capillaries; from there, the yttrium-90 irradiates the cancerous tissue. Because its energetic beta radiation has a limited range in body tissue, unnecessary and potentially hazardous irradiation of healthy tissue is minimized. MRF has applied for federal approval to use yttrium-90 as an experimental cancer treatment in humans.

Yttrium-90 is also being studied as a promising new treatment for liver cancer by medical researchers at the Johns Hopkins Oncology Center in Baltimore. More than 100 patients suffering from advanced liver cancer are being treated experimentally with polyclonal antibodies labeled with yttrium-90. The genetically engineered antibodies are specially coded to recognize proteins linked to a specific type of cancer cell. Once in the bloodstream, each antibody carries the short-lived yttrium-90 directly to the tumor, where radiation destroys the cancerous cells. In a sense, the antibody acts as a guided missile, and the isotope is the warhead that destroys the target.

The use of ORNL-produced yttrium-90 at Johns Hopkins follows the conclusion of the first phase of a highly successful, internationally recognized research effort completed in the summer of 1985. According to Johns Hopkins researchers, the first major



Schematic of osmium-191–iridium-191m generator system developed for intravenous injection of a solution of iridium-191m for imaging heart defects in adults and children. A highly efficient generator was developed recently at ORNL and is now used for patients in Belgium and the Federal Republic of Germany.

study—involving the use of iodine-131-labeled antibodies—resulted in partial remission for 50 of 107 patients. Seven patients were disease free following treatments. Researchers hope for even better results in the current study because, with its potent energy, short range, and short half-life, yttrium-90 is considered better suited than iodine for use with polyclonal antibodies. Another advantage of treatment with yttrium-90-labeled antibodies is that it can be done on an outpatient basis.

• Tritium for radioluminescent devices. ORNL has been making and testing tritium-powered landing lights for airfields in remote regions. These lights, now in limited use in Alaska (which has more than 800 airfields), may help reduce the accident rate among Alaskan bush pilots, the highest in the nation. ORNL's landing lights on one Alaskan airstrip allowed an emergency medical team to quickly reach a critically injured retired gold miner whose house had burned down; the man, found lying in the snow, was saved. The radioluminescent lights produce a yellow-green glow visible up to 11 km (7 miles). They consist of phosphor coated on the interior of a glass tube containing the tritium. The tritium's beta radiation excites the phosphor and causes it to glow continuously. Because they require no electricity, the tritium lights are particularly useful in remote areas that lack electric power lines. The lights also require no batteries or maintenance and can last 10 years. They were devised by Neil Case; further development and testing are being done under the direction of Karl Haff.

Tritium is the best seller in the ORNL radioisotope inventory. Gadolinium-153, the top selling medical radioisotope, is the sixth best seller. In between are iridium-192, for industrial radiography applications, such as inspection of pipe welds; americium-241, for ionization-type smoke detectors and oil-well logging; krypton-85, for leak testing of sealed electrical components; and cobalt-60, for sterilizing medical instruments and food (to prevent spoilage). The revenue received by the U.S. Department of Energy from the sale of radioisotopes at ORNL ranges from $7 million to $10 million a year.

History of ORNL Radioisotopes

For 30 of ORNL's 43 years, the radioistope program was led by Art Rupp, a chemical engineer with Du Pont who joined the Manhattan Project at the University of Chicago before coming to Oak Ridge in the fall of 1943. Rupp, now retired, rubbed elbows with the scientific giants of the Manhattan Project, such as Arthur Compton and Enrico Fermi, whose group demonstrated the first self-sustained chain reaction in fissionable uranium at the University of Chicago's Stagg Field West Stands in December 1942.

U.S. Air Force employee installs a tritium light developed at ORNL on an Alaskan airstrip.

ORNL's tritium lights at the McIntyre Air Force Base in South Carolina. The lights were tested later in the Federal Republic of Germany and then Alaska.

One of Rupp's first tasks in Oak Ridge was to separate milligram amounts of plutonium from the spent fuel of the X-10 Pile, which was later called the Graphite Reactor. After it was demonstrated in Oak Ridge that a reactor could produce plutonium, Rupp was sent to the state of Washington to work on the Hanford plutonium project, which helped produce the bomb that ended World War II.

After the war Monsanto, the operating contractor at the Laboratory, offered Rupp a new position in Oak Ridge that he could not refuse. He was asked by Miles Leverett to build up a radioisotope development program. Purposes of the program included separating radioisotopes from the reactor's fission products and testing the effects of direct neutron irradiation of most of the elements and on many materials, ranging from seeds to test animals to piston rings.

In the June 1946 issue of *Science*, Waldo Cohn and colleagues from the Clinton Laboratories (now ORNL) announced the availability of its services in providing radioisotopes with applications in science, medicine, agriculture, and industry. Later, sales and distribution offices were set up under Jim Cox to handle the licensing details, customer contacts, and accounting.

In 1946–47 Rupp designed facilities for processing, handling, and shipping radioisotopes. The facilities were built in about 18 months at a cost of $3 million. In a series of articles published in November 1984 by *The Oak Ridger*, Rupp wrote, "I was influenced by my experience in high-explosives research to design the process buildings as small, separate buildings to minimize the effects of accidents such as fires or explosions. Such accidents would be confined to a small area, making it unlikely that many people would be injured. This design was a butt of a good many jokes ('Are they outhouses or tool sheds?'), but for more than 30 years of operation, no serious accidents have occurred that injured personnel or closed down the area for very long."

At about the same time, the radioisotope group became part of a larger program that included stable isotopes separations, carried out at the electromagnetic separators at the Y-12 Plant. Separations of stable isotopes (many of which are irradiated in accelerators to produce highly pure radioisotopes) were conducted under the leadership of Chris Keim, Leon Love, and Phil Baker.

In 1949 ORNL first produced cobalt-60 for cancer treatments to replace the more costly radium. By 1950 ORNL had completed 20,000 shipments of radioisotopes, which were used for treating cancer, detecting diseases, combating insect pests, and aiding the identification of oil and gasoline products in pipelines.

During this time, radioisotope container design, methods of packaging and shipping, and safety procedures were worked out, later to be copied by commercial and government institutions all over the world. ORNL's radioisotope technology was transferred through technical reports and visits to the Laboratory.

Craftsmen secure roll bars on a railway car at Oak Ridge Gaseous Diffusion Plant that was to return empty cesium-137 carriers to Hanford Engineering Development Laboratory. HEDL sent the cesium-137 by rail to ORNL for processing. ORNL then transported the empty carriers to ORGDP for return to HEDL.

To be usable, these radioisotopes had to have certain characteristics. The half-life (time for half the atoms to decay) had to be long enough for the product to be packaged, shipped, and put to use, but not too long (the radioisotope chlorine-36 was not produced, for example, because its half-life of 308,000 years made it impractical for radiobiochemistry). The radioisotope had to emit radiation in a useful energy range and have a desirable specific activity. Furthermore, the isotope had to be easily produced by the available neutron fluxes. One good example is cesium-137, which was first separated in large quantities from spent reactor fuel in 1954; it was found useful for cancer research and treatment. Another example is iodine-131, which was produced in large quantities at ORNL in the mid-1950s to meet the growing demand for this diagnostic agent for thyroid disorders.

In 1953–54 the Fission Product Pilot Plant was built at ORNL to separate and purify individual fission products and to fabricate heat sources of up to several hundred thousand curies. Its main contribution to the radioisotope program was the separation by chemical processing of very large quantities of pure fission products.

By 1957 ORNL offered its customers as many as 85 processed radioisotopes, ranging from antimony-122 to zirconium-95. But it was not to hold a monopoly in the radioisotope business much longer. At the request of the U.S. Congress and the Atomic Energy Commission (AEC), much radioisotope production was gradually transferred to private industry. Eventually ORNL ceased to make bulk shipments of radioisotopes to Mallinckrodt in St. Louis and New England Nuclear in Boston—two companies that prepared radiopharmaceuticals and products for direct use in hospitals and research laboratories. These companies and others began obtaining their radioisotopes on the open market or manufactured their own. But ORNL continues to make exotic isotopes that industry shows no interest in producing. Some of these isotopes are particularly useful for heat sources or food sterilization but have not been widely used because they are expensive to produce (in the first instance) or because of public fears about radiation (in the second instance).

By the 1960s ORNL's radioisotope development and production work had shifted to three newer reactors—the Low-Intensity Test Reactor, the Oak Ridge Research Reactor, and the HFIR. Methods were developed for improving the purity and specific activity of the radioisotope products, for separating transuranic isotopes from the HFIR's fuel and special targets, and for fabricating strontium-90 and curium-242 into heat sources for auxiliary space power plants. ORNL's radioisotope group also conducted research on isotopes obtained from other AEC facilities and on irradiated targets from university cyclotrons.

How Twinkling Atoms Aid Medical Diagnosis

Radioisotopes are used mainly as chemical tracers, revealing information about phenomena that cannot be directly seen or touched. The "twinkling atoms" of radioisotopes send signals to the outside world about the places where they are confined. These signals know few barriers because they come in the form of radiation—usually X rays, gamma rays, beta rays, positrons, or neutrons—that penetrates various thicknesses of matter. If these signals are picked up by detectors and analyzed, they can convey valuable information.

Consider iodine-131. If this radioisotope is introduced with ordinary iodine into the human body, it will concentrate in the thyroid gland, where normal iodine tends to concentrate. The movement of radioiodine to the thyroid gland—and within it—can be traced by a radiation detector, or body scanner. How does the scanner work? Gamma rays from the radioiodine excite the electrons of the sodium iodide crystal in the scanner. As the excited electrons relax, they give up their excess energy in the form of light. By measuring the varying intensity of the light (which is proportional to the energy of the radioactivity), photomultipliers in moving collimators scanning the body can determine the spatial distribution of the radioactivity. This distribution information charts the flow of blood and indicates the existence of diseased tissue or a tumor.

Similarly, a body scanner can be used to determine if a person has had a heart attack or has diseased cardiac tissue. Heart scans are made on patients injected with radioisotopes such as thallium-201, which allows blood flow in the heart muscle to be followed. In the case of a heart attack, some of the tissue will show reduced blood flow because of blockages or clogging in arteries. After interpreting the gamma-ray messages that the radioisotope sends from the heart, a physician can tell whether the patient had a heart attack and how much tissue has been damaged. From this "picture" of the heart the physician can recommend therapy (drugs, exercise, rest, etc.) to help the patient live a longer, healthier life.

Today many physicians are relying on a new generation of imaging instruments that use single-photon emission computerized tomography (SPECT). With this technique, a computer can generate a three-dimensional image of the target organ by integrating numerous images taken by a moving detector from different angles. Because of the extended time required to obtain all the images, researchers at ORNL and elsewhere have been trying to develop radioisotope-labeled agents that stay in one place in an organ and are not readily redistributed, thus minimizing the error introduced into the final SPECT image. One such agent, a methyl-branched fatty acid developed at ORNL, is now being tested in heart patients in Boston and Vienna.

From 1966 to 1972, ORNL published the journal *Isotopes and Radiation Technology*, edited by Phil Baker (now retired). This journal is still considered the best technical source of information about the government's isotope program at that time.

ORNL's radioactive and stable isotope program is still going strong. Until June 1985 it was managed by Eugene Newman, and then it became the responsibility of Joe Setaro; both men work in the Operations Division. Several isotopes (e.g., iodine-123) are being studied for use in imaging heart and brain tissue by Russ Knapp's Nuclear Medicine Group.

ORNL not only developed the technology of radioisotope production used throughout the world but also made Oak Ridge a mecca for people interested in the characteristics and applications of

Packaging isotopes and preparing them for shipping required considerable staff time when ORNL was a major isotope production center.

Hoyce Bailey operates the process control panel board in ORNL's Fission Power Development Laboratory.

For two decades ORNL was an isotope production center. Here, clockwise, Bob Byrum, W. G. Tatum, and Tom Rice use master-slave manipulators in hot cells for preparing isotopes for customer use.

radioisotopes. Rupp credits another Oak Ridge institution for stimulating the worldwide use of radioisotopes for medicine. In the 1950s the School of Radioisotope Technology of the Oak Ridge Institute of Nuclear Studies (now Oak Ridge Associated Universities) attracted physicians, radiologists, physicists, and biologists from all over the world to Oak Ridge to learn the fundamentals of working with radioisotopes. These "students" returned to their hospitals, universities, and research institutions and spread their new knowledge about radioisotope applications and established or expanded departments of nuclear medicine. Since then millions of radiometric analyses using radioisotopes have been made in hospitals and research laboratories. Rupp believes that the greatest contribution by radioisotopes to human welfare is their use for medical diagnoses and treatment and for biomedical research. ornl

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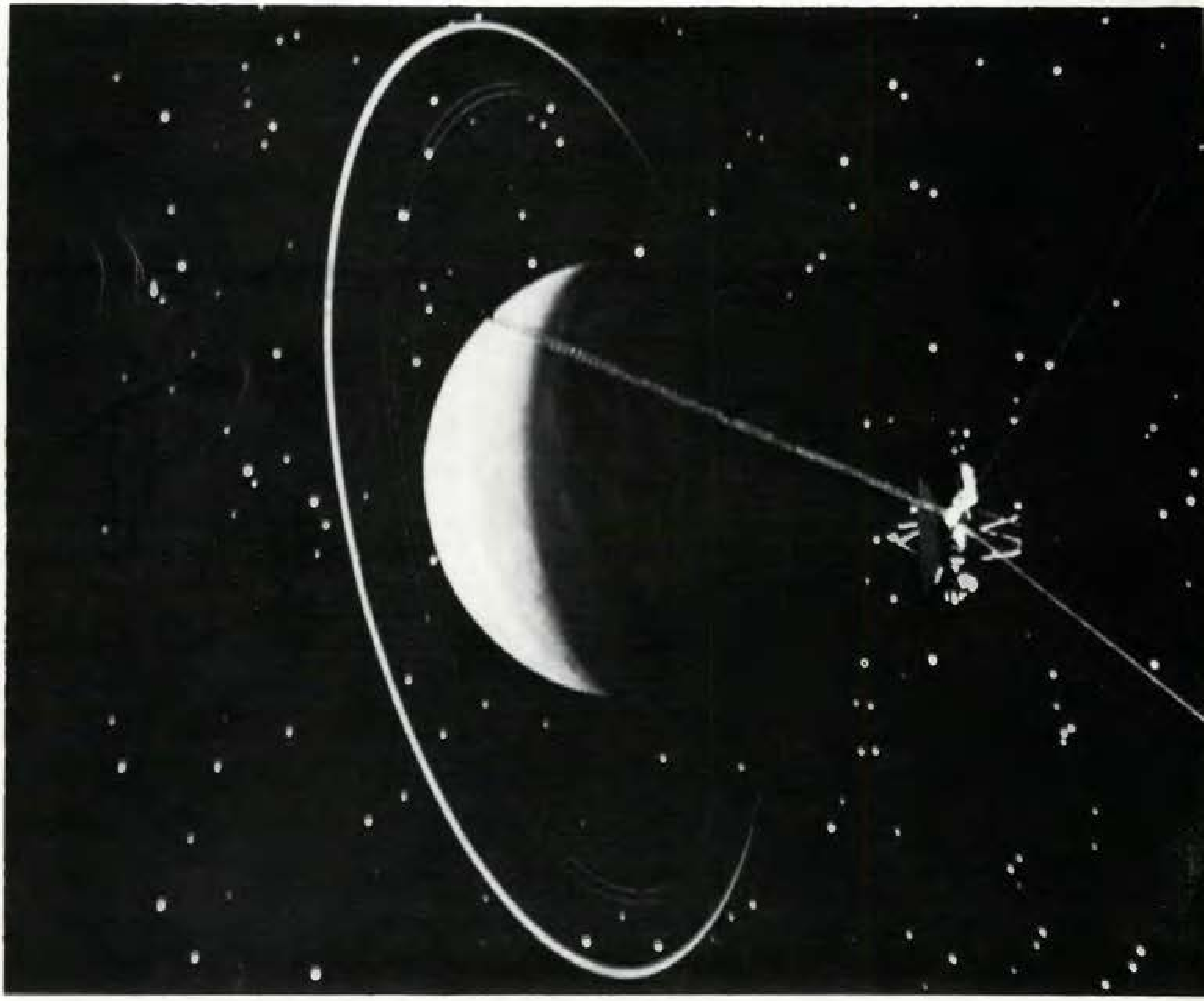

Voyager 2, which swooped past Uranus on January 24, draws its power from a radioactive heat source that is clad in an alloy developed and produced at ORNL. For more information, see "News Notes," page 45. (Courtesy of NASA.)