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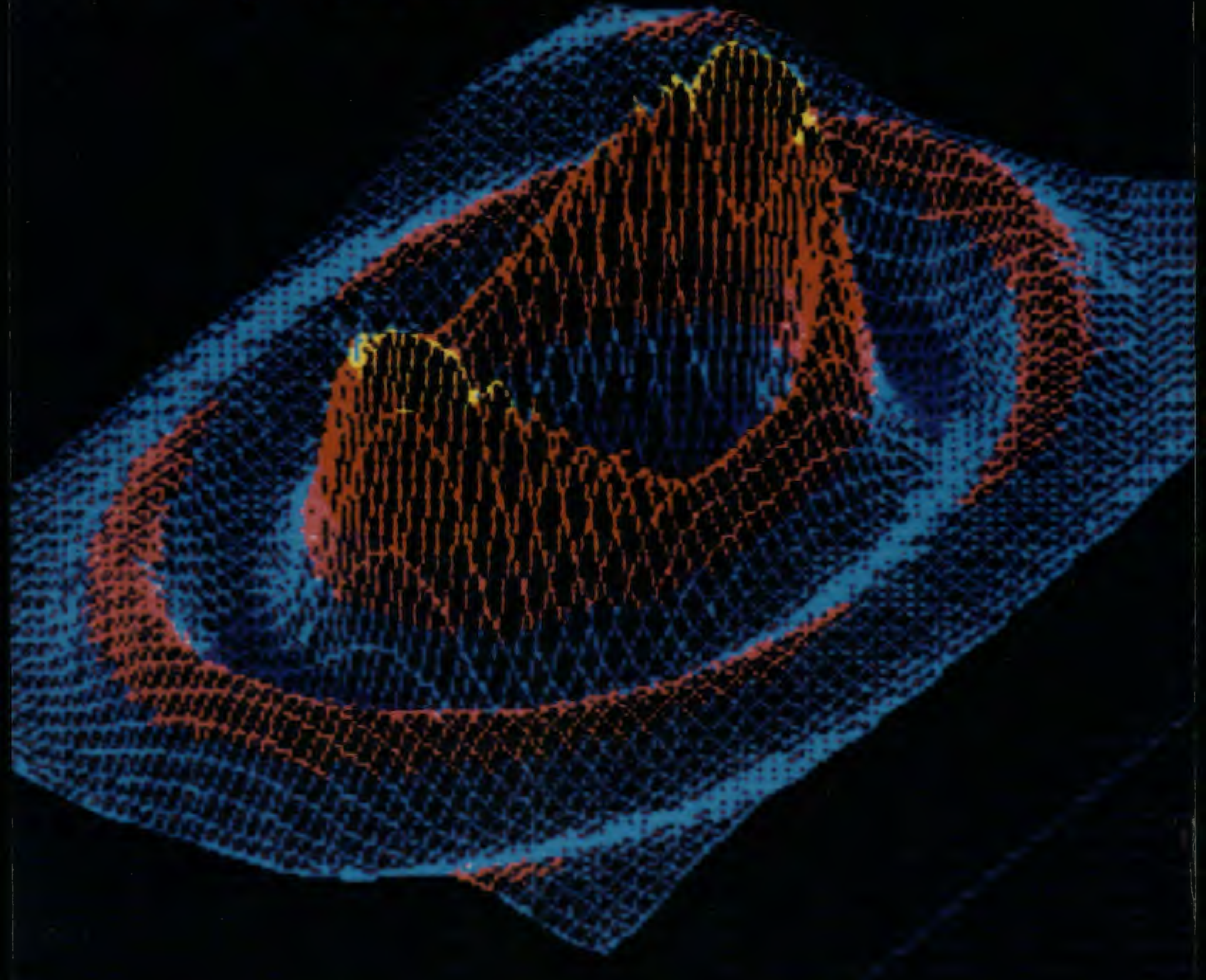

Volume 22

REVIEW

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Oak Ridge National Laboratory is a multiprogram, multipurpose laboratory that conducts research in the physical, chemical, and life sciences; in fusion, fission, and fossil energy; and in energy conservation and other energy-related technologies.

ON THE COVER

The cover illustration is a computer-generated visual representation of the calculated structure factor of a magnetically saturated ferrofluid. The structure factor, which describes the intensity of the neutrons in a small-angle neutron scattering experiment at a nuclear reactor, depends on the relative position of spherical magnetic particles suspended in a fluid with their magnetic moments aligned by an external magnetic field. Magnitude of the structure factor is indicated by color coding, ranging from purple (minimum) through yellow (maximum). Reactor applications, including neutron scattering, are the special focus of this issue, and the cover visual is related to one of the featured articles—"Neutron Scattering at Research Reactors," by Ralph Moon, on p. 86.

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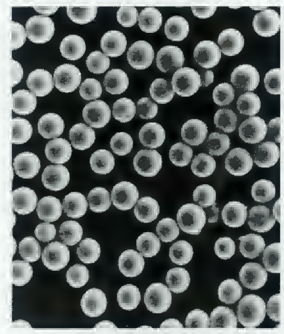
Features

Reactor Technology at ORNL



Energy Strategies

Departments

A Resurgence of Nuclear Energy?

By Alexander Zucker

"Electrical energy should be an issue of concern for Americans in the next decade."

If you ask the average American to name the serious problems this country faces, you likely would receive this answer: drugs and drug-related crimes, AIDS, homelessness and other forms of poverty, and the crisis in education. Avid newspaper readers might list the rising costs of health care and garbage collection, the breakdown of the family, the poor condition of bridges and highways, the decline of our nation's competitiveness in world markets, and the global consequences of pollution—the ozone hole, the damaging ecological and health effects of acid rain, and climatic warming. Very low on the list, if anywhere, does energy appear, and if it appears at all, the concern is for exhaustion of domestic oil and gas reserves or perhaps another Middle East crisis that could cut the U.S. supply of imported oil.

Nevertheless, electrical energy should be an issue of concern for Americans in the next decade (see figure). True, the utility companies have overbuilt generating capacity by a wide margin. Normal reserve margin—the amount by which the power-producing capacity exceeds the normal demand—is about 20%. This additional capacity is used to cope with major demand surges for very hot summer days, extremely cold winter periods, and outages of large power stations. From 1975 to 1990, largely because of energy conservation, this margin has been around 30%. However, the projection for 1995 shows the margin dipping below 20% and dropping toward zero after the turn of the century.

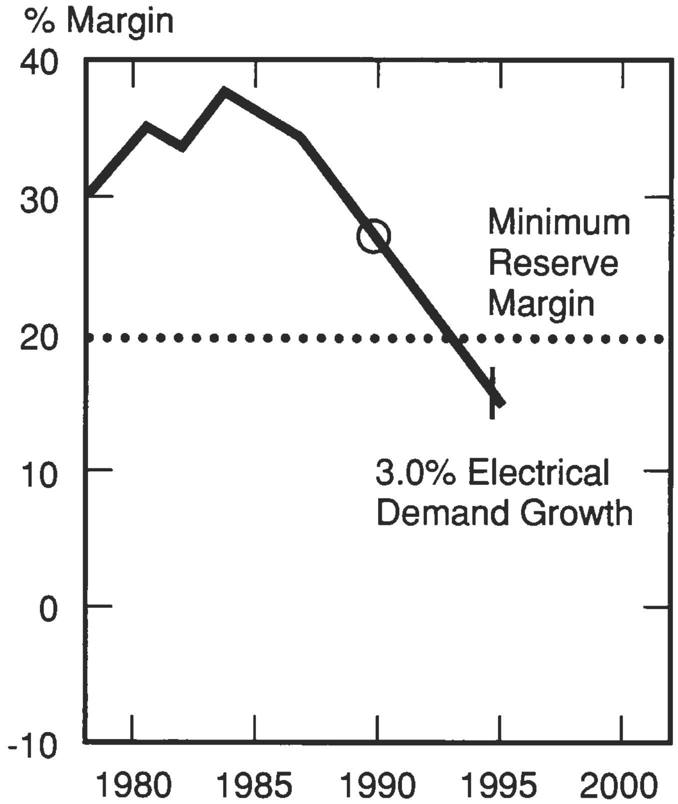
At least two factors enter into these projections. First is the actual amount of installed power, which consists mainly of plants fired by coal (provides 57% of U.S. electricity), nuclear energy (21%), oil and gas (12%), and of hydroelectric facilities (9%). The second factor is demand, which is much less certain because it depends on cost, the state of the economy, and the degree to which conservation or alternative forms of energy are substituted for electricity. For the past five years, total energy use has been growing at 2.5% per year, but at the same time, electrical energy demand has grown annually by 3.5%—a trend expected to continue.

In the near term, the most likely way this country will cope with declining margins is to build gas-fired turbine plants, import more power from Canada to serve the northeastern states, and transfer more power from surplus to deficit regions. Some new coal-fired plants will be built, and the availability of nuclear plants will no doubt increase. But, what if fear of global warming becomes a major national and international issue by the year 2000? What if, as a consequence of this concern, a moratorium is imposed on building new coal-fired plants and other sources of carbon dioxide? Farfetched? Not if you recall that just last fall at an international conference of environmental ministers in Holland, a recommendation of such a moratorium was adopted by a nearly unanimous vote; only Japan, the Soviet Union, and the United States opposed it. Is the handwriting on the wall?

In the face of a moratorium, the world has few alternatives: a drastic revision of lifestyles to get along with less energy or greatly increased efficiency of energy use, expanded use of renewable resources, and nuclear energy.

Nuclear power is one option that should command our attention, despite the Three Mile Island and Chernobyl nuclear plant accidents. Reports of its decline are greatly exaggerated. According to the 1989 year-end review of the U.S. Council for Energy Awareness, "During the decade, nuclear generation almost doubled in the United States, to become the nation's second largest source of electricity. Forty-six new nuclear units were added, bringing the total to 112. In 1980 it [nuclear energy] passed oil; in 1983 it overtook natural gas; and in 1984 it overtook America's massive hydropower resources. The industry accomplished that growth despite the challenges of high interest rates, mounting construction costs, and extreme regulatory uncertainty." The Council noted that U.S. nuclear power has reduced consumption of foreign oil by 4 billion barrels since the 1973 oil embargo and, in 1988, cut utility emissions of carbon dioxide by 20%. Although this news sounds impressive, very little growth in nuclear electricity is expected in the next decade.

The perceived need for a resurgence of nuclear energy (including research reactors at ORNL) has inspired this issue of the *Review*. It contains a look at reactors of the future, a future in which safety becomes the guiding principle of designers, builders, and operators of nuclear power stations.



Source: Available Resources 7/86 National Electric Reliability Council Electrical Power Supply and Demand

The U.S. electrical capacity margin is projected to drop below 20% by 1995 and approach zero by the turn of the century unless trends change.

We are encouraged by what we see. New concepts for safe reactors have emerged over the last decade, and now it remains to flesh out their development and find utilities to order them. To see what is new and why the nuclear future looks brighter than many of us suppose, read this issue. It may surprise you.

Alex Zucker is ORNL Associate Director for Nuclear Technologies.

Reactors Are Central to ORNL's Missions

By Alvin Trivelpiece

"Though the number of U.S. reactors has steadily decreased, the needs for research reactors are expected to grow."

During the past three years, the Department of Energy has extensively reassessed the safety of research reactors at the national laboratories and other research institutions, resulting in shutdown of many reactors. ORNL's research reactors have been shut down for extended periods, intensely examined, and modified to ensure that future operations will be as safe as possible. Almost all ORNL programs have been affected by our dedicated efforts to prepare these reactors for restart. Therefore, in this issue of the *Review*, it is most appropriate to reflect on the important role of research reactors in ORNL's history and to recognize the enormous importance of reactors to present and future programs at ORNL—including some current programs developing and evaluating new reactor designs that may benefit the worldwide commercial nuclear industry.

Nuclear reactors have been central to our missions here since the 1940s, when we served the Manhattan Project as the Clinton Laboratories. In those early years, ORNL's efforts had a profound national impact. The Graphite Reactor produced fissile materials for the war effort and became the first U.S. reactor dedicated to isotopes production and nuclear research, including basic nuclear and solid state physics, reactor design and construction, operational characteristics of reactors, and behavior of reactor materials. ORNL staff members helped formulate and staff the Oak Ridge School of Reactor Technology (ORSORT), which was, for many of those earliest years, the U.S. training center for reactor designers and managers. Among the ORSORT attendees of 1958 was current Secretary of Energy, Admiral James Watkins. Results of ORNL reactor research guided the selection of materials and designs commonly used in the past 30 years by the international nuclear establishment and by the commercial nuclear power industry.

Many of the Laboratory's early programs focused on the design, construction, and operation of unique research reactors at ORNL. Using the proven design of the Materials Test Reactor (a design developed primarily at ORNL), three reactors were built here during the 1950s for studies of radiation effects on materials: the Low Intensity Test Reactor, the Oak Ridge Research Reactor, and the Bulk Shielding Reactor. Other reactors were designed and built in Oak Ridge to demonstrate new reactor concepts. These concepts included the fluid-fuel reactor (Homogeneous Reactor Experiment and the Molten Salt Reactor Experiment) and the gas-cooled reactor (Experimental Gas Cooled Reactor).

Other special-purpose reactors have been built over the years at ORNL. The Tower Shielding Reactor, built in 1954, was designed originally to determine radiation shielding needs for the crew compartments of proposed aircraft propelled by nuclear systems. The fast-pulsed Health Physics Research Reactor, delivered here from the Nevada Test Site in 1963, had helped the U.S. Army estimate radiation dose rates from nuclear weapon blasts; at ORNL it was deployed for health physics and dosimetry applications.

The design, construction, and operation of ORNL's High Flux Isotope Reactor, completed in 1966, was a remarkable achievement for the Laboratory. Built primarily to produce transplutonium elements, the HFIR was once known for having the world's highest neutron flux, making it especially useful for isotope production, irradiation of test materials, and neutron-scattering research.

During the 1970s, ORNL continued to be involved in the design of advanced reactors (e.g., the liquid-metal fast breeder reactor and the high-temperature gas-cooled reactor) and in the improvement of reactor safety (mostly through research for the Nuclear Regulatory Commission). In response to the general national trend during these years, however, the emphases of ORNL's research missions shifted to alternative energy forms and the environmental and health impacts of energy production and use. As universities, other laboratories, and private companies began operating research reactors and establishing reactor technology programs, most ORNL researchers gradually moved from designing reactors to using them as tools of research. In the 1980s, our operating reactors assumed the role of user facilities, as they were made available to DOE for specialized research by qualified industries and other government agencies. Before they were shut down, our research reactors were widely used as radiation sources for biological and physical sciences research and for services such as neutron activation analysis and criticality alarm calibration. They were also the sole free-world source of some radioisotopes, such as californium-252, needed for medical and industrial research.

In response to the growing need for improved facilities for neutron science experiments (i.e., cold sources, more beam facilities, higher flux, etc.), ORNL staff proposed a conceptual design of a new reactor, the Advanced Neutron Source.

For many years, the ORNL research reactors operated safely and without serious incidents. Consequently, our reactor operations were perceived as a routine business needing little management attention. We now realize this perception created an environment in which problems could develop.

Shortly after the April 1986 nuclear power plant accident at Chernobyl, ORNL management initiated internal reviews of the Laboratory's research reactors to determine if any deficiencies existed and to recommend any needed safety improvements. The most significant finding was a failure to properly monitor the radiation-induced embrittlement of the HFIR pressure vessel; as a result of this finding, the HFIR was ordered shut down in November 1986. Additional internal and external reviews of the safety and management of the HFIR led to the Department of Energy's order that all ORNL research reactors be shut down in March 1987 until needed improvements, primarily in management and procedures, could be made.

At the same time that ORNL's research reactors were out of operation, a number of universities and other institutions also had to close down their research reactors because of increases in operating costs or inability to meet the increasingly stringent regulations. The following article points out that the United States is confronted with a dilemma because, though the number of U.S. research reactors has steadily decreased, the needs for research reactor facilities are expected to grow. In addition to a continuing need for research reactors to support neutron radiography, activation analysis, medical isotopes production, biomedical irradiations, materials studies, and commercial isotope product preparations, reactors will be needed for important new future research programs characterizing high-temperature superconductors and advanced ceramics.

During the three years that ORNL's research reactors have been idle, their previous users were forced to cancel, postpone, or transfer work to other reactors. Our efforts to assist these former users in relocating their research, along with the large number of calls ORNL normally receives from users trying to find an appropriate reactor for their work, have made us keenly aware of the urgent national need for a system to match researchers with the available U.S. research reactors having the needed capabilities and radiation characteristics. A 1988 study by the National Research Council also pointed out the need to develop a centralized reactor user network.

To reestablish U.S. leadership in nuclear technology, we believe a national research reactor data base should be established and coordinated through DOE. A national survey with assistance and input from all U.S. owners and operators of research reactors is the logical first step to identify the existing and projected needs of the user community for research reactors, to collect data on users and facilities, and to develop a strategy that will ensure the satisfaction of user demands.

Because of the collective reactor expertise here and ORNL's outstanding history in designing research reactors and operating them as user facilities, ORNL would be willing to assist in coordinating such an effort. We hope ORNL will be given the opportunity to continue our reactor missions, help our nation optimize use of existing research reactors, and become a world-class institution again in reactor-related research.

Alvin Trivelpiece is director of ORNL.

"We hope ORNL will be given the opportunity to . . . help our nation optimize use of existing research reactors..."

The Research Reactor Dilemma

By Howard Kerr, Fred Mynatt, and Stan Hadley

ORNL's Tower Shielding Facility, which was restarted December 8, 1989, is being used for a Japanese-American joint program to develop shielding for advanced liquid-metal reactors.

During the "golden era" of the 1950s and 1960s, numerous reactors were built in the United States to serve the research and educational needs of our country. Reactors having higher power levels or unique features for research were usually built at the national laboratories and often were designed for specific primary missions. Reactors built at universities or industrial centers were usually of multipurpose design and operated at lower power levels. The university reactors were considered essential for educating technological personnel for the nuclear industry and for adjunct educational fields, such as nuclear medicine. Although university research reactors serve multidisciplinary users, much of the research and educational effort at the university research reactors was stimulated by and focused on the use of nuclear energy for electric power production.

This interest in nuclear power reactor technology declined sharply during the 1970s, as the public became increasingly concerned about the economics, safety, and waste disposal issues relating to nuclear power. Enrollment in the nuclear science and engineering curricula has declined steadily for many years, and some nuclear engineering departments have been closed. As the use of the university research reactors declined, many were permanently shut down. With fewer students and fewer research activities, owners of those reactors that remained active began expanding commercial services to generate the revenue needed for continued operation.

In the decade of the 1980s, the worldwide increase in concerns about the proliferation of nuclear devices and the reactor accidents at Three Mile Island and Chernobyl further sensitized the public to safety issues for all reactors. As a consequence, reactors in this country, including research reactors, have been subjected to intense scrutiny to identify potential safety problems and to define the efforts needed to upgrade them to significantly more stringent standards.

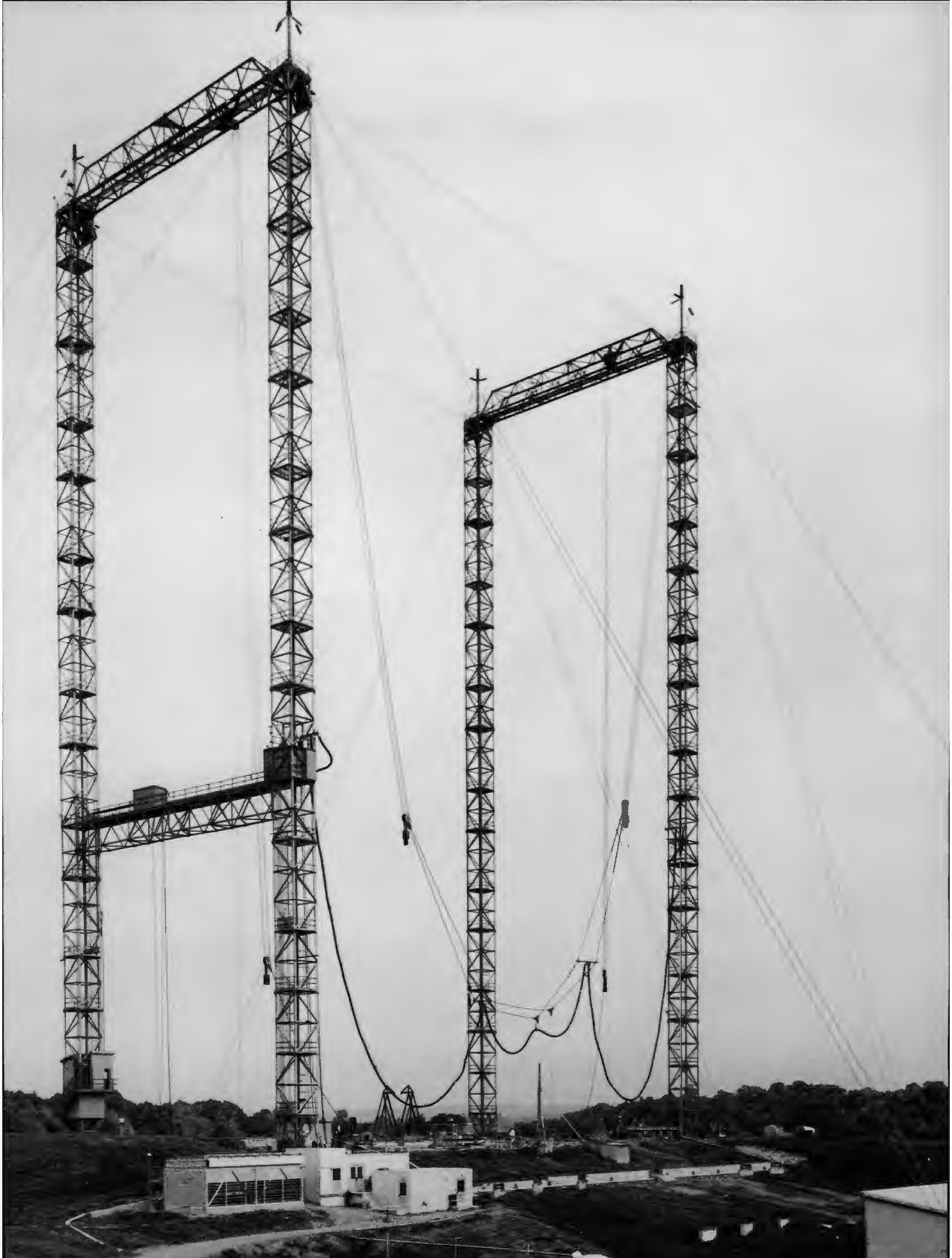
The High Flux Isotope Reactor (HFIR) and all other research reactors at ORNL have been temporarily shut down for an exhaustive review of their entire operations, as have other DOE reactors. Researchers here at ORNL have had to seek other facilities that could provide the proper combination of neutron flux, irradiation sample space, temperatures, and other parameters for their experiments. At the same time, we have had numerous requests from researchers around the world inquiring about using our reactors, which we have had to decline.

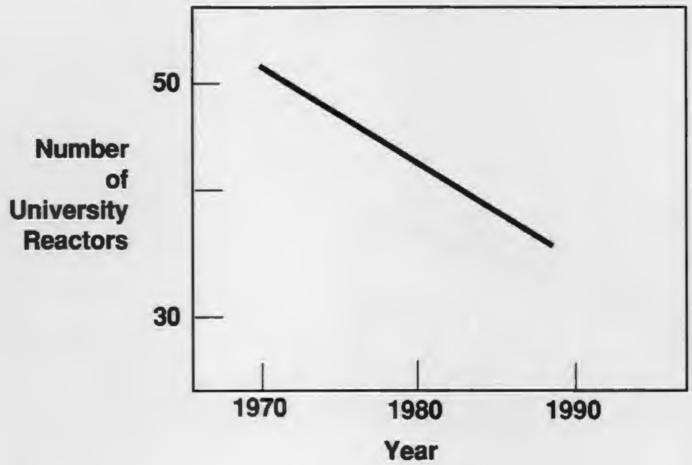
As more stringent standards are adopted, increased operating costs and greater restrictions for all reactors can be expected. Because the research reactors as a group are older than the commercial power reactors and research reactor funding has been very constrained, meeting the increased standards will be very difficult, and some reactors may not be allowed to continue operations.

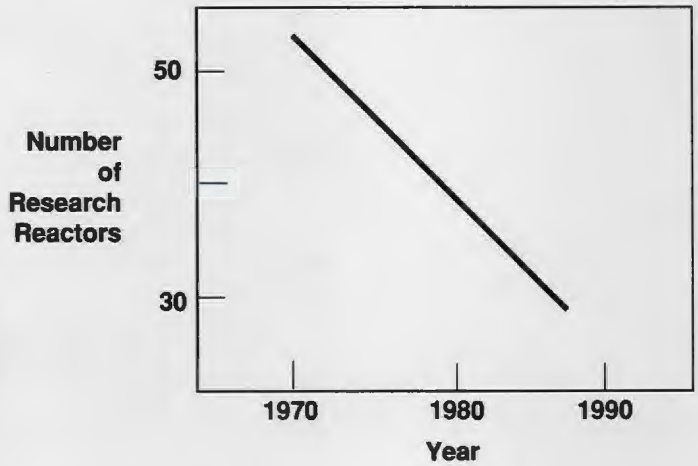
Defining the Problem

We face a serious national dilemma because, although the number of research reactors has steadily declined, the needs for research reactor facilities in this country have continued, and the needs for the future are expected to be even greater. The traditional uses of research reactors have developed in fields such as neutron radiography, activation analysis, medical isotope production, biomedical irradiations, materials studies, and commercial product preparations and are anticipated to continue.

In addition, much of the exciting work yet to be done in many areas will involve research reactors. For example, research in advanced ceramics and high-temperature superconductors use neutron irradiation or scattering techniques to determine certain characteristics of materials. The uses of neutrons in experimental research could increase significantly if an effort is made to identify potential users and to inform them of the availability of the reactor facilities.







The number of research reactors in the United States has decreased significantly. About 30 research reactors are being constructed in developing countries for radioisotope production, research, and training.

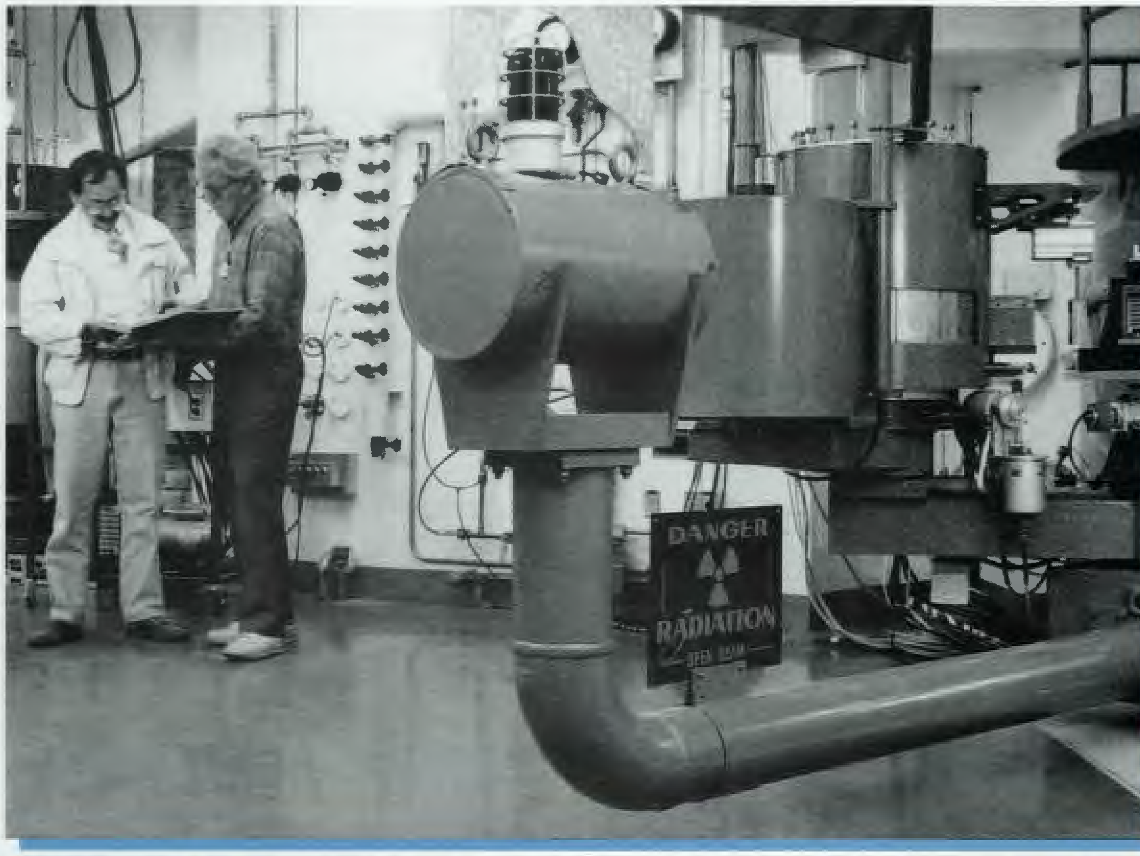
As the world community addresses the role of fossil fuels in global warming, it is reasonable to expect that nuclear energy will reemerge as a major power source in the world economy. If our nation is to play a significant part in this future nuclear power economy, our institutions must maintain viable research and development (R&D) programs for improved power reactor systems. Also, our universities must maintain or expand high-quality educational programs in the nuclear technologies to provide the researchers and engineers that will be needed. Modern well-equipped research reactor facilities will be essential to both of these efforts.

Reactors can be thought of simply as research tools; for them to be used and to be used effectively, their capabilities must be known to the researchers. A researcher must find a reactor that offers the set of performance characteristics he or she needs and also has space available for the experiment. To do so usually requires phone calls to numerous facilities such as ours, and yet the researcher still may not find out about a reactor that meets his or her needs perfectly. A better method is needed to match users with reactors.

University research programs will survive and flourish largely through the use of local reactors, either on-campus or easily accessible off-campus facilities. In many cases, these low-power reactors are appropriate facilities for research. However, some of the researchers in these programs will become interested in research that needs unique facilities such as the HFIR or ORNL's proposed research reactor, the Advanced Neutron Source (ANS), if they know about them and have ready access to them. This "feeder system" of multiple research programs is important to the HFIR and ANS. By having a "fleet" of reactors easily available, research programs will be stimulated and the overall effectiveness of the country's research reactors will be improved.

The serious dilemma of declining numbers of operating U.S. research reactors combined with projections of increasing needs for these facilities has not escaped the notice of the nation's research community. A 1988 study of university research reactors done by the National Research Council *(University Research Reactors in the United States: Their Role and Value)* pointed out that this problem must be resolved soon, if the United States is to maintain technological leadership in many important scientific areas. Its four principal recommendations concerned:

- development of university and national laboratory centers of excellence in specific areas of the neutron sciences and reactor technology for world-class research as well as for education
- anticipation that as some university reactors are upgraded and a user's network is created (see below), others are likely to close
- mechanisms to ensure that such closures do not damage the national interest related to research



Neutron beams from the HFIR have been used for neutron-scattering research on material and biological samples. In the future powerful neutron beams will be needed to characterize high-temperature superconducting materials.

and educational capabilities in the nuclear sciences and engineering, and

- development and support of a reactor network to facilitate improved use and productivity of U.S. research reactors involving researchers from universities with and without on-campus reactors and from the national laboratories.

There is also evidence that the dilemma with research reactors is being recognized by the U.S. Congress. The FY 1990 Appropriations Committee reports (accompanying H.R. 2696, Energy and Water Development Appropriations Bill, 1990) described the Committees' concern that no unified strategy exists for integrating and supporting university-based research reactors. The House and Senate Committees directed DOE to complete a utilization plan for all research reactors and to determine the feasibility of establishing a national advisory committee to advise DOE on the plan. DOE is required to report to the Committees by March 1, 1990.

How Did It Happen?

How did this dilemma develop? What can be done about it? These are important questions that need to be addressed. During the early growth of the nuclear industry, the institutions that acquired research reactors believed it was necessary to have on-site reactors for research, training, and educational purposes. Each of these institutions conducted research reactor programs in its own independent environment, with very little collaboration between programs. Consequently, parallel capabilities developed at several locations, particularly the universities operating the lower-power reactors. In the last two decades of nuclear industry decline, the growing economic and regulatory pressures caused many of these "marginal" competing reactor operations to be shut down.

Other reactor operators with more viable programs have been required to upgrade various systems, which brought about greater competition among institutions for routine irradiation service fees to meet the increased operating costs. Because government and other funding resources for reactor upgrades have been severely limited in these decades, most reactor operators have been unable to modernize their facilities to the extent desired.

"Outside researchers often call ORNL personnel for help locating a reactor appropriate for their experiments."

One of the problems leading to the present dilemma has been the lack of any institution having the purpose or the resources to identify the existing and projected needs of the user community for research reactor facilities and to develop an integrated strategy that will ensure these needs can be met. Outside researchers often call ORNL personnel for help locating a reactor appropriate for their experiments, because of the lack of an official source and the Laboratory's reputation in reactor-based research. This situation clearly reflects the finding of the previously cited study by the National Research Council.

What Can Be Done?

As a positive step toward resolving these problems and reestablishing U.S. leadership in nuclear technology, ORNL staff members have proposed the organization of a Research Reactor Program within the Department of Energy. Specific objectives of this program would be to

- determine existing and projected user needs for research reactor facilities
- collect, analyze, evaluate, and maintain data on existing research reactor facilities, relative to current and projected user needs
- develop a unified national strategy for establishing and maintaining a viable network of research reactor facilities
- establish and maintain research reactor center(s) to meet the needs of the user community and to stimulate new and expanded use of research reactors.

Such a comprehensive research reactor program should encompass all U.S. research reactors at both universities and the national laboratories and should involve individuals from throughout the entire nuclear technology community, including representatives of industrial users.

The proposed program plan would require significant initial effort, with the aim of accomplishing the first three objectives within the program's first year. Beginning in the second year, a network of research reactor centers would be established to provide ongoing coordination and integration services between the reactor operators and prospective users. ORNL's proposed program plan is designed to establish that institutional entity whose purpose is to increase communication and interactions between the reactor operators and the user community. The ORNL plan has absolutely no provision for any operational responsibilities for the reactors; the full responsibility for operating each reactor in compliance with respective regulations must remain with the owners. The ORNL Research Reactor Program Plan will stimulate increased usage of the reactors and help make the facilities more "user friendly."

Phase I of the plan is a formative period during which a comprehensive data base is generated for the existing research reactor facilities. The data will include technical descriptions on the facilities as well as status indicators relevant to potential facility modifications and upgrades. In addition, a detailed assessment will be made to determine the projected scope of both existing and potential uses of the reactor facilities. Use categories will be defined and estimates will be made of "user demands" in each category and for each class of facility. Then an estimate can be made of the research reactor population needed to meet the projected user demand.

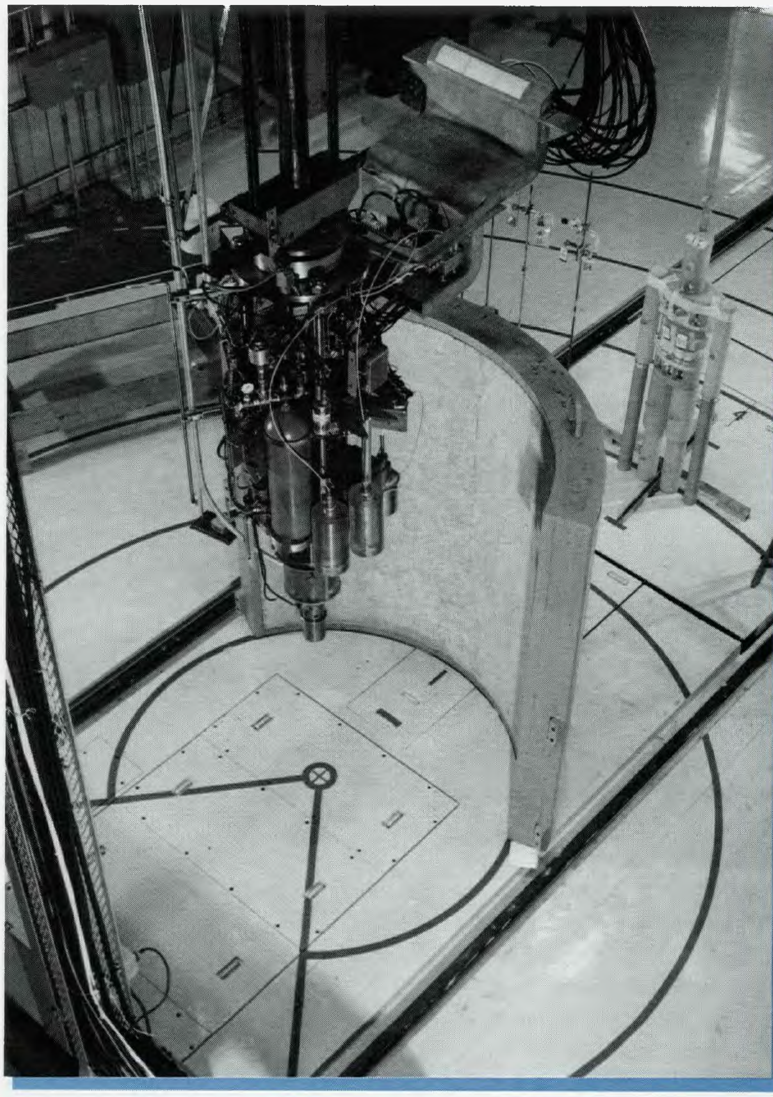
During Phase I, a high-level oversight committee would provide general guidance to the working group and would evaluate the work performed by the group. The oversight committee would meet periodically (e.g., quarterly) and direct the working group as needed. The working group would consist of a full-time chairman and several part-time specialists performing the detailed data collection and assessments.

The output from Phase I will include an extensive data base on research reactors, a projection of user needs, and an estimate of the reactor population needed to meet user demands. The intent of Phase I is to build on existing information and to provide a mechanism for maintaining the data base.

After the Phase I activities are complete, the Phase II effort will seek to establish and maintain an appropriate number of research reactor centers across the country. Each research reactor center will be an alliance of facilities within a geographic region or facilities with selected specialized capabilities. The principal mission for each center is to help ensure the highest utilization of the facilities and to provide both technical and administrative support service to the user community.

During Phase II the oversight committee will remain essentially unchanged except meetings will be less frequent. The working group of Phase I will be replaced by a Research Reactor Coordination Center located at ORNL. This new entity will have responsibility for maintaining effective interfaces and cooperation between the various research reactor centers. The chairman of each research reactor center will work closely with the operators within that center and with the various technical support groups available within that center.

With the commitment of ORNL to the ANS and the expected restart of the HFIR and other research reactors, we are heavily committed to the research reactor mission; so it is appropriate for us to be a leader for the national effort. This center would serve as a focus for user needs for the HFIR, the ANS, and all U.S. research reactors willing to participate in the collaboration. We believe this approach will best serve the users and will maximize the services from both existing and planned reactors.



The Health Physics Research Reactor has irradiated the "organs" of human-simulating phantoms to determine internal radiation doses at various levels of exposure. These findings have influenced the radiation guidelines set by the International Commission on Radiological Protection.

Implementation of the Plan

The first step in implementing the plan proposed by ORNL is to obtain a broad base of institutional support for the plan. Clearly, the interests of DOE will be served by an objective and comprehensive effort to improve utilization of DOE-owned research reactors. Also, the U.S. government has a general responsibility to ensure the availability of those facilities needed for advanced R&D activities, and modern well-equipped research reactors are needed. The Nuclear Regulatory Commission must also be interested in efforts to strengthen and enhance the scope of programs at university reactors regulated by NRC. ORNL will seek a funding commitment from one or more DOE offices for our proposed Research Reactor Program Plan. ORNL will also solicit NRC participation in the program plan.

The support and participation by other DOE laboratories is also important for the success of the comprehensive plan. Those laboratories with operating research reactors should be directly involved in the facility aspects of the plan. All potential users at national laboratories will be encouraged to provide input in the user-related aspects of the plan. Also, the national labs would be expected to provide technical support in select areas of expertise.

The university community support for the plan is especially important. First, those universities with an on-campus research reactor should readily endorse a program plan that provides real positive benefit to the university reactor programs. The plan proposed by ORNL—if properly implemented—would increase utilization of the university reactors and would provide increased access to other reactors with specialized facilities. Those universities without on-campus reactors would apparently support ORNL's proposed plan simply to improve access to needed research reactors. In both cases, implementation of the ORNL plan must not inflict penalties on university programs.

University support for the plan would be greatly enhanced with the participation of entities such as the Oak Ridge Associated Universities. These groups can serve as the interface between the universities and the reactor program, especially in the formative period of Phase I. Their relationship with numerous regional universities will bring a needed perspective to the development of the program while, at the same time, communicating back to the universities the progress made.

In a very practical sense, the operation of a research reactor involves significant responsibilities and now requires substantial resource commitments on the part of the owner-operator. Consequently, the driving force or justification for the continued operation of a research reactor must be clearly established in terms of the user community needs. The research reactors must be viewed as a versatile tool that can serve a broad spectrum of research, industrial, and educational needs. If, for a given reactor, the scope and magnitude of user needs is sufficient, then the necessary resources should be made available, the appropriate responsibilities should be accepted, and the reactor should continue to operate. This logic is the current reality for research reactors in the United States and explains why a significant commitment must be made by the research reactor community toward addressing the needs of its users.

The research reactor dilemma is widely recognized within the nuclear community, and everyone believes that some corrective actions are desperately needed. The approach embodied in the proposed ORNL plan has been presented to representatives from various segments of the nuclear community, and they have been highly supportive of the general approach. Some comments and questions have been expressed about specific possible adverse impacts on some existing reactor programs if a cohesive national approach is adopted. Clearly, these concerns must be addressed. The basic purpose of a national approach is to ensure the long-term continued availability of research reactor facilities needed to meet national needs, and ORNL wants to have an important role in that program. ornl

Howard Kerr

Stanton W. Hadley

Fred R. Mynatt

Biographical Sketches

Howard Kerr is leader of the System Development Group in ORNL's Engineering Technology Division. He has a B.S. degree in nuclear engineering from the University of Tennessee. Since joining the ORNL staff in 1965, he has been involved in reactor core design, neutronic analyses, experimental irradiations, criticality safety experiments, and design of safeguards systems for nuclear fuel reprocessing facilities. His other technical interests include defense, arms control, and advanced technologies for beekeepers.

Stanton W. Hadley is technical assistant to Fred Mynatt, ORNL's associate director for Chemical, Environmental, and Health Protection Technologies. He was previously associate director for Reactor Systems. Before these assignments, he spent eight years in the Operations Analysis and Planning Division at Oak Ridge Gaseous Diffusion Plant. In 1980, he worked on nuclear plant safety issues at Sandia National Laboratories. He received a B.S. degree in nuclear engineering in 1979 and M.S. degrees in engineering management and nuclear engineering in 1981 from the University of Missouri at Rolla.

Fred R. Mynatt is Energy Systems vice president for Compliance, Evaluations, and Policy. His previous positions during his 25-year tenure at ORNL have included associate director for Chemical, Environmental, and Health Protection Technologies (1989–90), associate director for Reactor Systems (1987–1989), associate director for Nuclear and Engineering Technologies (1984–1987), director of the Instrumentation and Controls Division (1981–1984), and director of Nuclear Regulatory Commission Programs (1977–1981). He earned his B.S., M.S., and Ph.D. degrees in nuclear engineering from the University of Tennessee. In 1978 he was elected a fellow of the American Nuclear Society, and in 1981 DOE presented him the E. O. Lawrence Memorial Award for his work in radiation shielding.

The HFIR: Lessons Learned

By A. L. (Pete) Lotts

ORNL's High Flux Isotope Reactor, shown in this early photograph, was once the source of the world's highest neutron flux and the major supplier of transuranium isotopes for the Western world.

The High Flux Isotope Reactor (HFIR), which was conceived at the Oak Ridge School of Reactor Technology in the mid-1950s, was brought to reality in steel, aluminum, and concrete in the 1960s. For 20 years, the HFIR, operating at 100 MW, was an illustrious star of ORNL science, engineering, and technology and supplied radioisotopes for research throughout the western nations. That complacent era ended abruptly on November 14, 1986, when the HFIR was shut down because of concerns about pressure-vessel embrittlement. After about three years of exhaustive procedural reviews and extensive pressure vessel testing, the HFIR began operation again on April 18, 1989, beginning a power excursion from 2.5 MW to a new maximum power of 85 MW. On May 9, when it was operating at a level of 10 MW, the HFIR was inadvertently shut down just moments before the planned time for actual shutdown—and it remained idle for months while aspects of this operator error were addressed. On January 29, 1990, after receiving Department of Energy (DOE) permission, ORNL resumed the operation of the HFIR at an initial power level of 8.5 MW.

Post-Chernobyl Revelations

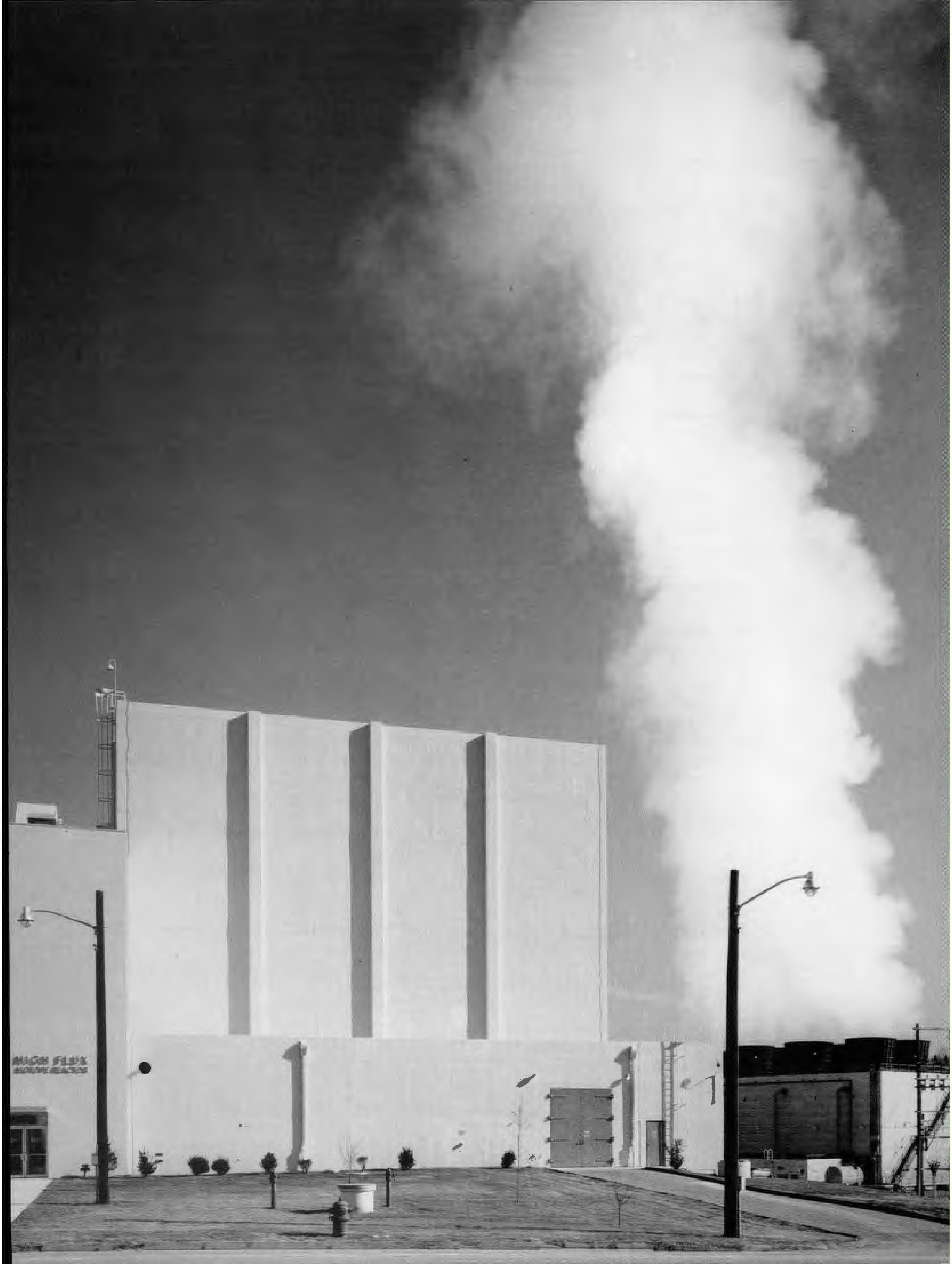
During its 20 years of operation, the HFIR had an extraordinary record of achievement. It reliably operated more than 90% of the time, except for planned outages to allow for component replacement. The HFIR was the major supplier to the free world of at least ten transuranic isotopes for industrial, military, and medical research uses, including the californium-252 used as a portable source of neutrons in research, industry, and cancer treatment. Because it was one of the best neutron sources in the world, thousands of researchers used HFIR for materials irradiation tests and neutron-scattering experiments. Hundreds of professionals at ORNL depended on this remarkable machine, which operated without event. The lessons learned from the nuclear power plant accidents at Three Mile Island (March 1979) and Chernobyl (April 1986) did not seem relevant here. Nevertheless, ORNL management ordered a thorough review of the status of the HFIR with respect to their lessons learned.

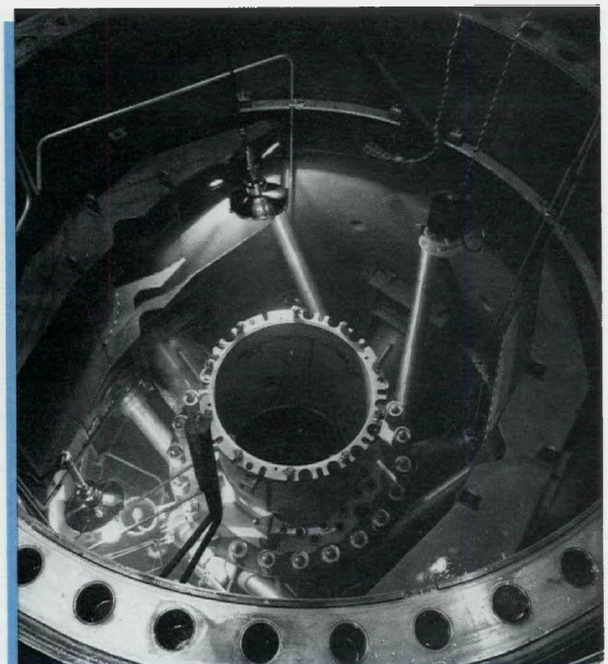
We were shocked, in November 1986, as if we'd been doused by a bucket of ice water, when ORNL's internal Reactor Review and Audit Committee (RRAC), chaired by Don Trauger, shook us out of our complacency with some cold, hard technical questions: "Have you recently examined the specimens of pressure vessel materials irradiated in the HFIR? Have you analyzed recent data to determine the extent of their embrittlement?" The answer was something like, "No, but the vessel is sound." The committee pressed for better answers; this inquiry led to subsequent discoveries of deficiencies in quality assurance, safety documentation, reactor operator training, and emergency planning at the HFIR and ORNL's other reactors.

The RRAC had been appointed in May 1986 by Herman Postma, ORNL's director at that time, to assess the safety of all ORNL reactor operations. In some cases, the committee discovered, data were not available because the carbon-steel specimens removed from the reactor vessel three years earlier had not yet been analyzed.

Analyses of these old samples and samples more recently removed from the vessel revealed that the vessel's embrittlement rate was greater than had been predicted 20 years earlier (based on data from reactor materials tests, which of necessity accumulate exposure time at higher than design irradiation rates). This embrittlement was of concern because it created the potential for cracking of the vessel and, if this occurred, possible loss of sufficient cooling water to cause core damage. Anticipating the possibility of such a phenomenon, the designers had organized a pressure-vessel materials surveillance program.

I was introduced to the HFIR problems in December 1986, when Postma asked me to take a "short-term" assignment leading the HFIR's recovery program. I had just returned to ORNL after a three-year stint as director of the Atomic


HIGH FLUX



An interior view of the HFIR vessel components.

Vapor Laser Isotope Separation (AVLIS) Division at the Oak Ridge Gaseous Diffusion Plant. Because of my background in materials science and engineering and my trouble-shooting experience in helping establish AVLIS as the advanced technology to be developed for uranium enrichment, I was willing to tackle the challenges of the HFIR project. The style of examining management and operations typical of the Institute of Nuclear Power Operations (INPO) was familiar to me, but I did not, at this stage, anticipate that INPO standards would become the ones by which our research organization and approach would be measured. More surprises lay ahead.

By the time I started work on the HFIR's problems, the fate of the reactor was no longer in the hands of ORNL's internal investigators. DOE had already formed several staff teams from local and national headquarters to investigate the embrittlement, operational safety, and management problems of the HFIR. The National Academy of Sciences–National Research Council later also decided to include the HFIR in their review of DOE reactors, and others began to climb on the bandwagon. Over the next two years, some 20 government teams or committees were involved in investigating the HFIR.

The investigation led by John Rothrock of DOE's Oak Ridge Operations (ORO) Office found, among other things, that (1) the HFIR pressure vessel surveillance program had not been kept current because of a lack of accountability in the management system and (2) the HFIR safety analyses were not up-to-date.

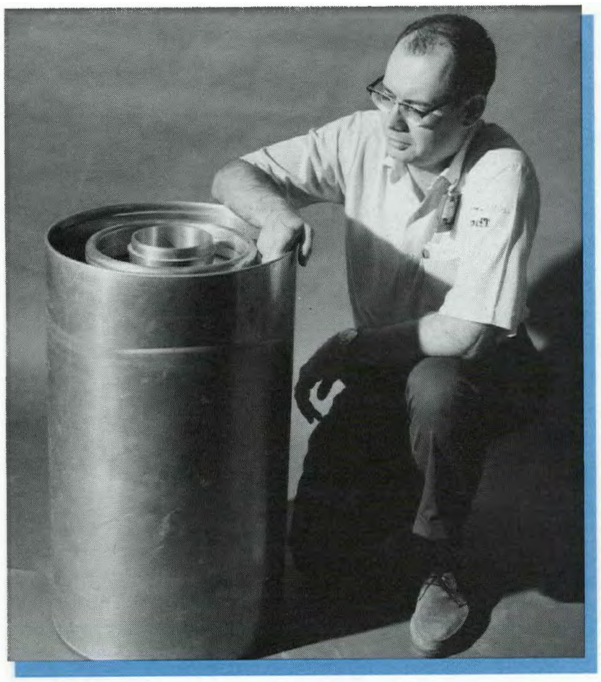
Two committees chartered by the Environment, Safety, and Health Organization of DOE Headquarters and led by Lorin Brinkerhoff came to examine the HFIR in February and March 1987. They first performed a design review of the HFIR and recommended that the design basis and safety analyses for HFIR be brought up-to-date. The committee was particularly concerned about ORNL's failure to maintain an effective surveillance program to check the reactors for vessel embrittlement and other potential problems. The second committee reviewed management and operations practices; the strongest concerns were deficiencies in management oversight, the quality assurance program, and timely grading of the examinations taken by reactor operators being trained, retrained, or recertified.

Four More Reactors Shut Down

The results of the committee reviews proved devastating because a few members of the review team thought the deficiencies sufficient to justify shutting down four other ORNL reactors. On March 26, 1987—exactly 11 months after the Chernobyl accident—the DOE-ORO Office ordered the shutdown of the Oak Ridge Research Reactor (ORR), the Bulk Shielding Reactor (BSR), the Health Physics Research Reactor (HPRR), and the Tower Shielding Facility (TSF). (See sidebar on page 24.) We had reached the lowest point thus far in the HFIR restart program; in fact, the event was seen by top management as the greatest institutional calamity in ORNL's history because it created the negative impression that the laboratory that had a principal role in developing nuclear reactors was now unable to operate them in an acceptable manner.

ORNL's first step toward recovery from this institutional blow was a management realignment. DOE had recommended that a high-level manager be appointed to oversee ORNL reactor operations and help the Laboratory restore its credibility as a manager of reactors. Fred Mynatt was designated ORNL Associate Director for Reactor Systems and the Research Reactors Division (RRD) was chartered on April 6, 1987. I was named to head the RRD. Fred and I had concurrent, limited goals—to build a sound reactor operations organization and to restore the reactors to operation.

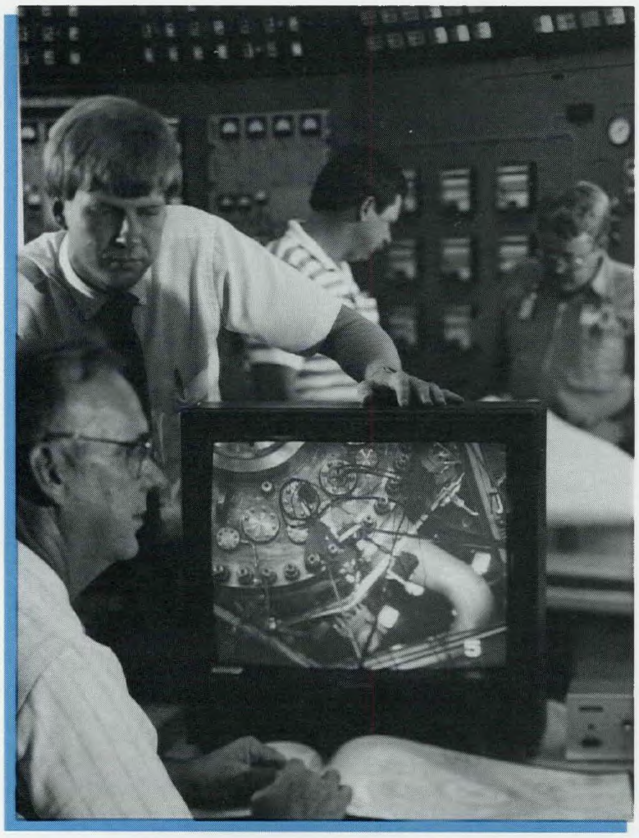
The work of reanalyzing the HFIR had progressed well. Dick Cheverton, one of the engineers who had helped design the HFIR and now head of the Pressure Vessel Technology Section of ORNL's Engineering Technology Division (ETD), led a team that quickly determined the extent of the pressure-vessel embrittlement and the projected operating life of the vessel if the reactor were operated at lower power and water pressures. Because data were lacking on the effects of neutron irradiation on welded structures, a Metals and Ceramics Division group led by Randy Nanstad supplied the needed numbers by (1) constructing weld structures from the exact archive materials to simulate the HFIR vessel structures and (2) irradiating them in the ORR. Based on the data and calculations, Cheverton, Nanstad, John Merkle (ETD), and other members of the team concluded that the HFIR vessel's life could be extended by at least 10 years by reducing the power level from 100 MW to 85 MW, allowing a vessel pressure drop from the normal operating level of 750 psi (5.2 MPA) to 500 psi (3.4 MPA).



This fuel assembly, first used in the HFIR in the mid-1960s, could produce 100 MW of thermal power.

The ORNL team worked with two DOE committees chartered to examine the basis for replacement or continued operation of the pressure vessel. In the end, the committees agreed with the recommendation that the vessel be pressure-tested to determine its fitness for service. In August 1987, the vessel was successfully tested at 900 psi—or 1.8 times its proposed new operating pressure. The integrity of the pressure vessel was confirmed.

During the same time, the RRD grew in strength and numbers. Tom Dahl, who had previously been HFIR plant manager, became head of reactor operations. Bill Craddick agreed to transfer from the Engineering Technology Division to lead the Reactor Technology Section. George Flanagan began leading the HFIR probabilistic risk assessment (PRA), which was executed by the private firm Pickard, Lowe, and Garrick. Roy Fenstermaker took charge of setting up our approach to quality assurance based on NQA-1, which is the standard in the nuclear power industry. We attracted a number of excellent people from outside ORNL and from within Energy Systems. Sam Hurt and his colleagues in the RRD began redesigning systems to meet the new operating conditions and to correct the HFIR deficiencies discovered as a result of the PRA and seismic analyses. We also



Ken Belitz and Mike Farrar check the monitor for signs of leaks during a 1987 hydrostatic test of the HFIR pressure vessel. The overpressurized vessel gave no sign of cracking, indicating that the vessel wall is tough enough to withstand normal and abnormal operating conditions.

implemented a new management system based on well-founded principles of documented policies and procedures and strict accountability.

On June 22, 1987, DOE-ORO received permission from DOE Headquarters to restart the Tower Shielding Facility. However, at that time ORNL's reactor operators, fire-fighting forces, and craft workers were not employed at normal strength because of a strike by the Atomic Trades and Labor Council union members, so it did not seem prudent to operate any reactor then.

On July 20, 1987, after almost 30 years of operation, the ORR was permanently closed. Actually, DOE had planned to shut it down permanently in 1986, but then decided to extend its operation a year to permit Argonne National Laboratory to complete experiments there on the feasibility of using low-enrichment (rather than high-enrichment) uranium fuels in research reactors to reduce the possibility of diversion of fissionable material. In addition to its contribution to fuels development and nuclear research during its extended life, the ORR in late 1986 and early 1987 also filled in for the idled HFIR in neutron-scattering experiments and isotope production (e.g., gadolinium-153, for bone scans to detect osteoporosis).

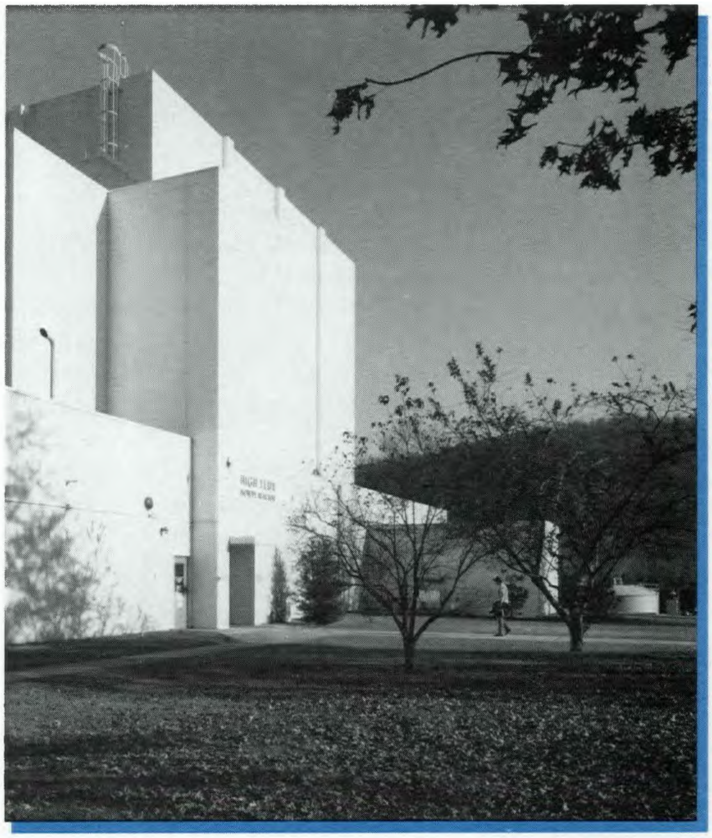
On September 30, 1987, ORNL submitted a formal HFIR Restart Proposal to ORO. A few days later, the date of restart was set for January 31, 1988. Assuming resolution of all restart issues, the planned date for restart was based on the estimated time needed to retrain and requalify the HFIR operators, who had been on strike from June 2 through October 4.

Many people were eager for the HFIR restart. The impacts of the extended shutdown had been sorely felt. Our neutron-scattering users had to go elsewhere (to the limited extent possible) to conduct their beam experiments. The new Neutron Activation Analysis Facility at HFIR is still awaiting initial operation; it had only recently been completed at the time of the HFIR shutdown. As another consequence of the shutdown, changes had to be made in the plans for performing collaborative experiments with the Japanese Atomic Energy Research Institute on irradiation of candidate fusion reactor materials. The production of heavy elements for research stopped because it could be done only at the HFIR. Production of other radioisotopes needed for industrial and medical uses was transferred to other reactors when this was possible. The supplies of californium-252, needed for research and therapy of advanced cervical cancer, became severely depleted because this isotope is produced only at the HFIR.

Phase II of HFIR Restart Efforts

In October 1987, after the employee strike was over, ORO Manager Joe La Grone, inspected three Category B reactors—the BSR, HPRR, and TSF—to determine whether they met the criteria for restart. He did not inspect the HFIR, a Category A reactor, or the ORR, the other Category B reactor.

In November 1987, before permission to restart the Category B reactors could be granted, we were obliged to inform ORO upper management about an unresolved alleged forgery (or improper signature) on a 1986 dimensional inspection form for a machined part intended for the HFIR. That marked the end of what I term Phase I of the restart of ORNL reactors. By that time, ORNL reactor operations had been examined by six DOE committees and three Energy Systems committees. We then thought that most of the required actions for restart had been taken. Nevertheless, restart of the reactors was still many months away.



This view of the HFIR shows the new front addition containing the Neutron Activation Analysis Facility.

For the people in ORNL's reactor organization, the alleged forgery incident ended our naivete. We, as well as DOE-ORO personnel working with us to resolve reactor issues, began to recognize that an intense self-assessment would be necessary to reach the standards required to restart the reactors. However, after the announcement of the alleged forgery, the Inspector General's office was asked to investigate. Although we have never seen a written report, we were told that the Inspector General's staff determined that fraud was not involved. After the Inspector General was finished, we conducted internal reviews and implemented improvements, but the person responsible for the improper signature was never discovered.

During the same period (December 1987 through February 1988), because of the improper signature, an ORO team investigated the ORNL Quality Assurance program and found that the reporting system was deficient in many respects. This finding was not surprising to us, because our implementation of the RRD quality assurance program was incomplete, and the cited deficiencies were being addressed by our newly developed improvement plans. What changed was that DOE began to take the position that full implementation of the NQA-1 quality program was a pre-restart requirement.

A number of changes occurred in the first half of 1988. Martin Marietta Energy Systems, Inc., decided to retain an experienced utility manager. Robert Montross, ex-Naval nuclear submarine officer and utility plant manager, was hired as director of Reactor Operations in April 1988, reporting directly to the President of Energy Systems. Montross was succeeded in October 1988 by Jackson Richard, ex-Naval nuclear submarine officer and nuclear utility executive. We began a comprehensive self assessment and upgrade program (CSAUP) in March and

"Restart was to be at a deliberate pace, highly structured, and subject to intense review."

completed the assessment work in June 1988. More than 700 recommendations were made by a group of consultants experienced in conducting assessments of nuclear power plants. The objective of the CSAUP was to determine corrective actions required to meet appropriate commercial standards—that is, the U.S. Nuclear Regulatory Commission (NRC) standards and INPO standards that commercial nuclear power plants in the United States must meet. Early in 1988, we also chartered an Independent Review Committee, which now reviews RRD quarterly on an ongoing basis, to give us additional insight into our operations.

In the first half of FY 1988, the HFIR and the RRD were reviewed by several other committees to evaluate the adequacy of the RRD improvement program and to determine readiness to restart HFIR. These groups included an ORO-Headquarters Energy Research team; a group from the Environment, Safety, and Health organization of DOE Headquarters, a National Research Council committee, and a subcommittee of the DOE Advisory Committee on Nuclear Facility Safety. All these review teams agreed that the HFIR should be restarted, providing that certain conditions were met.

The ORO Operational Readiness Review Team, headed by Doug Underwood, which followed our resolution of all issues and audited their satisfactory completion, finished its work and endorsed HFIR restart in November 1988. ORNL's new Office of Operational Safety, headed by Henry Piper, also intensively reviewed all design changes and the operating documents associated with the HFIR. Martin Marietta Corporation also became involved, sending its chief operating officer, Caleb Hurtt, and special consultant, Don McCarthy, on personal visits to the HFIR. Energy Systems management asked for permission to restart the HFIR in October 1988. From that date through March 1989, we worked with ORO staff and with personnel and consultants of the DOE Headquarters Office of Energy Research, headed then by Robert O. Hunter, to establish the basis for restart of the HFIR.

We tried to get a decision to restart the HFIR from DOE before January 1989 because we thought it might be more prolonged and difficult to obtain a decision after the presidential administration changed. We were right. Not until the new Secretary of Energy, Admiral James Watkins, was asked about the HFIR startup schedule at a Senate Budget Committee hearing in March was the date set. The admiral announced that the HFIR would restart within five weeks.

Restart was to be at a deliberate pace, highly structured, and subject to intense review. For example, the HFIR was to be operated at low power (2.5 MW) for an extended time; the power level was to be raised to 11 MW and then, in additional preplanned steps, to full-power operation at 85 MW over about a three-month period. All "events" that were not planned or directly anticipated were to be reported to DOE. This latter requirement set the scene for further delays. The system was not set up to handle even small procedural deviations that did not challenge the reactor safety systems, such as the "events" of May 5 and 9. Two problems frustrated us. First, the requirement for strict adherence to procedures had not been implemented as thoroughly as we thought and, second, the method for resolving problems reported to DOE Headquarters was deficient. As from the beginning, other problems in the DOE system compounded our difficulties. When DOE commissioned another series of reviews by a consultant team, we experienced an additional delay of months as we revalidated the lineup of valves, switches, and circuit breakers and made other changes. Primarily, the operators were trained to follow procedures directly according to the book, except in emergency situations.

From my viewpoint, the technology and engineering components of RRD and its supporting Energy Systems and contractor organizations passed the test when ORNL was granted permission to restart the HFIR. These organizations also improved as they became more experienced and had better tools. Restart of the HFIR was a time for testing the operations organization, along with its support, to see if our people were ready to operate according to the new expectations. We needed perfection but, as it turned out, did not quite achieve it. Today the objective is to approach error-free operation as nearly as is humanly possible.

Summary of Findings and Corrective Measures

For the restart in April 1989, some 20 teams and committees had reviewed the HFIR and the operating organizations (the old Operations Division and the new RRD). These reviews provided recommendations and issues for us to deal with. They had investigated the adequacy of virtually every aspect of the HFIR design and the status of the plant, as well as the adequacy of organizational functions—including management—from top to bottom. They examined quality assurance, oversight of the reactor programs by DOE and Energy Systems, operations and maintenance practices, design practices, training efforts, and safety and health practices. In their original assessments, the reviewers found many areas of management and operations lacking. They found that we needed much more analysis and documentation to prove the adequacy of the HFIR design.

Overall, we found that the deficiencies could be traced to just three root causes:

- lack of sufficient staff
- lack of sufficient funds and
- lack of discipline in training, operations, maintenance, and management.

Deficiencies were so pervasive that we were unable to prove we could operate safely, and our corrective approach was simple:

- completely revamp the systems for training, operations, maintenance management, and quality assurance
- staff the program adequately
- fund the program adequately and
- prove that we are capable of operating reactors safely.

Personnel and funding for the HFIR are now almost three times the levels existing before the HFIR shutdown. We increased the operations and maintenance staffs and added strong support sections for reactor engineering and safety analysis, compliance, training, and management systems. The RRD is supported by an eight-person quality assurance group.

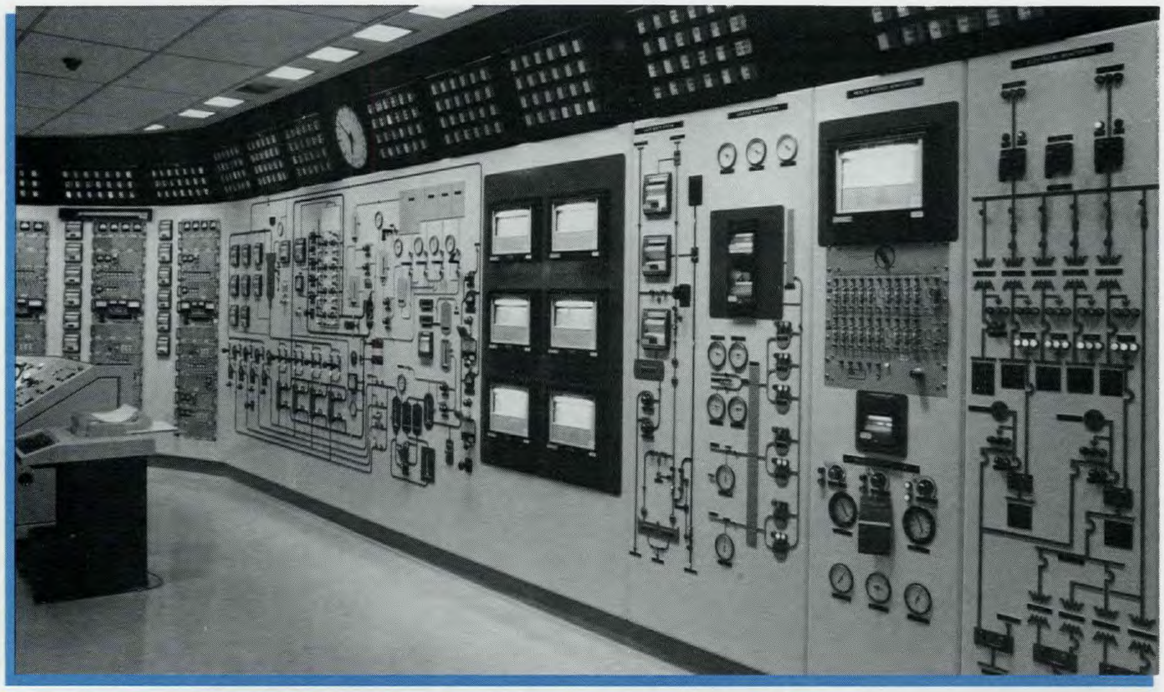
As for safety oversight, a member of the Office of Operational Safety is in residence at the RRD. In addition, an office at the HFIR is staffed with seven DOE employees who oversee reactor operations. Thus, considerable effort is being expended to ensure the adequacy of RRD operations and corrective actions.

The measures we took were all intended to provide staff to do the work and achieve a sufficient level of oversight. What was done at the HFIR to place the reactor in a condition to operate according to upgraded standards? How did we determine that the HFIR is technically safe to operate?

Obviously, we had to deal with the pressure vessel embrittlement problem; the vessel and primary system passed the pressure test, as previously noted. We also conducted a probabilistic risk assessment to determine the probability of events that could lead to serious consequences such as damage to the fuel core. Several minor improvements were made to lower the core damage probability.

We conducted seismic analyses and implemented seismic improvements to ensure that the HFIR would meet more stringent criteria for earthquake resistance. We recalculated radioactive material source terms and release rates to ensure that, even under accident conditions that have a very low probability of occurrence, there would be little consequence to people and the environment. As a result of these analyses, we designed and made some improvements to the HFIR. We developed more disciplined operations and maintenance approaches. We had to prove point-by-point that we are meeting or exceeding nuclear industry standards for the safety of the HFIR design and its operations. The RRD staff showed initiative and success in meeting these high performance standards.

"Today the objective is to approach error-free operation as nearly as is humanly possible."



The HFIR control room has a streamlined new look.

Lessons Learned

In reflecting on the events finally leading to the restart of the HFIR, I think the principal lessons we learned about the process of responding to a crisis are:

• In organizational crises caused by operational or performance deficiencies, do not underestimate the magnitude of the problems and therefore limit the resources applied.

• Get the best, most-critical reviewers possible to examine the organization and its approach, and take the initiative to understand, disclose, and correct your deficiencies.

• Initiate comprehensive reviews as quickly as possible, so that the organization rapidly becomes fully aware of the issues.

• At the beginning, organize an approach to managing the issues and formulate objective criteria to establish priorities in addressing them. (The RRD used risk-based criteria to determine the best allocation of resources to corrective actions.)

We were slow to respond to the HFIR shutdown crisis, so we learned the best approaches the hard way—through pain, rework, and a protracted schedule.

With respect to other lessons learned in this process, we found that managers must continually assess the environment in which they are operating to determine whether these operations are meeting present standards and will meet future expectations. For example, managers should be constantly seeking answers to these questions:

• What are the expectations of Congress, DOE, the State of Tennessee, and the regulatory agencies?

• What changes do customers want?

• Where is DOE headed?

• What are other DOE contractors doing about operational standards?

• How do our operations compare with industry practice?

The list could go on. The ORNL reactor crisis might have been avoided if similar questions had been asked a long time ago.

Reflections on Changes in Regulatory Climate

The HFIR was designed to accommodate a wide range of failures, but in 1966 it was not expected to operate under today's rigorous procedures. None of the reviews has identified serious deficiences in the design or construction. It fully met the standards of the 1960s and stands well with respect to the more stringent requirements of today.

The serious consequences of the Chernobyl accident and changes in the U.S. regulatory climate contributed to the shutdown of the ORNL reactors and the difficulty in preparing them for restart. Because we live in a risk-averse society, the U.S. government has been under increasing pressure to minimize the risks of radiation releases and possible reactor incidents by tightening standards.

ORNL's problems stemmed both from changes in the regulatory climate and from years of inattention to reactor improvement because of underfunding and understaffing. During these years, ORNL operated the reactors with minimum staff and spent little on quality assurance, technical analysis, training, and documentation. That has now been changed by DOE and ORNL to a current regulations-conscious approach that meets very high standards but constantly reassesses to meet rising expectations. Maintaining this approach should ensure that ORNL will have many more years of successful reactor operation. ornl

Biographical Sketch

A.L. "Pete" Lotts retired from ORNL in July 1989 and currently works as a consultant with TENERA Risk Management Services in Oak Ridge. Lotts joined the staff of the Metals and Ceramics (M&C) Division in 1959 after receiving his B.S. and M.S. degrees in metallurgical engineering from Virginia Polytechnic Institute and State University. In his 30 years of service at ORNL, Lotts managed a number of multidisciplinary programs, directing the Fuel Cycle Technology Operations of M&C Division (1966–1974), serving as associate laboratory director of Gas Reactor Programs (1974–1978), director of Nuclear Fuel and Waste Programs (1978–1981), and director of Nuclear Regulatory Commission Programs (1981–1983). From 1983 to 1986, Lotts directed the Atomic Vapor Laser Isotope Separation Division and Program at the Oak Ridge Gaseous Diffusion Plant. In 1986 he became director of the Department of Defense Technology Programs at ORNL but was asked, in December 1986, to become program director for operational assessment of the High Flux Isotope Reactor (HFIR) and to assume responsibility for the effort leading to restart of the HFIR. In April 1987, Lotts was appointed director of a new Research Reactors Division at ORNL. He served in this capacity until his retirement in 1989, after permission to restart the HFIR had been given by DOE and restart operations had begun.

Lotts is a fellow of the American Nuclear Society and received the E.O. Lawrence Memorial Award in 1976 for his work in fuel cycle technology. He has been a member of the Knox County Board of Education since 1972 and has served as its chairman since 1977. He is also a member of the Board of Commissioners of the Tennessee Technology Development Authority.

Storage area for the HFIR's remote-handling tools, as seen from the bottom of the tool rack on which they hang.

ORNL's Research Reactors

ORNL's four research reactors are valuable national resources that offer a variety of services. Their description, history, and past and projected uses are presented here.

High Flux Isotope Reactor. The HFIR, designed to operate at 100 MW when it went critical in 1966 and modified recently to operate at 85 MW, is one of the world's best sources of high-flux neutrons—about 5 million billion neutrons per square centimeter per second. Its uranium-235 fuel is clad with aluminum plates and cooled by ordinary water. Its neutrons are moderated to desirable energies by water and are reflected by beryllium rings back into the fuel core to sustain fission.

The HFIR's primary purpose has been to produce elements heavier than uranium by bombarding target materials (e.g., plutonium and curium) with neutrons. Probably its most famous transuranium element product is californium-252, which is in special demand for advanced cancer therapy research. Besides its contributions to isotope production, the HFIR has also been heralded for neutron scattering research and studies of radiation effects on materials. During its second era of operation, the HFIR will also be used for neutron activation analysis studies in the unique new Neutron Activation Analysis Facility.

When the restarted HFIR attains 85 MW, it will generate about one-thirtieth of the thermal energy output of most commercial nuclear power plants and will begin meeting national research needs again.

Why does the United States need the HFIR?

For one thing, the HFIR is the only source of transuranic elements such as californium-252, einsteinium-253, berkelium-249, curium-246, plutonium-244, and actinium-227. The HFIR is also our nation's best source of many of the lighter radioisotopes such as cobalt-60, iridium-192, and nickel-63. It is the only source of ultrahigh-specific-activity cobalt-60 (440 Ci/g vs 100 Ci/g), the highest-performance cobalt source for industrial radiography and cancer therapy. Orders for californium-252 have gone unfilled, while the HFIR remains closed and officials ponder the needs that must be met to make DOE's Fast Flux Test Facility in Richland, Washington, suitable for californium-252 production. Both physicians and cervical cancer patients have expressed the urgent need for californium-252, which has been used in therapy to improve the survival rate of treated patients by 40%. It is also needed for neutron radiography for military and industrial purposes. Neutrons from californium-252 are superior to X rays in detecting defects in certain composite structures, as in some military aircraft. It is used for obtaining radiographs of weapons components by DOE's Mound and Pantex facilities.

The HFIR is also needed for neutron scattering research. The HFIR has hosted 4000 to 5000 users a year, and it can supply almost one-third of the U.S. neutron scattering capacity needed for research. If the High Flux Beam Reactor at Brookhaven National Laboratory, which has 47% the user capacity of the HFIR, is shut down for long periods because of aging problems, the HFIR will become even more indispensable for neutron scattering research. Loss of U.S. neutron scattering capacity has made our country less competitive with other nations in advanced materials research, particularly in the characterization of high-temperature superconducting materials. Specifically, the prolonged HFIR shutdown has disrupted a DOE-Japan cooperative agreement involving fusion materials research and has interrupted the National Science Foundation's small-angle neutron scattering program.

In materials and fuels testing, the HFIR's high neutron flux makes it the preferred source for rapidly determining the effects of prolonged neutron irradiation. It is needed now to test the structural materials and fuels for fusion research programs, ORNL's Advanced Neutron Source (ANS), and DOE's Modular High-Temperature Gas-Cooled Reactor (MHTGR) Program. The HFIR shutdown has delayed fuel testing for the ANS and HTGR production reactor and the planned DOE-Japan fusion materials experiments, which had to be transferred to lower-performance reactors. These tests have taken 3 to 4 times as long as equivalent HFIR experiments would take to yield results.

Finally, the prolonged shutdown of the HFIR has delayed for more than three years the opening of the new Neutron Activation Analysis Facility, which will be the best of its kind in the world. The new facility includes a pneumatic tube to replace a similar but lower neutron flux system that was lost when the Oak Ridge Research Reactor was shut down. The new pneumatic tube adds to an existing HFIR pneumatic tube having the world's highest neutron flux. Together, the two irradiation systems have a combination of features, including automated irradiation capability, that make them the world's most powerful radiation source for

A number of programs need the shielding data that operation of the Tower Shielding Facility can provide.

materials analysis. They will be used to support a wide variety of ORNL programs and work for others. One past application that will likely continue is the measurement of uranium and thorium contaminants in materials used to make computer memories. Because these radioactive impurities can alter information stored in memory chips, the ORNL facility will help guide the memory chip industry in selecting high-purity materials.

Tower Shielding Facility. Protecting the pilots and passengers of a proposed "nuclear airplane" from radiation was the original motivation for building ORNL's unique Tower Shielding Facility (TSF), in which a reactor is suspended between four towers. The TSF was built in 1954 to study asymmetric shield configurations for the Aircraft Nuclear Propulsion Project. To obtain the information needed for designing shields to block neutron transport, the radiation source had to be located far enough away from the ground and building structures to avoid neutron scattering; thus, the TSF reactor used to hang in midair. The reactor radiation source was hoisted between two of the four 96-m-high guyed towers erected at the corners of a 30.5- by 61-m rectangle; the other two towers hoisted additional testing equipment. Underground buildings near the towers house the control equipment and operating crew, and a reinforced concrete handling pool provides shielding during reactor maintenance.

The original Tower Shielding Reactor (TSR-I), a 500-kW Materials Testing Reactor (MTR) neutron source, was replaced in 1960 with the spherically symmetric TSR-II, which has a maximum power output of 1 MW. From 1960 until 1973, the TSR-II operated in both ground-level and elevated positions at a variety of power levels. In 1973, the TSR-II was moved to the Beam Shield Facility, which surrounds the reactor on three sides with concrete and stainless steel shielding. The fourth side consists of a shutter that allows the neutron beam to exit the reactor and irradiate shielding experiments set up outside it. The TSR-II reactor core consists of aluminum-clad uranium-aluminum fuel plates that are cooled and moderated with ordinary water. The plates are curved to form a sphere from which the radiation is emitted symmetrically. Outside the fuel annulus is the reflector region, which may hold material samples for experiments.

In 1975, ORNL began using the TSF to conduct drop tests to determine the integrity of a cask designed for shipping fuel elements to the tritium production reactor at the Savannah River Plant. The 21,000-kg (23-ton) cask was raised between two TSF towers to a height of 9 m (30 ft) and allowed to fall freely onto an armor-plated concrete drop pad weighing about 45,000 kg (50 tons). Drums from the Oak Ridge Y-12 Plant were also drop-tested at the TSF. In 1976, a new, stronger, reinforced drop pad, weighing 670,000 kg (740 tons), was constructed at the same location. Between 1978 and 1985,

The Bulk Shielding Reactor offers the capability for analyzing samples chilled to extremely low temperatures that "freeze in" defects of interest.

the new drop pad was used for 25 drop tests involving weights ranging from 227 to 22,680 kg (0.25 to 25 tons). The drop pad is located 43 m (110 ft) from the TSR-II.

Restart of the TSR-II is important, mainly because of its value in validating shielding designs for several types of new reactors. It is urgently needed to complete studies for the Japanese-American Shielding Program of Experimental Research (JASPER) for the U.S. Advanced Liquid Metal Reactor Program. Shielding design experiments for the new MHTGR production reactor will also require the TSR-II. In addition, shielding data may be needed for the new heavy-water-cooled production reactor. The commercial HTGR community has planned experiments on neutron streaming for the TSR-II. The ANS designers may need the TSR-II to verify shielding data and to resolve source-term issues. DOE's Space Power Program may also need to conduct verification tests at the TSR-II for the prototype flight shield.

Bulk Shielding Reactor. From 1951 to 1963, the 1-MW(t) Bulk Shielding Reactor (BSR) was used as a source for radiation shielding experiments. Because of a change in emphasis in the national neutron physics program and the shutdown of ORNL's Graphite Reactor, the BSR was made available in 1963 for use as a general-purpose research reactor. At that time, the facility was provided with a forced-cooling system and upgraded to permit

continuous reactor operation at a thermal power level of 2 MW.

The Bulk Shielding Facility includes two reactors: the 10-kW Pool Critical Assembly (PCA), which is used for special low-power testing, and the BSR, which uses aluminum-clad uranium-aluminum-alloy fuel elements similar to the MTR type. Water introduced to the reactor by forced convection is used to cool the fuel core and moderate the neutrons and reflect them back into the core to sustain fission.

The BSR offers U.S. researchers a unique capability for studying the effects of neutron irradiation on materials at extremely cold temperatures. Such a capability "freezes in" radiation-induced material defects that migrate in samples at ambient temperatures, permitting a better atomic-level understanding of how radiation alters material properties. The BSR's Low-Temperature Neutron Irradiation Facility (LTNIF) is available for qualified experiments at no cost to users; it provides a large flux of fast neutrons for irradiating up to 50 g of material at temperatures as low as 5 K. Specimens irradiated in its cylindrical chamber can be moved into a test chamber in the irradiation cryostat or transferred at 4.2 K into an external device for testing. Massive experimental assemblies can be irradiated at higher temperatures up to about 400 K in the irradiation cryostat and from 350 to 800 K in an auxiliary Ambient Temperature Neutron Irradiation Facility (ATNIF), which provides an in-core location for radiation damage studies of nonfissile and noncontaminating samples.

Although the ORNL facility was originally built for studies of radiation shielding, its great accessibility and variety of equipment make it ideal for a wide range of experiments. In addition to the LTNIF and the ATNIF, it provides

- a Thermal Neutron Irradiation Facility, which has readily available space for irradiating material in a well-thermalized neutron flux

- the North Face Facility, which is used for irradiating large capsules and maintaining them in a constant and reproducible position

- the Core Position 15 Irradiation Facility, which allows irradiation of low-priority samples requiring relatively long irradiation times, and

- the PCA, which can be used for training reactor operators and nuclear engineering students.

Health Physics Research Reactor. The Health Physics Research Reactor (HPRR) is the primary research tool at ORNL's Dosimetry Applications Research (DOSAR) Facility. The HPRR is an unmoderated fast reactor that can be operated in the steady state at power levels ranging from 0.1 W to 10 kW or in the pulse mode to produce up to 10^{17} fissions per pulse.

The reactor is supported by a 10-m-high positioning device mounted on a track that traverses the length of the aluminum building and extends 21 m along an exterior concrete pad. The design of the reactor, its use of enriched uranium-molybdenum alloy in the reactor core, and its location ensure that normal operation will not result in radiation levels that are hazardous to either operating personnel or to the general public.

The HPRR can provide neutron doses from a few millirads to hundreds of thousands of rads, depending on operational mode, power level, duration of exposure, and location of the experiment relative to the core. A variety of shields can be used to change the dose, dose rate, and energy distribution of neutrons reaching experiments.

The reactor, which first operated in May 1963, has been used for

- training in radiation dosimetry and nuclear engineering

- radiobiology studies—determining the effects of known radiation doses on animals, plants, blood samples, etc. Rhesus monkeys were once irradiated at the HPRR to simulate the radiation effects of space travel, and mice have been exposed to various radiation doses during cancer-induction studies

- dosimetry studies that have influenced the development and calibration of personnel dosimeters for measuring radiation exposure. For almost 25 years, some 60 organizations involved in the Nuclear Accident Dosimetry Study tested dosimeters under simulated accident conditions produced by operating the HPRR in the pulse mode. For the Personnel Dosimetry Intercomparison Study, dosimeters from more than 120 organizations were mounted on humanlike phantoms, exposed to a variety of low-level, mixed-field radiation doses, and then returned for evaluation and comparison with reference values

- simulations of human-body radiation exposure under normal and accident conditions. The reactor has irradiated the "organs" of human-simulating phantoms to determine internal radiation doses at various levels of exposure. These findings have influenced the radiation guidelines set by the International Commission on Radiological Protection.

Many users have indicated interest in employing a restarted HPRR for criticality alarm testing, nuclear accident and personnel dosimetry intercomparison studies, dosimeter development, weapons spectra simulation, reactor training, and radiobiological studies.-*C.K.*

The Health Physics Research Reactor (upper right) is operated from the control room in the building over the hill (lower left). Results obtained from use of the reactor have influenced radiation guidelines and dosimetry.

New Insights on Reactor Vessel Embrittlement

By L. K. Mansur and K. Farrell

Section through the HFIR (opposite page). Neutrons from the reactor core can induce embrittlement in the steel wall of the pressure vessel.

Recent measurements on surveillance specimens of ferritic steels irradiated at the inner surface of the High Flux Isotope Reactor (HFIR) pressure vessel revealed that the material was becoming embrittled at an unexpectedly rapid rate. The neutron-induced embrittlement rate was about an order of magnitude faster than would be projected based on a large body of data accumulated in materials testing reactor irradiations. The HFIR was shut down in November 1986 because of concerns raised by these findings.

After considerable work by Dick Cheverton, who led the engineering analysis, Randy Nanstad, who led the materials work, and many others, this phenomenon was fully characterized. Shortly after the initial testing work, we became interested in the physical mechanisms underlying the early embrittlement.

We have developed a hypothesis based on theoretical considerations to explain the faster-than-expected embrittlement of the HFIR pressure vessel. Contrary to traditional views, we believe that slow neutrons, rather than fast neutrons, are chiefly responsible for the vessel wall's accelerated embrittlement. If we are correct, it may be possible to avoid this type of problem in future reactors by relatively unobtrusive reactor design changes.

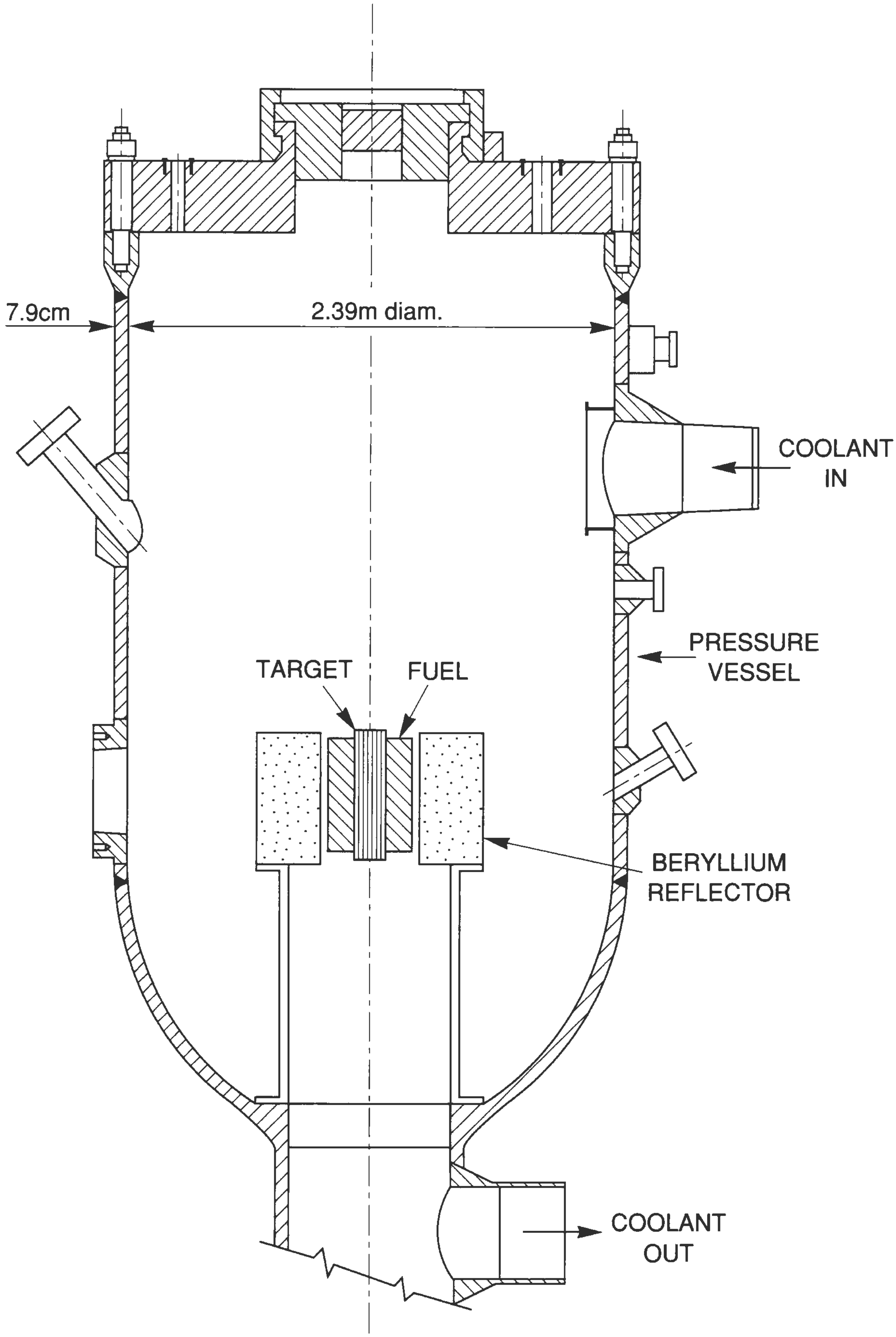
The key to understanding the early embrittlement lies in the fates of the point defects produced by neutron irradiation. Neutrons interact with lattice atoms through elastic and inelastic collisions that displace atoms from their lattice sites, pushing atoms into interstitial positions and leaving behind vacancies. These point defects are produced in spatially localized bunches termed cascades, where each cascade is initiated by a single interaction between a neutron and a lattice atom. The fates of the point defects are depicted in the flow diagram on p. 33. It is in essence a schematic of the main features and interrelations of the theory of radiation effects in materials, a discipline in which ORNL has played a leading role. The majority of point defects undergo mutual annihilation when an interstitial atom meets with a vacant lattice site (recombination) and no property change results. The remaining point defects may survive, clustering with like defects or with solute atoms and causing changes in properties.

One property change is hardening, which leads to embrittlement. The clusters block the crystal's propensity for plastic deformation. Normally, dislocations, which can be thought of as the bounding lines of extra planes of atoms terminating in the crystal, can glide through the crystal, providing a mechanism for planes of atoms to translate with respect to one another and allowing relatively easy deformation under applied stress. These irradiation-produced clusters of point defects can pin the dislocations, suppressing the plastic deformation and, therefore, hardening the crystal. When the hardening is so great that the stress needed to deform the material is greater than the fracture stress, the material is likely to fracture with little plastic deformation and is said to be severely embrittled.

To explain the embrittlement on a physical basis, we suggest that under the conditions at the HFIR pressure vessel, which are quite different from the conditions near the core during test reactor irradiations, fewer of the point defects are annihilated by mutual recombination, leaving a larger fraction available to form clusters. This increased rate of survival of point defects arises from two closely related mechanisms, one termed a rate effect, the other a spectral effect.

Rate Effect

A *rate effect*, based on *bulk recombination*, emerges from recognition that different atomic displacement rates result in different relative fractions of bulk recombination. Bulk recombination is the mutual annihilation of point defects by diffusional encounters that occur with


7.9cm
2.39m diam.
COOLANT
IN
PRESSURE
VESSEL
TARGET
FUEL
BERYLLIUM
REFLECTOR
COOLANT
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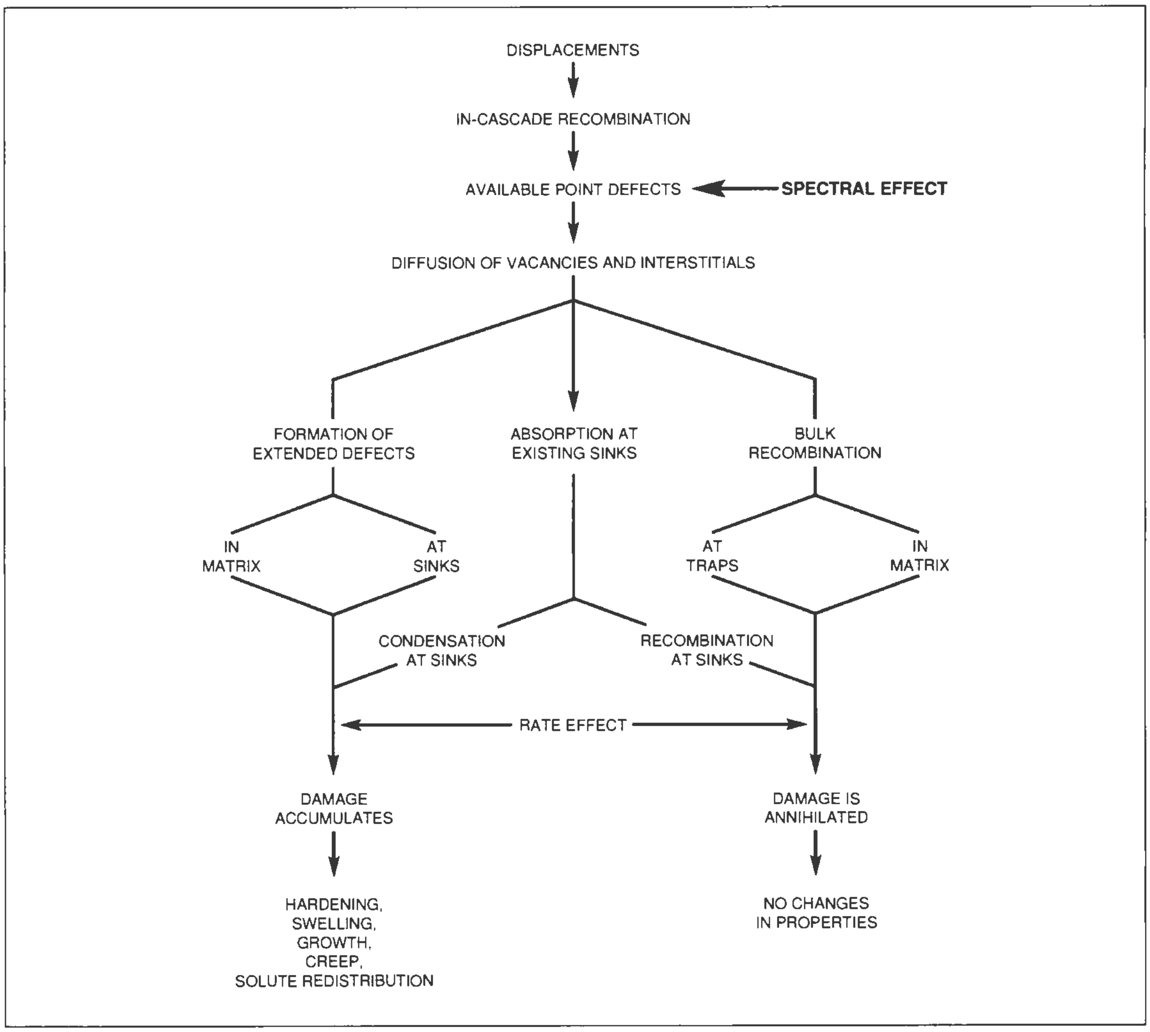
uniform spatial probability, when the point defects have diffused significant distances from the region in which they were originally produced in cascades. The bulk recombination rate is proportional to the product of the average vacancy concentration and the average interstitial concentration. Because lower displacement rates generally lead to lower average vacancy and interstitial concentrations, lower displacement rates generally give lower bulk recombination fractions, leaving larger fractions available for diffusional clustering processes. At the HFIR pressure vessel the displacement rate is as much as five orders of magnitude lower than the displacement rates of the test reactor irradiations, which were carried out in and near reactor cores. The bulk recombination rate effect, therefore, is one mechanism that may contribute to the early embrittlement of the HFIR vessel. However, because vacancy diffusion is extremely slow at 50°C, the temperature at the HFIR pressure vessel, we would expect this rate effect to be of diminished importance.

Spectral Effect

The second mechanism affecting point defect annihilation is based on *in-cascade recombination* and can be termed a *spectral effect*. A collision cascade is a highly disturbed local region, whose dimensions are typically tens of nanometers or less, consisting of spatially correlated bunches of vacancies and interstitials produced by the energetic interaction of a neutron with the crystal lattice. The spectral effect mechanism recognizes that many point defects created in collision cascades do not escape the cascade region, but rather they undergo rapid in-cascade recombination. These are not available to participate in the long-range migrational processes of diffusional clustering and bulk recombination. For macroscopic property changes like embrittlement, those defects that avoid recombination within the cascade are the only ones capable of producing permanent changes. If conditions were such that nearly all defects could avoid in-cascade recombination, the embrittlement process would obviously be greatly accelerated. We suggest that this is the key to understanding the early embrittlement of the HFIR vessel. It is more fundamental than the rate effect. In the schematic diagram showing the disposition of point defects (opposing page), it can be seen that raising or lowering the neutron flux (i.e., the point defect production rate) can only shift the balance between bulk recombination and clustering. On the other hand, the spectral effect scales all processes because it dictates how many defects are available at the very source.

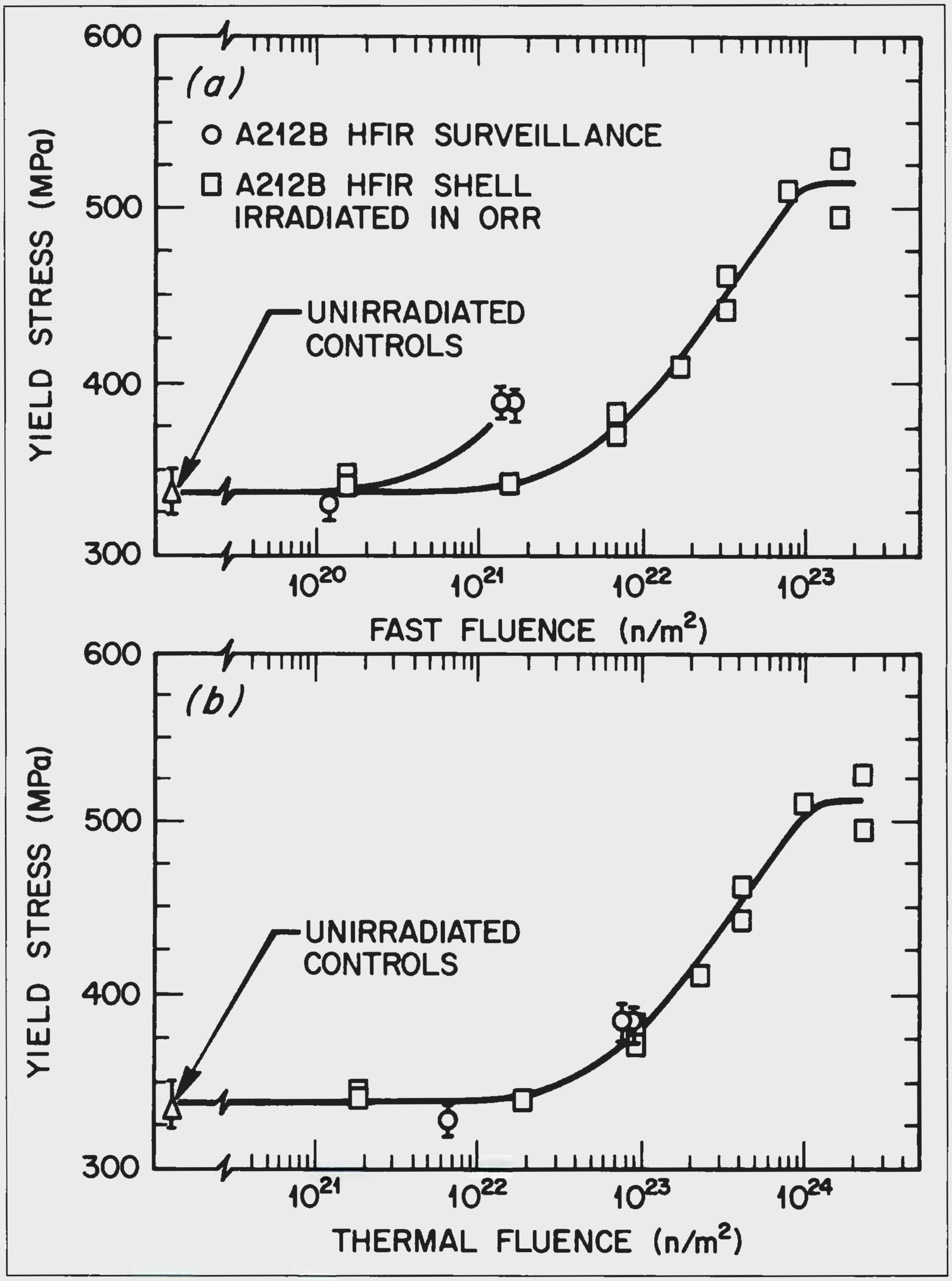
When fast neutrons with energies in the range of tenths of MeV or more bombard the crystal lattice, large numbers of vacancies and interstitials are created in the cascades thus initiated. In the test reactor irradiations of pressure vessel materials, essentially all point defects were created in such high-energy cascades. A variety of experimental evidence suggests that only 1 to 10% of the defects created in such cascades actually are available for bulk processes such as bulk recombination or diffusional clustering. And, of course, in such irradiations, the changes in properties correlate with fast neutron dose.

Less-energetic neutrons produce smaller displacement cascades in which the number and spatial density of defects within the cascade are lower and, therefore, the fraction that can avoid in-cascade recombination and become available for subsequent bulk processes, such as recombination and clustering, is higher. At the lower end of the energy spectrum, thermal neutrons having energies less than ~1 eV do not possess enough energy to displace atoms by elastic collisions. However, they can create very small displacement cascades of perhaps 3 to 5 vacancies and interstitials by the recoil of a nucleus that occurs after a (n, γ) nuclear reaction in which a neutron is absorbed and a gamma ray is emitted. The recoil atom transfers its energy to a few other atoms, which are displaced. There is now strong evidence that most of the defects created in such small cascades will avoid in-cascade recombination. The greater availability of point defects means that thermal neutrons will produce more than an order of magnitude more "usable" defects per displaced atom than fast neutrons.



Schematic illustration of the disposition of point defects, showing the pathways controlling radiation effects such as hardening and embrittlement.

Hitherto, the role of thermal neutrons in radiation embrittlement was generally considered to be minor; their greater efficiency of production of available point defects was not widely recognized and, indeed, for hard neutron spectrum conditions in a reactor core, it is not important anyway. However, at a reactor pressure vessel, which is at some distance from the reactor core, the conditions are greatly modified. Neutrons traveling from the fuel to the pressure vessel are moderated by the beryllium reflector and cooling water that they pass through. Consequently, the flux of neutrons striking the vessel is considerably reduced and their energy spectrum is strongly altered toward the lower energies. At the HFIR vessel, the neutron flux is highly thermalized, with a ratio of thermal (slow) to fast neutron flux up to about 50; in other words, for every high-energy neutron, about 50 low-energy neutrons are present. By comparison, the thermal-to-fast neutron ratio in the test reactor irradiations is much lower, typically only about 2:1. We have stressed the significance of this difference in understanding the rapidity of the HFIR vessel embrittlement. Because nearly half the total displaced atoms in the HFIR vessel materials are produced in such small cascades, we expect that the defects produced by the thermal neutrons, An analysis of irradiation test data from both the HFIR vessel and from an out-of-core position in the ORR shows that embrittlement is better correlated with thermal-neutron than fast-neutron fluence. Data from the work of R. K. Nanstad, K. Farrell, D. N. Braski, and W. R. Corwin.



because of their much higher survival against recombination, should dominate the property change and be the major contributing factor to the vessel's early embrittlement.

Our hypothesis, then, is that embrittlement, as well as other radiation effects, should directly correlate with thermal neutron fluence, not fast neutron fluence, provided that at least ~10% of the displaced atoms are produced in low-energy cascades. Preliminary experimental results suggest this is the case. An analysis of irradiation test data from both the HFIR vessel (>30% of displacements produced by thermal neutrons) and from an out-of-core position in the Oak Ridge Research Reactor (~10% of displacements produced by thermal neutrons), shows that embrittlement is better correlated with thermal neutron fluence than with fast-neutron fluence (see graphs).

We are now setting up experiments designed to investigate our spectral effect hypothesis. These experiments will be conducted in reactor positions having high ratios of thermal-to-fast neutrons and will use cadmium wrappers for some specimens. These wrappers effectively eliminate thermal neutron displacements because they absorb a large fraction of slow neutrons. If our hypothesis that thermal neutrons are the major contributing factor to embrittlement when thermal neutrons produce a significant fraction of the displacements is true, then unwrapped specimens irradiated at the same locations should experience significantly higher embrittlement rates per unit displacement. Related experiments also are planned to establish the magnitude and temperature dependence of the rate effect.

In view of our analysis, it would be prudent to closely monitor components of reactor pressure vessels and support structures for accelerated radiation effects wherever the neutron energy spectrum is highly thermalized. The implications for engineering solutions to the accelerated embrittlement problem are different if the *spectral effect* mechanism suggested here, rather than the rate effect, is the main contributor. Low damage rates in components such as light-water reactor pressure vessel supports are hardly avoidable. However, it may be relatively easy to make design modifications (e.g., add thermal neutron shields) to reduce the thermal component of the neutron spectrum, where it is excessive in components remote from the core. By understanding the physical mechanisms operating at the atomic scale, we can, therefore, expect to solve the technological problem of accelerated embrittlement of reactor materials. ornl

Biographical Sketches

Louis K. Mansur, leader of the Defect Mechanisms Group in ORNL's Metals and Ceramics Division, has worked at ORNL since 1974. He has a Ph.D. degree from Cornell University. The group has received a DOE Materials Sciences Award for research having significant implications for energy technology. He has received Martin Marietta Energy Systems, Inc., technical achievement and publication awards. Mansur serves on the editorial boards of three journals in the field of materials science. He is a fellow of the American Nuclear Society and the American Society for Metals.

Kenneth Farrell earned his Ph.D. degree in metallurgy from the University of Sheffield in England in 1962. Two years later he joined the Metals and Ceramics Division, where he has worked principally in plastic deformation, embrittlement, and radiation effects. He is a fellow of the British Institute of Metals.

The Oak Ridge Research

Reactor: A Requiem

By Luci Bell

When the Oak Ridge Research Reactor (ORR) was completed in 1958, it was the best general-purpose research reactor in the world. Many long-term employees of Oak Ridge National Laboratory were involved in the excitement and productivity of those early years at the ORR. Royalty and presidents visited the new facility, internationally famous scientists and engineers from throughout the United States and foreign nations competed to use the reactor, and the ORR became the scene of pioneering experiments in the fields of nuclear and solid state physics.

This illustrious segment of the Laboratory's history ended with the July 1987 permanent shutdown of the ORR. After 29 years of successful and safe operation, the ORR's record-breaking service life ended as new and improved irradiation and neutron scattering facilities at the High Flux Isotope Reactor (HFIR) became available to continue and extend its work. At that point, its mission honorably completed, the ORR was taken out of service—an administrative decision announced by the Department of Energy's Oak Ridge Operations Office.

A World-Class Facility

In the decade following the construction of the ORNL Graphite Reactor for the war effort, research on radioactivity and possible uses of radioisotopes grew rapidly. Many practical applications for isotopes, especially in medicine, soon became well established. Isotope production at the Graphite Reactor was a slow and cumbersome process however, and the demand began outstripping the supply. A more powerful reactor was needed.

By the mid-1940s, it also became obvious to scientists doing research in nuclear physics and chemistry that a reactor having a higher neutron flux was necessary to advance their work. In addition, the government recognized the need for a high-flux reactor to test the materials and potential fuels for the power-producing reactors that were being planned even during that early stage of nuclear development.

As wartime activities came to an end, planning was started in Oak Ridge for the construction of the Materials Testing Reactor (MTR), which was to be the first U.S. high-flux research facility. After the government decided in 1948 to construct the MTR in Idaho, rather than Oak Ridge, scientists here continued to press for a powerful research reactor at ORNL. In 1952, funding was received for a small preliminary study.

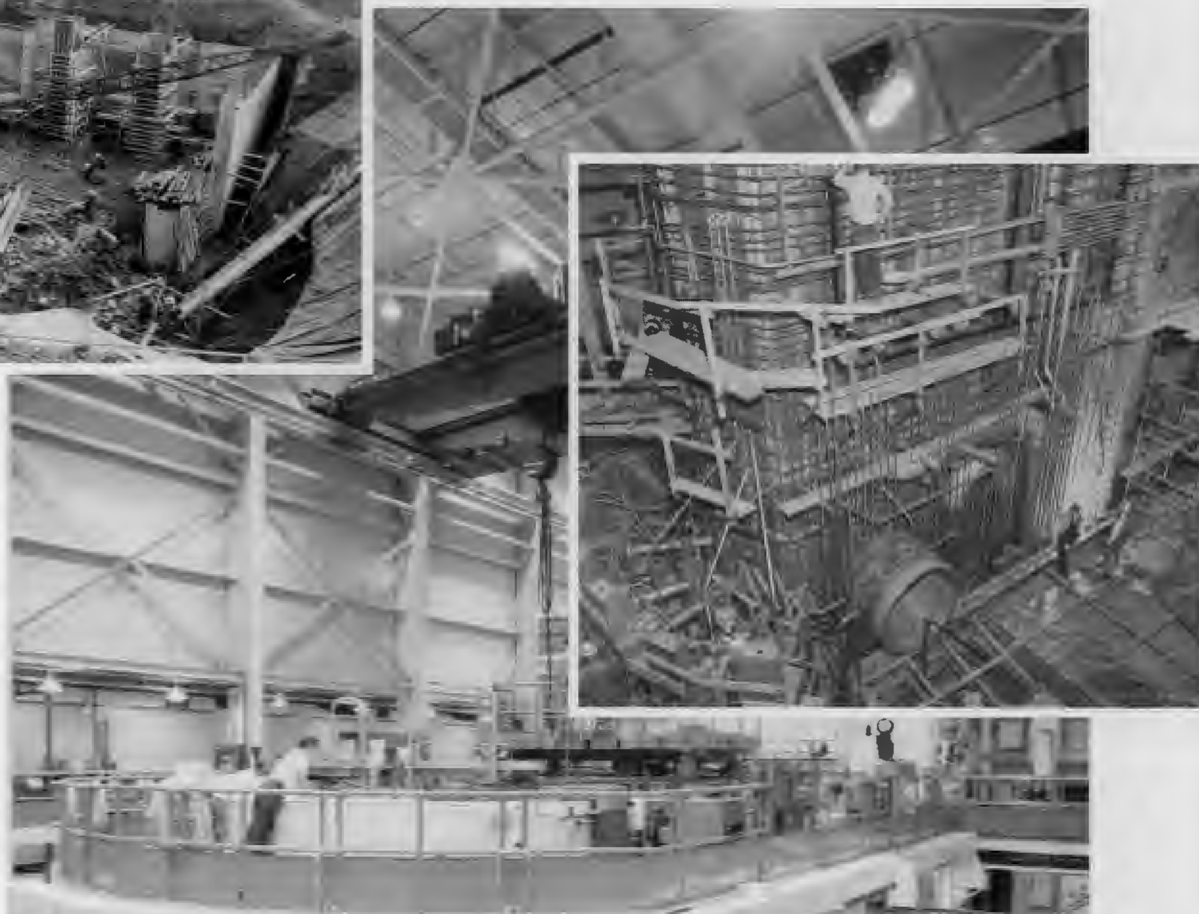
As a result of this effort, the Atomic Energy Commission (AEC) eventually authorized the construction of the ORR, which emerged finally as a world-class neutron source of unparalleled flexibility and versatility. The ORR was constructed at the Oak Ridge X-10 site during the 1950s for only $4.7 million and was brought to criticality in 1958.

Design Features

The ORR was designed to provide a much higher thermal neutron flux than any then available at ORNL—levels greater than 10^{14} neutrons/cm^2·s at reactor power levels as high as 30 megawatts (MW). This neutron flux and the ORR's unique research and production features allowed it to produce the isotopes needed for research, medicine, and industry faster, more economically, and in greater quantities than any other reactor anywhere at that time. After the ORR began operation, ORNL soon became the primary supplier of neutron-produced radioisotopes for the entire western hemisphere and an international center for nuclear and solid state physics research.

The instrumentation, control, and safety systems of the ORR were patterned after the ORNL-developed systems used in the MTR. The safety features, certainly the most advanced of their time, included a filter and scrubber system and a "dynamic-confinement" building around the reactor to protect the off-site population against any accidental radioactivity releases. These and other new safety concepts built into the ORR by Tom Cole, the project director, and J. P. Gill, project engineer, were later modified and

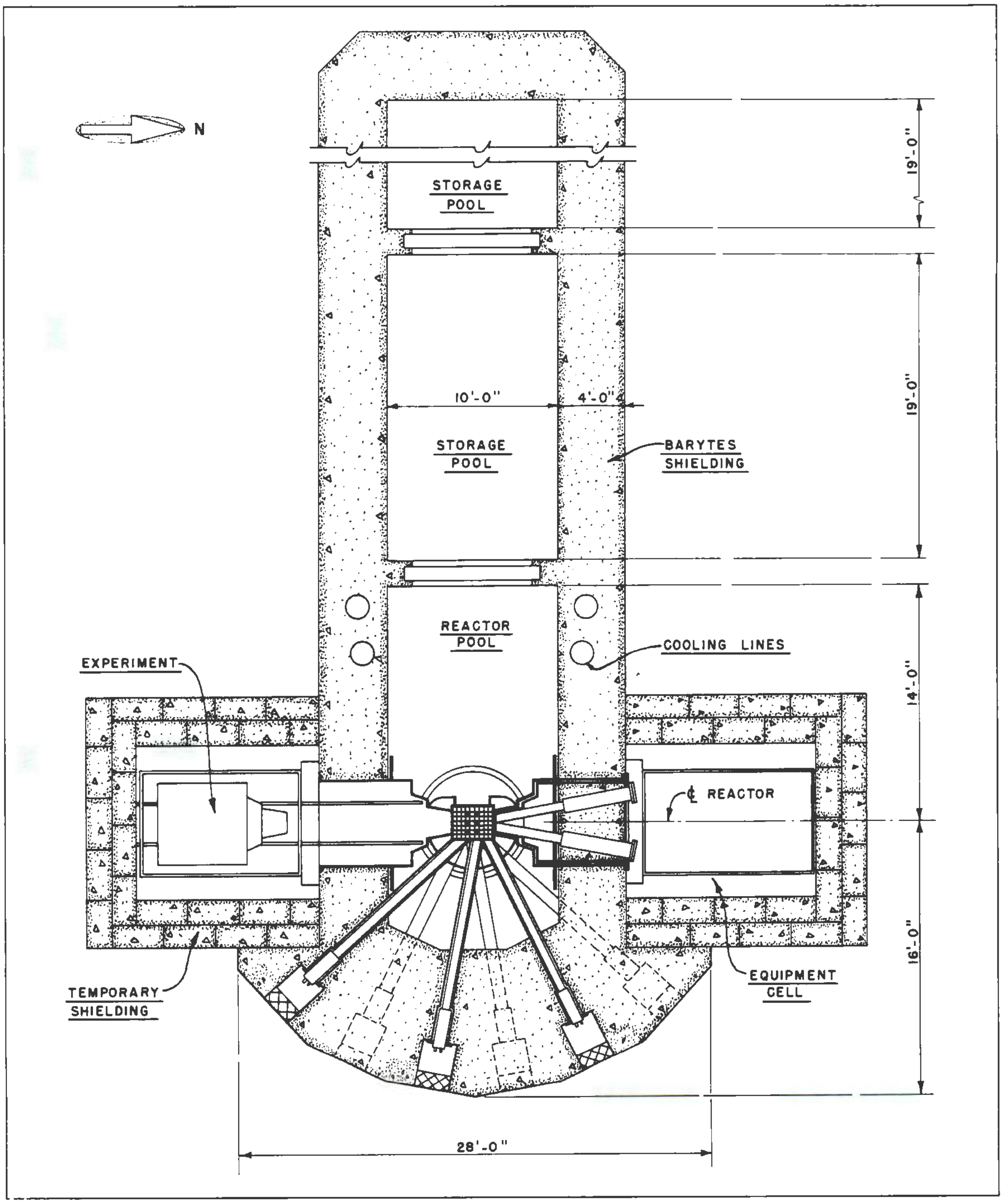
"Royalty and presidents visited the new facility; internationally famous scientists and engineers from throughout the United States and foreign nations competed to use the reactor."



1955—Construction of the ORR begins.

1956—(inset) The reactor and storage pools take shape. (Note neutron beam ports in left foreground and cooling water outlet at bottom right.)

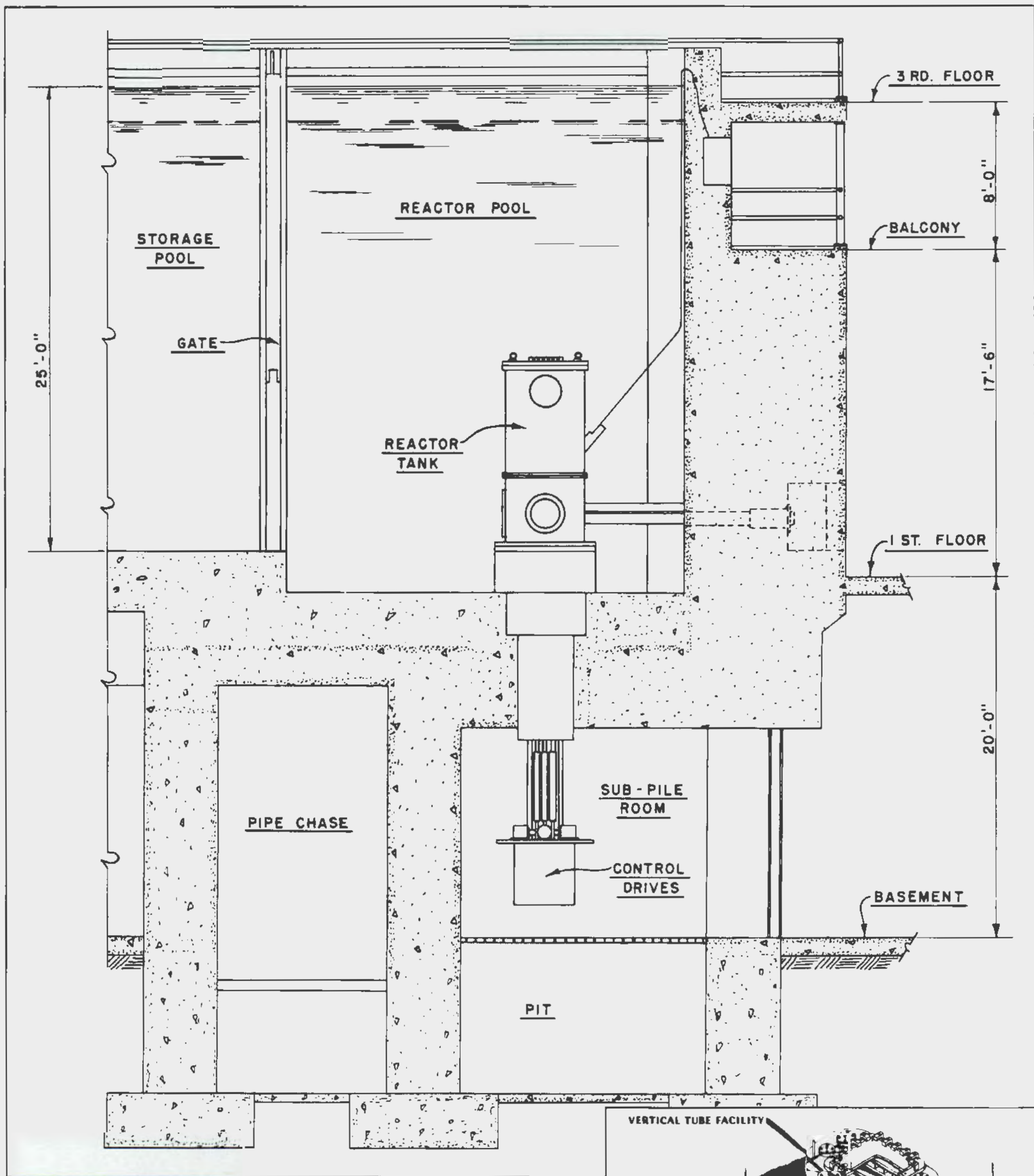
1956—The ORR, with its four working levels for research and isotope production, is completed. Criticality achieved on March 21!



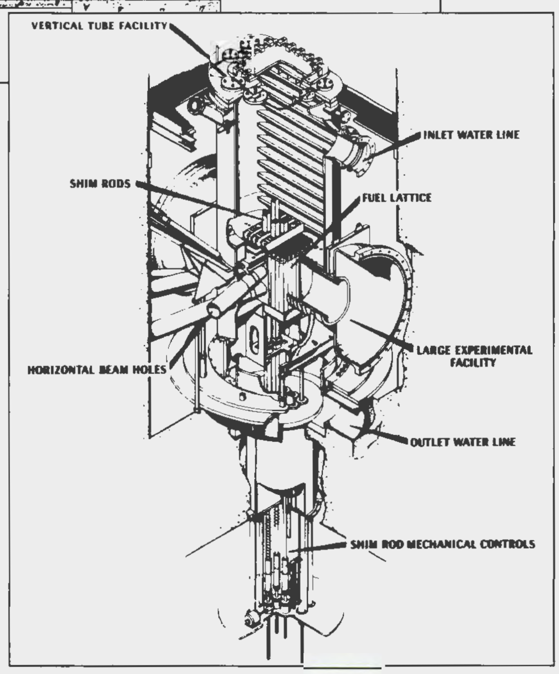
Reactor and storage pool structure, horizontal section.

incorporated in the HFIR and other reactors both here and abroad.

Tom Hamrick, who became the ORR's final supervisor in 1985, points out that few safety-related incidents of significant consequence occurred during the ORR's entire 29 years of operation. Hamrick recalls only two incidents serious enough to require shutdown of the reactor. During startup after refueling in 1963, part of a gasket became lodged so as to restrict the flow of cooling water to one of the fuel plates, causing it to melt; none of the other fuel plates were affected, and the situation was corrected within a few days. On another occasion, an isotope sample came loose and wound up in a water pump. This also caused a shutdown of several days while the water pump was disassembled and the sample removed. There were no personnel exposures



Vertical section of the ORR's structure. (Note the control drive mechanism located beneath the reactor to increase accessibility for research.)



Vertical schematic of the ORR—a world-class facility.

exceeding the radiation dose limit in either case, and, altogether, the ORR had a safety record that Hamrick and the other reactor supervisors are proud to recall.

An outstanding design feature of the ORR was the location of its reactor tank in a pool of water, an idea that was originated by Cole and that was often used in later reactor designs. The pool provided shielding for the core and for radioactive experiments and refueling operations; it also overcame a limitation of the MTR reactor design by giving researchers easy access to the core region (see horizontal and vertical schematic views). The adjoining storage pools, containing nearly 455,000 liters (L) of demineralized water, also provided shielding and storage for the reactor's depleted fuel elements. The separate cooling system inside the reactor tank contained about 223,000 L of ordinary demineralized water, which was circulated through the reactor's core at a rate of about 45,000 L/min for 20-MW reactor operation and at 68,000 L/min for 30-MW operation. With these circulation rates, heat from the reactor caused only a small temperature increase between the inlet and outlet water (from about 49°C to 55°C).

ORR Accessibility

Because the ORR's design emphasized flexibility and ease of access, it could accommodate a broad range of experimental programs and research needs. The reactor was used for many basic studies on the properties of metals, alloys, ceramics, and nuclear fuels, as well as for neutron spectrometry and neutron scattering research and fundamental engineering studies of radiation effects on materials.

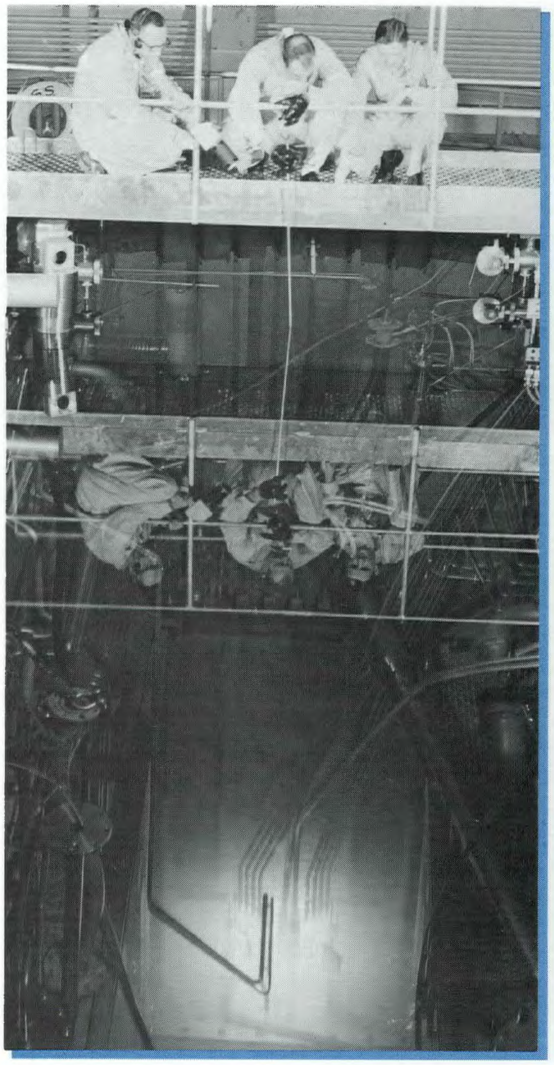
An ORR pool-side facility that allowed the placement of irradiation test assemblies close to the reactor's core, yet outside the pressure tank, was unique for its time. This convenient feature was later incorporated, in a modified form, in research reactors built in Sweden, the Netherlands, and South Africa.

Another convenient feature was a hot cell located above one end of the reactor's fuel storage pool. This allowed irradiated material samples to be moved underwater from the core region directly into the cell. Depleted fuel and control elements could also be removed from the ORR through a rectangular hatch in the top of the reactor tank and then moved underwater to the storage pool area or to the adjacent hot cell for experimental use.

Without disturbing refueling operations, as many as 10 experiments could be placed in the ORR at the same time through the system of flanges and curved insertion tubes in the reactor tank's cover. The tubes were connected with shielded experiment control facilities located in basement rooms. In the early photograph shown here, workers on a platform above the reactor pool are using a long rod to adjust one of the many experimental rigs in place near the reactor tank below. The intense glow seen in the reactor pool (foreground) is Cerenkov radiation produced when gamma rays from the core of the reactor collide with electrons of the pool's water molecules. Accelerated by the energetic gamma rays, the electrons travel through the pool at velocities greater than the normal speed of light through water, causing the beautiful blue glow that was a much-photographed feature of the ORR.

Fuel Irradiation Tests

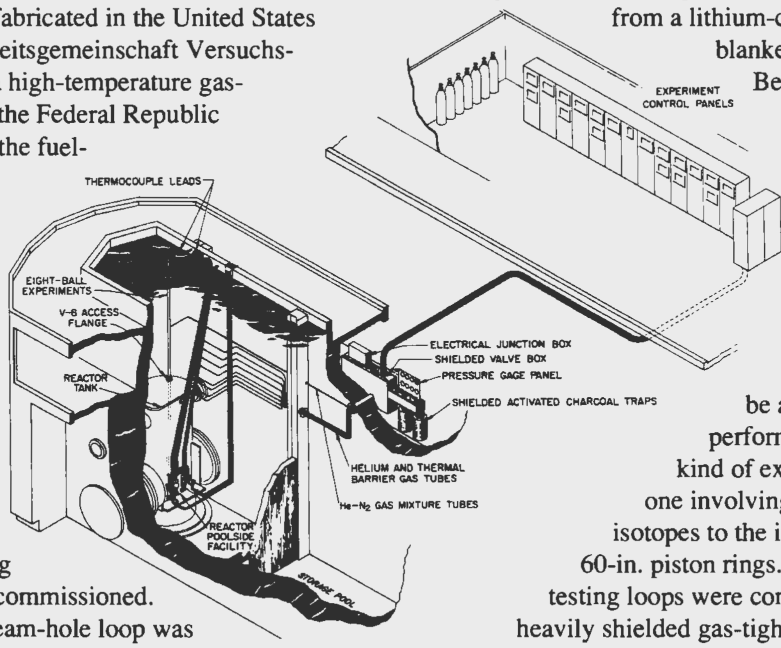
The ORR was greatly welcomed by researchers involved in the early development of irradiation



Workers are using a long rod to adjust one of the experimental rigs in place near the reactor tank below. (Cerenkov radiation glows in the foreground.)

tests for nuclear fuels, according to ORNL's Don Trauger, one of the pioneers in this work. Research reactors built prior to the ORR either had inadequate neutron flux or more limited facilities for fuel testing.

Fuel assembly designs for the Experimental Gas-Cooled Reactor (EGCR) were tested in a specially designed gas-cooled loop in the ORR, but the EGCR was never operated to confirm the validity of these tests. A second round of ORR tests was called the "eight-ball" irradiation experiments because each test assembly contained eight fuel spheres (the figure here shows the experimental setup at the ORR for the eight-ball experiments). The coated-particle fuel assemblies were fabricated in the United States for use in the Arbeitsgemeinschaft Versuchs-Reaktor (AVR), a high-temperature gas-cooled reactor in the Federal Republic of Germany, and the fuel-test results obtained at the ORR were later validated through AVR operation.



To provide more realistic fuel-testing conditions, three fluid-circulating loops were added to the ORR. The EGCR fuel-testing loop was later decommissioned. A second large beam-hole loop was built to test fuel elements for ORNL's High-Temperature Gas-Cooled Reactor (HTGR) Program. The third fuel-testing loop, called the Maritime, was designed to test fuels for the anticipated second and third refueling of the nuclear ship, *N. S. Savannah*. The loop operated successfully for six years, but its operation was terminated in anticipation of the nuclear ship's decommissioning. In addition, a smaller test loop for the ORNL Homogeneous Reactor fuel system was later operated at one of the beam tubes.

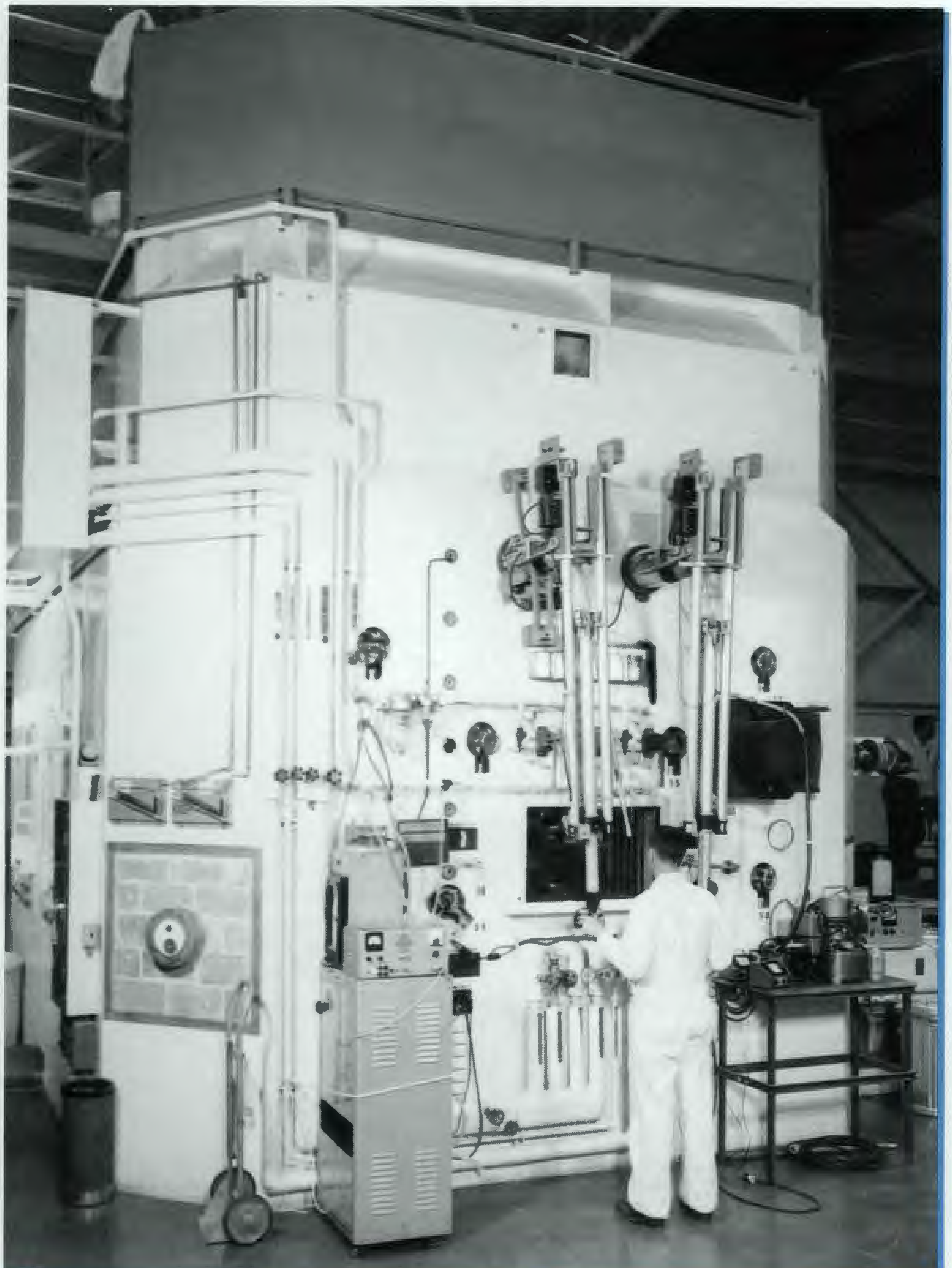
This exciting early period in the development of nuclear fuel systems, made possible by the ORR, helped to establish ORNL as an international leader in the development of nuclear fuels and irradiation testing equipment. Trauger states that some features of these early ORR facilities are considered advanced even today and have contributed to subsequent research reactor designs. The photo here shows the heavily shielded hot-cell located above one end of the storage pool and equipped for handling highly radioactive materials such as the irradiated fuel samples.

In 1983, the ORR was used in a collaborative effort of scientists from ORNL and Argonne National Laboratory (ANL) to demonstrate the breeding of tritium, a proposed fusion reactor fuel, from a lithium-containing blanket material. Bernie Corbett, who supervised the ORR from 1982 to 1985, was in charge of the planning and setup for this project. Corbett says the ORR could be adapted to perform almost any kind of experiment—from one involving micrograms of isotopes to the irradiation of 60-in. piston rings. Reactor fuel testing loops were contained in heavily shielded gas-tight cells such as the one shown on this page. Unclad fuel elements could be tested at surface temperatures up to 2500°F.

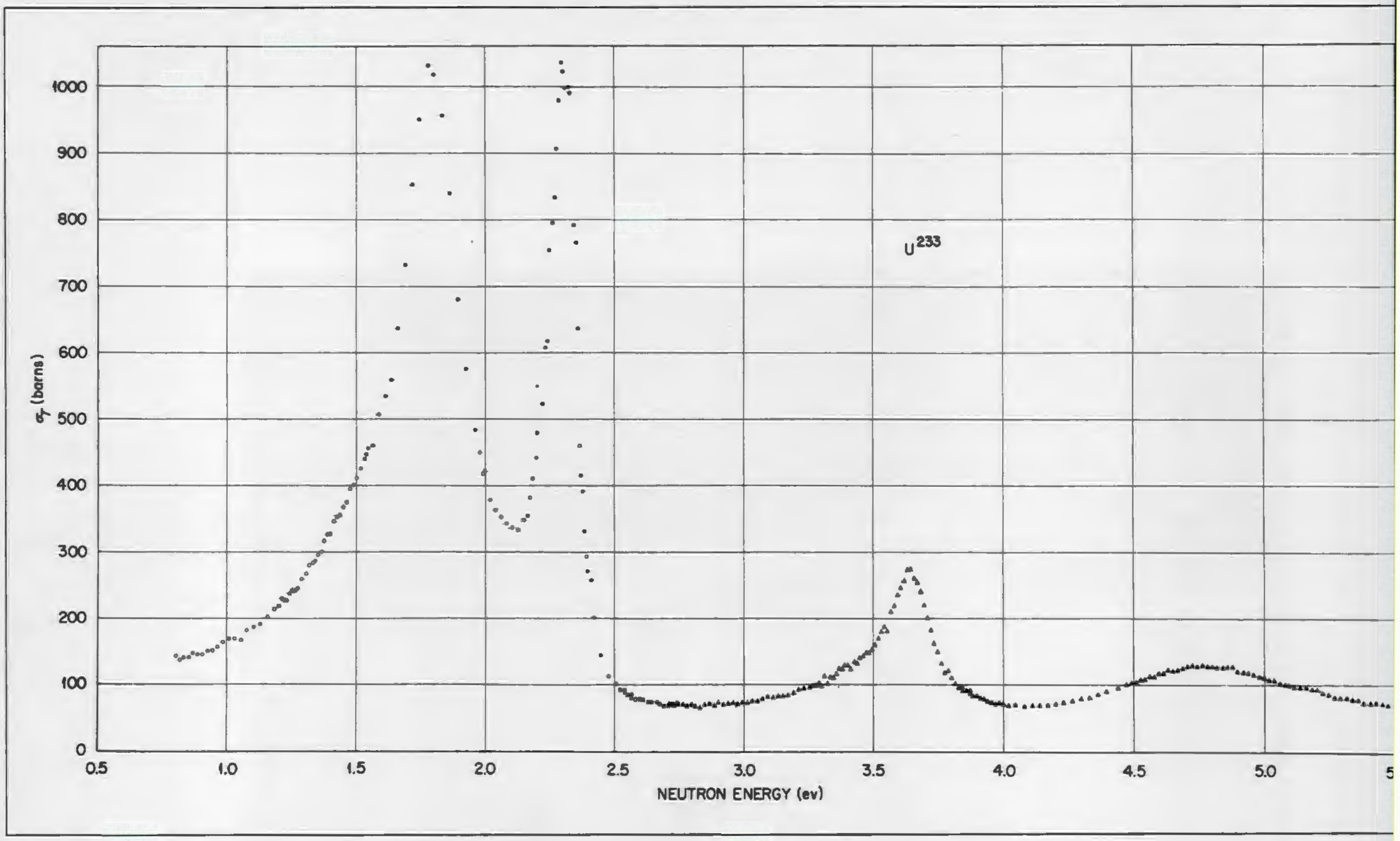
The last fuel-testing experiment at the ORR, an evaluation by ANL scientists of some low-enrichment uranium fuels for research reactors, was terminated prematurely in 1987, when DOE ordered the ORR's permanent shutdown.

Nuclear Physics

The diverse experimental facilities that made the ORR much sought after by the world's leading



Irradiated fuel samples were moved underwater from the core directly into this hot cell for testing.



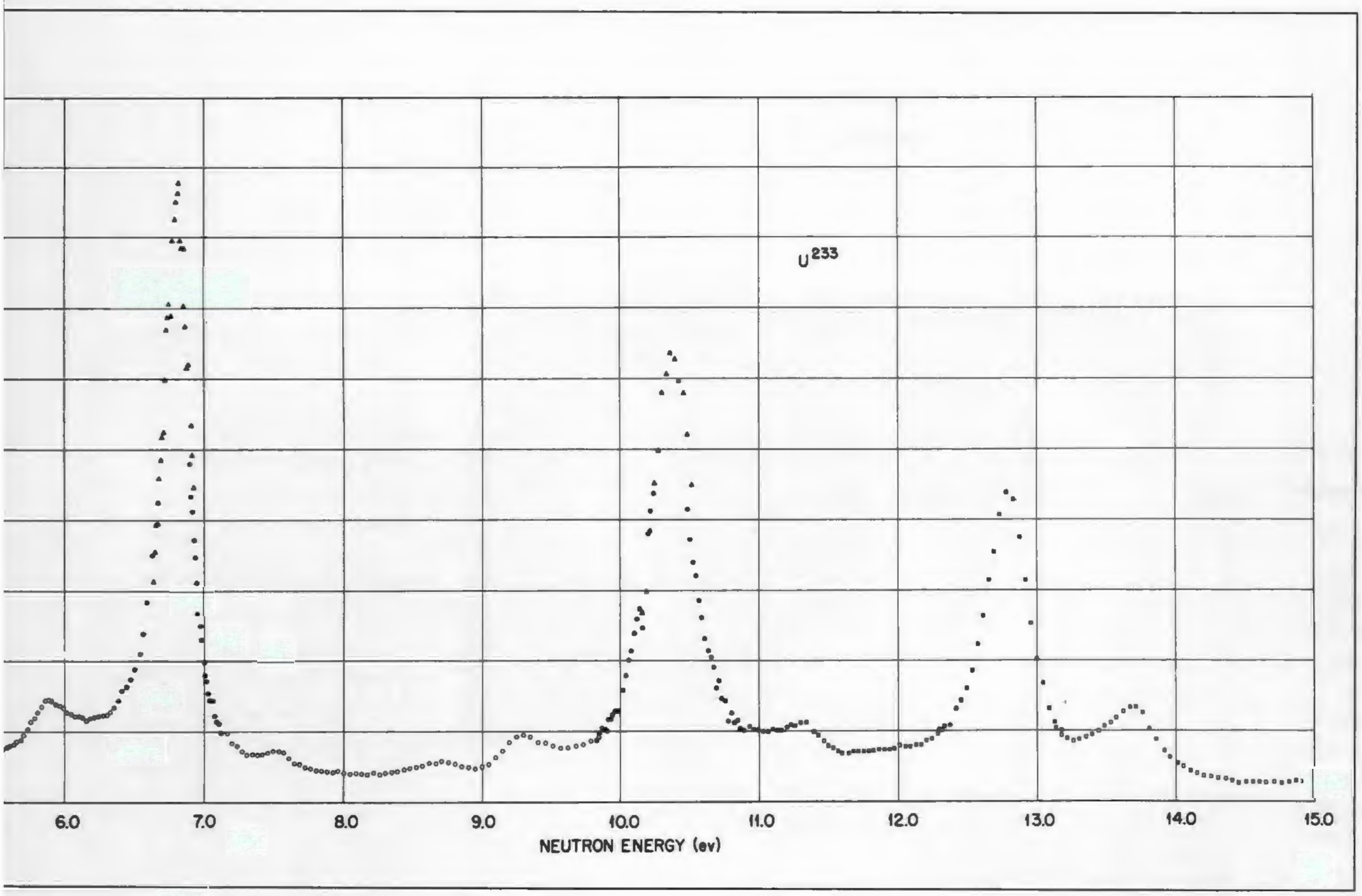
Cross-section data for uranium-233 (top of page) were obtained at the ORR. They are still the best available for this isotope.

scientists in the late 1950s and 1960s included six horizontal neutron beam tubes on the east face of the reactor. These tubes, and two additional beam tubes installed later on the reactor's north face, were designated for either nuclear physics research or experiments in solid-state science.

Neutron spectrometry. The neutron flux of the ORR provided an excellent probe for studying nuclear structures. In 1959, Jack Harvey, Bob Block, and Grimes Slaughter in ORNL's Physics Division began using a spectrometer at one of the ORR's neutron beam tubes to investigate nuclear resonance structures and to develop nuclear data needed for the design of fission power reactors. The group continued this fundamental research at the ORR for about seven years.

In the late 1950s, great interest arose in the possibility of a thermal-neutron, thorium-uranium molten salt breeder reactor (a thermal or "slow" neutron has a kinetic energy level similar to the energy distribution of the material in which it exists). At that time, accurate neutron cross-section data and fission data for thorium-232 and uranium-233 nuclei were urgently needed to evaluate these elements as possible nuclear fuels for what was called the Molten Salt Reactor Experiment. As part of this work, accurate (within ~1%) total cross-section measurements were made for neutrons ranging from thermal energy to 1000 eV, using several excellent samples of metallic uranium-233 (enriched to 99.76% especially for this project). Nearly 30 years later, Harvey says these are still the best cross-section data available for this isotope (see figure at top of page).

The first accurate cross-section measurements for several of the heavier nuclides, such as neptunium, americium, and various radioactive fission products were also done at the ORR. A second neutron spectometer installed at the ORR in 1960 was used to make important transmission measurements on all ten isotopes of tin. Detailed analyses of these data by T. Fuketa (a visiting scientist from Japan who is now vice-president of the Japan Atomic Energy Research Institute) confirmed important theoretical predictions concerning the optical model for neutron interactions. Some of the early data gathered at the ORR also helped confirm the nuclear structure

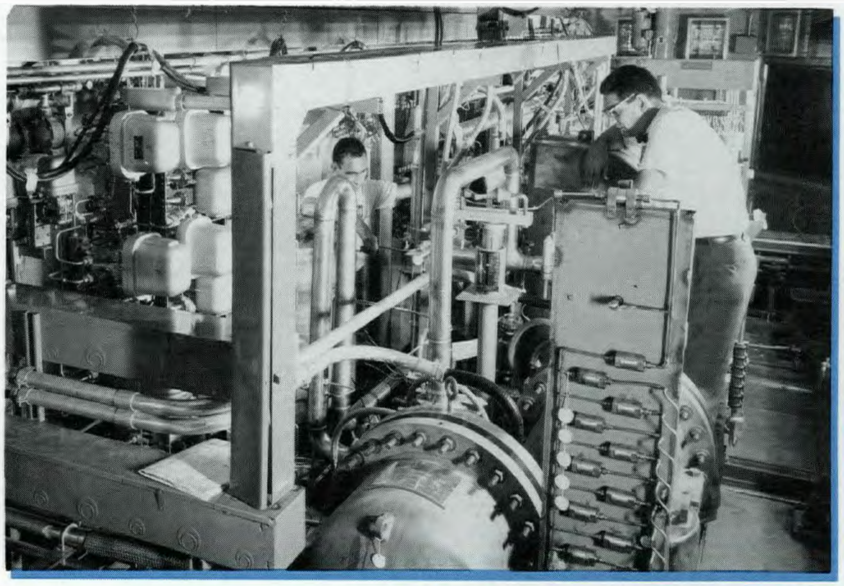


theories of Niels Bohr and clarify the intermediate nuclear states for neutron reactions with isotopes.

Nuclear resonance studies. In 1962, a large (0.75-m-diam) liquid scintillator tank was installed just outside the ORR building (see figure on this page). This facility allowed nuclear physicists to measure the neutron capture cross sections of nuclei at high energies (up to 10,000 eV), overlapping the energy region measured at the Van de Graaff accelerator at ORNL. A second facility for studying details of the capture process using thermal ("slow") neutrons and resonance-energy ("fast") neutrons was added in 1963, when a large sodium iodide crystal (23-cm diam by 30-cm length) was installed at an ORR beam hole.

Neutron resonance studies and gamma ray spectra for many nuclides were completed at the ORR, providing new information and confirming predictions made from the nuclear shell model theory (analogous to the atomic shell theory that electrons of all elements move about the nucleus as if in electrical "clouds" located at discrete levels or shells, depending on their energies).

Various types of nuclear physics experiments and measurements continued successfully at the ORR until 1966, when such efforts were shifted to the new Oak Ridge Electron Linear Accelerator (ORELA).



The cell for the ORR fuel-testing loop was shielded by concrete walls more than 1 m thick.

October 5, 1985—The ORR's 10,000th day of operation. ORR supervisors (from left) Sam Hurt (1973 to 1982), Bernie Corbett (1982 to 1985), Bill Tabor (1958 to 1973), and Tom Hamrick (1985 to 1987 shutdown) gathered for the occasion.

Nuclear fission research. In the 1950s ORNL researchers John Dabbs, Louis Roberts, George Parker, John Walter, Hal Schmitt, and others conducted important basic nuclear fission research at the ORR. Schmitt headed a study that investigated the dynamics of thermal-neutron fission (the situation that occurs when a nucleus breaks into two or more pieces). By measuring the energies of the fission fragments simultaneously with separate silicon surface-barrier detectors, detailed information was obtained about the masses of the fragments and their kinetic energies as a function of mass. For each of these experiments, ~106 nuclear events were recorded individually on punched paper tape—usually requiring several miles of the tape. An unexpected result of this work was the discovery that, in each nuclear fragmentation case, all the excess nucleons went to the light fragment, and the heavier fragment retained a stable mass.

The ORR was also the site of one of the early and crucial experiments relating to the electron-neutrino theory of nuclear beta decay, the theory that a beta decay event in a radioactive nucleus produces not just one particle or energy wave, but three separate entities: a beta particle (electron or positron); a neutrino (a neutral particle having essentially no mass); and a decay daughter isotope, with a different positive charge than the original element.

The first "in-pool" physics experiment at the ORR confirmed this decay theory on a simple system; fast neutrons at the face of the ORR were used to produce a helium-6 sample by irradiating very fine beryllium oxide powder. A group of ORNL physicists that included Cleland Johnson, Toni Pleasanton, and Tom Carlson accurately measured the helium-6 half-life (0.797 s) and decay energy (3509 keV), the ionic charges resulting from the several possible beta decay modes of the helium-6, and the range of lithium-6 recoil energies. The magnitude of this task (given the extremely short half-life of helium-6 and the lack of today's modern computerized measuring instruments) earns respect for both the patience and skill of the researchers and the adaptable research facilities of the ORR. Later, similar measurements were made for the beta decay products of other radioactive gases, such as neon-23 and argon-41.

These and other early experiments in nuclear and solid state physics at the ORR helped to broaden our understanding of matter and energy on the most basic levels.

Condensed Matter Research

The first applications of neutron scattering techniques to studies of condensed matter were performed at the ORNL Graphite Reactor, beginning in late 1945. This work, which was pioneered by Ernie Wollan, Cliff Shull, Wally Koehler, and their associates in the Physics Division, laid the foundation for the neutron scattering programs at ORNL and others that developed later.

The ORR, which offered neutron beams of 100 times greater intensity than any previously available at ORNL, was eagerly awaited by solid state physicists, according to Mike Wilkinson, a research leader in this area. The ORR was used extensively for investigations of magnetic phenomena, particularly the magnetic order transitions that occur in metals at very low temperatures. For this work a unique magnetic diffractometer, designed so that both the strength and direction of the magnetic field could be varied, was located at one of the ORR beam ports (see photo on p. 51). At other beam ports, researchers used a variety of instruments to study structural properties of solids and radiation-induced defects in materials.

Experiments performed at ORNL by Wollan, Koehler, and Wilkinson, along with Joe Cable, Ralph Moon, and Ray Child determined the first magnetic moment distributions for metallic chromium and chromium alloys, rare-earth metals and alloys, and alloys of the iron-group metals. The chromium work supplied evidence to support the theory of spin-density waves in that material. The research on rare-earths, which explained many of their unusual magnetic properties, was of international interest and continued over many years at the Graphite Reactor, the ORR, and later at the HFIR when it became operational in the 1960s.

Neutron diffraction investigations by ORNL's Chemistry Division were done at the ORR, focusing on details of atomic bonding, particularly in compounds containing hydrogen. Henri Levy, Selmer Peterson, Harold Smith, Bill Busing, George Brown, and their associates were pioneers in single-crystal neutron diffraction work, using a custom-designed instrument that included the first transistorized control system to be installed at ORNL. Their investigations of the crystal structures of xenon difluoride and xenon tetrafluoride were of particular importance, because the bonding properties of xenon were completely unknown at the time and many scientists had doubted that xenon compounds could exist. A later project (in 1962) determined the crystal structure of sucrose, using 5800 individual neutron intensity measurements. This was by far the largest crystallographic problem that had been solved by neutron diffraction techniques at that time.

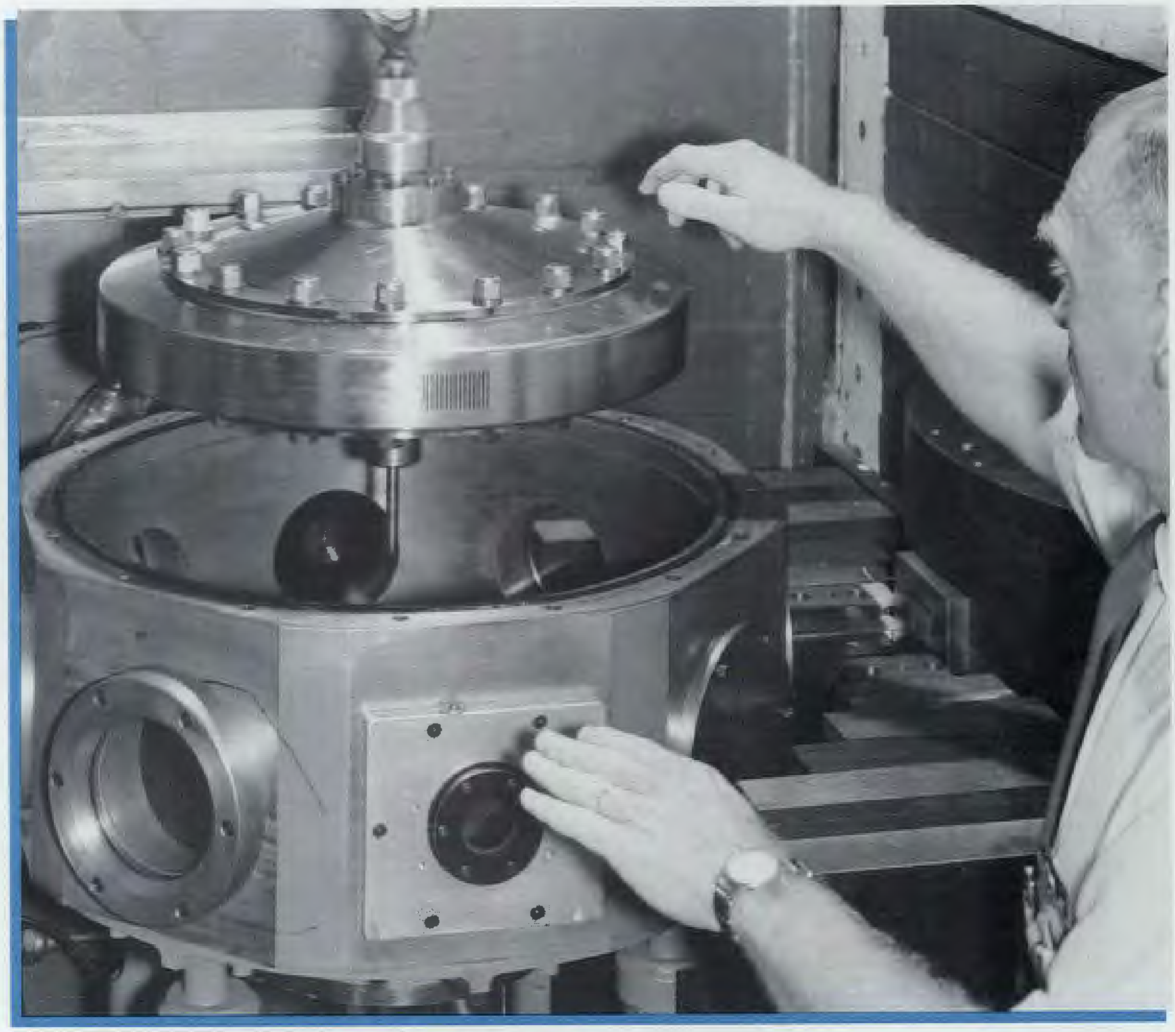
To supplement and extend the neutron diffraction work, Solid State Division physicists Harold Smith, Bob Nicklow, Herb Mook, and Wilkinson had a triple-axis spectrometer installed at one of the ORR beam ports. Using this instrument, they were able to gain new insights on the lattice dynamics of solids and the interatomic forces in ionic, covalent, and metallic crystals. The interesting magnetic properties of the superoxides of potassium and rubidium were also investigated by this group.

When the outstanding facilities and higher neutron flux of the HFIR became available, most of the neutron scattering research at the ORR was phased out. However, the ORR neutron beams were still used for special types of investigations and advanced instrumentation development projects that would have been difficult to perform at the HFIR.

After the Ames Laboratory research reactor in Iowa was shut down in 1977, Ames staff members began using the ORR to continue doing research and training graduate students in neutron scattering. Because of the total shutdown of the ORR and the two-year shutdown of the HFIR, these activities had to be temporarily discontinued. It is planned that most of this work will be accommodated at the HFIR, when operations there are resumed.

Radioisotope Production

Even before the ORR began operating in 1958, the use of radioisotopes grew from a research



Nuclear physics pioneer Jack Harvey and others contributed to and supported the fission decay theories of Niels Bohr with data from the "fast-chopper" spectrometer at the ORR.

status to well-established applications in medicine, agriculture, and industry. When the ORR was added to ORNL's older Graphite Reactor and the Low-Intensity Test Reactor, ORNL became the primary supplier of radioisotopes for the free world. This is still true for many isotopes, since the HFIR was designed to have even greater isotope production capabilities. Sam Hurt, who served as shift supervisor at the ORR in 1958 and as ORR supervisor from 1973 to 1982, says that he and other ORR workers felt it was "personally gratifying to know that, through the production of isotopes, we were contributing to advances in medical research and possibly saving or prolonging human lives."

The designers of the ORR recognized and planned for the growing need for radioisotopes by incorporating facilities specifically for radioisotope production. Small target samples could be irradiated to produce isotopes by inserting or removing the samples while the reactor continued to operate, and multiple-sample irradiations could be done on the same time cycle as normal reactor operation. Target materials for producing long-lived radioisotopes were placed in aluminum containers like the one shown in the photo above and positioned on special trays that were inserted in the reactor. To produce short-lived radioisotopes, targets in aluminum capsules were moved in and out of the reactor during

From target materials in containers like these, the ORR produced radioisotopes for the entire Western world. Commercial companies now fill most needs.

operation through a hydraulic tube installed in the reactor core.

The neutron flux, large sample capacity, and flexibility of the ORR provided ORNL scientists a powerful and reliable tool to meet the growing demand for radioisotopes. During the 1960s, ORNL began routine production of about 25 radioisotopes, which were processed and packaged here and distributed to users on preestablished schedules with virtually no delay. Because of this reliable supply from the ORR, the uses of radioisotopes expanded even more rapidly than before.

Major nuclides produced in the ORR included iodine-131, molybdenum-99, and phosphorus-32 (isotopes used mostly for medical applications), and a high-quality iridium-192 (used widely in industrial radiography). As new applications continued to develop, additional isotopes were routinely produced in the ORR, and small quantities of isotopes needed for special projects were provided on a make-on-demand basis.

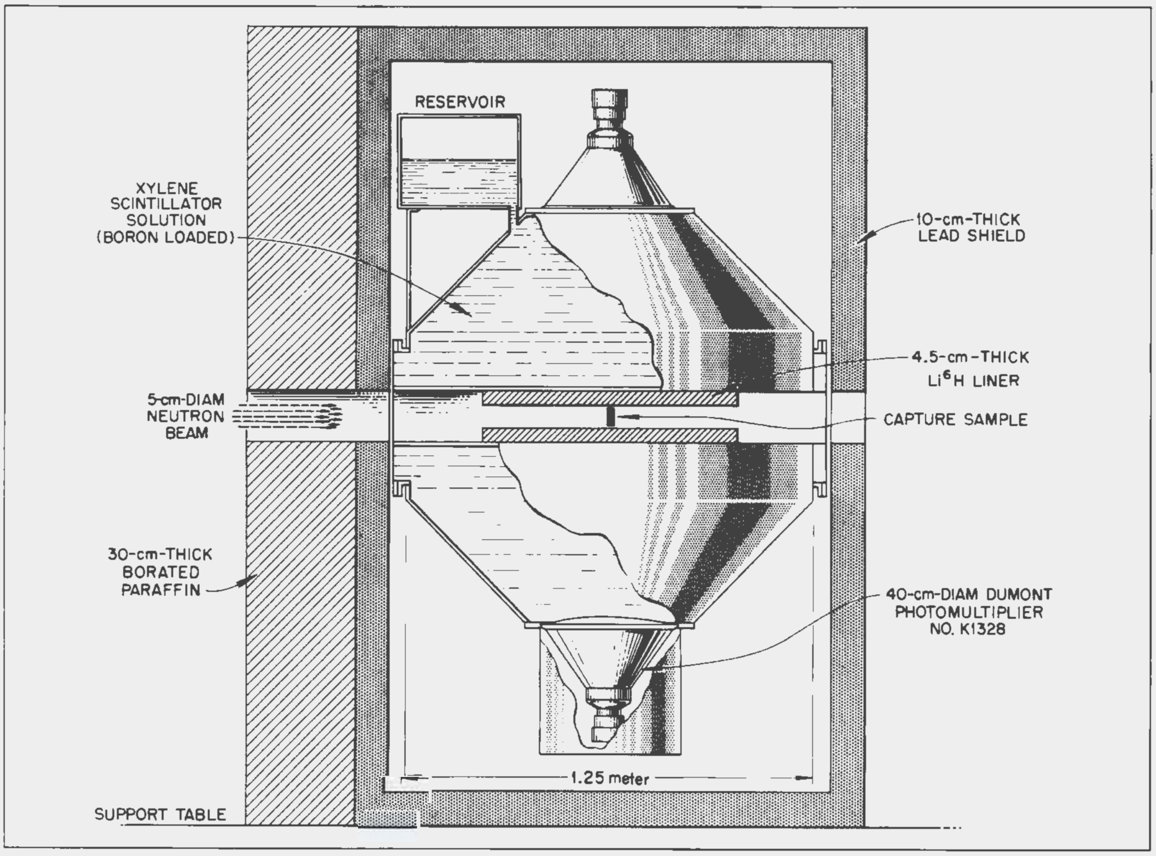
Because government policy dictates that ORNL may produce only those isotopes that commercial suppliers do not market, the ORR phased out its production of the major radioisotopes by the mid-1960s. The routine production of all radioisotopes in the ORR terminated in the 1970s, when the HFIR's intense neutron flux and superior facilities came into full use. The occasional production of a few specialty items continued throughout the service life of the reactor. For example, when the HFIR was shut down in November 1986 because of concerns about possible vessel embrittlement, the ORR briefly took over production of gadolinium-153, which is used in bone scans to detect osteoporosis.

Historic Contributions

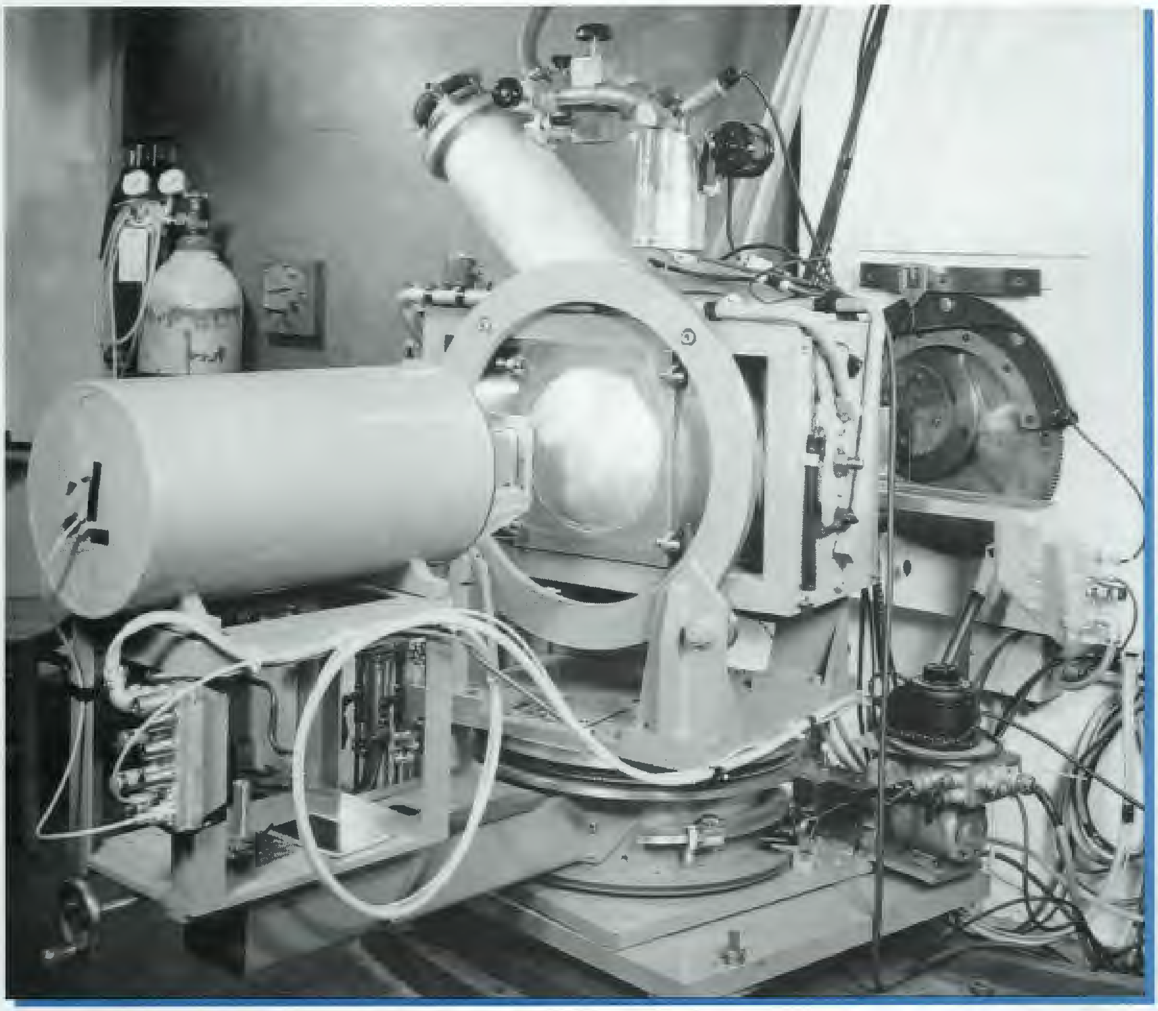
Although the ORR is now closed, many of its design concepts are perpetuated in other reactors. Examples are the R-2 reactor (Sweden), the HFR (Netherlands) and the SAFARI 1 (South Africa), which closely resemble the ORR. The HFIR (at ORNL) and the ILL High-Flux Reactor (Grenoble, France) incorporate many ORR features.

The broad international applications of radioisotopes today have developed partly because the ORR could provide a reliable supply of high-quality products in industrial-scale amounts for routine use. It was the first facility able to do so. These applications now make up a multibillion-dollar annual business that benefits many areas of science, medicine, commerce, and agriculture. Although commercial companies now produce most radioisotopes, the DOE's Isotopes Distribution Program, coordinated by ORNL, still supplies isotopes for special research needs that are not met by private production.

Because of the ORR and the outstanding staff here, many of the fundamental experiments in early nuclear physics were performed at ORNL. During the operating life of the ORR, the Laboratory became internationally known as a center for nuclear reactor development and nuclear fuel and materials testing, as well as the center of radioisotope production for the Western nations. Prominent world leaders came to view the ORR's mystical blue glow, and the most reknowned



The liquid scintillator tank outside the ORR was used for neutron cross-section studies; here researchers gathered data confirming nuclear shell model theories.



This special ORNL-designed magnetic diffractometer enabled scientists to conduct basic solid state physics research at the ORR.

scientists competed to use its powerful neutron beams. With the ORR's shutdown, a long and illustrious chapter of ORNL's history came to a close. ornl

The *ORNL Review* staff is grateful to Frank Hoffman, photographer for the DOE/Oak Ridge Operations Office, who supplied many of the photographs used in this article, and to the following scientists and engineers who supplied extensive background information on the history of the ORR:

- **Tom Cole, on reactor concept and design aspects;**
- **Jack Harvey and Cleland Johnson, on nuclear physics research;**
- **Mike Wilkinson, on solid-state physics research;**
- **Don Trauger, on nuclear reactor fuel testing; and**
- **C. T. Ottinger and J. E. Ratledge, on radioisotopes production.**

RECOLLECTIONS OF THE ORR

"The ORR's operation was always smooth and dependable, with few unplanned interruptions or incidents. For this reason, and because of its many useful design features, it became a model for research reactors all over the world."

"One of the most traumatic experiences of ORNL's early years was the Atomic Energy Commission's decision, around Christmas of 1947, to move all of the nuclear reactor development work from Oak Ridge to Argonne. A particularly painful result of this decision was the fact that the Materials Test Reactor, which we had been designing at ORNL and which we expected to be built here, was to be built instead at the Idaho Nuclear Test Station. Oak Ridge would be left with nothing—or so it seemed at the time. But the Oak Ridge team was not so easily discouraged.

As matters turned out, the ORR—a reactor essentially equivalent to the MTR (even, in usability and some other aspects, superior to the MTR)—was eventually built at Oak Ridge. This Mississippi Steam Boat reactor (as the ORR was sometimes called, because its shield resembled a riverboat, complete down to the life preserver) served as a central focus for much of ORNL's engineering, solid state, and neutron physics research, as well as a source of radioisotopes.

The reactor's blue glow of Cerenkov radiation made the ORR a mandatory stop for visiting dignitaries. Among the most famous were Jack and Jackie Kennedy, who came here just before he announced for the presidency. I remember asking ORNL's deputy director John Swartout to take Jack Kennedy and Senator Albert Gore, Sr., around the ORR while I, exercising my prerogative as director of the Laboratory, showed Jackie around!"—*Alvin M. Weinberg*

Alvin Weinberg came to ORNL in 1945. At that time, and until 1947, he was a staff member of the University of Chicago's Metallurgical Laboratory. He was among the group working with Enrico Fermi in initiating the world's first nuclear chain reaction and moved to Oak Ridge to continue his involvement with the Manhattan Project that developed the first atomic bomb. In 1947, Weinberg joined the ORNL staff as director of the Physics Division. He became ORNL's research director in 1948 and continued in this position until 1955, when he became ORNL director .

Weinberg did the nuclear calculations that were the basis for the design of the Materials Testing Reactor (MTR). The ORR, built half a dozen years later, resembled the MTR; although by that time Weinberg had become director of ORNL, he continued to be very interested in the ORR's progress. Weinberg says his main contribution to the ORR (other than his early calculations) was in the "politicking," which helped to bring a high-flux reactor to Oak Ridge only 10 years after ORNL's bitter disappointment when the MTR was "banished" to Idaho instead of being built here.

After serving as ORNL director until 1973, Weinberg retired from that position to become Director of the Oak Ridge Institute for Energy Analysis. In 1985 he assumed a less-active role in the Institute and now stays busy traveling, consulting, and serving in an advisory role as an Oak Ridge Associated Universities Distinguished Fellow.

"Initial criticality—an important event for any nuclear reactor—stands out in my recollections of the ORR. I recall the nervous anticipation we who were members of the ORR Project team felt on March 21, 1958, as the first fuel was loaded and the control rods were gradually withdrawn until criticality was achieved.

There were no great surprises. Each fuel rod contained ~168 g of uranium-235, and a total of ~1300 g had been loaded when criticality was reached. The fuel loading was about as expected, partly because of our extensive analyses of similar fuel elements in other reactors and partly because of the careful calculations carried out by team member Frank Binford, using the ORACLE, ORNL's first computer. The ORACLE was computational state-of-the-art equipment at the time; it had about 3000 vacuum tubes, and its computing power was probably not equal to that of today's ordinary personal computer.

Despite the lack of surprises, the occasion of the ORR's criticality was memorable. In addition to the general feelings of exuberance and exhilaration, I think members of the project team shared my personal hope that 'our' ORR would make a significant contribution toward 'working together' with scientists and engineers of other nations, as a step toward world peace."—*Tom E. Cole*

Tom Cole joined the Physics Division of Clinton Laboratories (now ORNL) in 1946, following his discharge from the U.S. Navy. His early work at ORNL involved the development of instrumentation, control, and safety systems for the proposed Materials Testing Reactor, the first U.S. high-flux research reactor. He was both a graduate and an instructor of the Oak Ridge School of Reactor Technology in its earliest years. In 1953, Cole became chairman of the steering committee and project director for the proposed new Oak Ridge Research Reactor (ORR). Following the completion of the ORR, Cole participated in the early discussions and studies that led to the High-Flux Isotope Reactor Project. He later became the technical director of the HFIR Project. After his many years of outstanding service in various ORNL nuclear reactor programs, Cole retired in 1987 as a senior staff member of the Engineering Technology Division.

"The hot summer of 1955, when construction of the ORR began across the street from my office in the old Graphite Reactor Building, was before the era of air conditioning at ORNL. I remember that the heat, noise, and dust coming through the windows made life difficult for those of us in the Operations Division with offices nearby. By the summer of 1956, I was head of the Operations Division, and we began training the crew to operate the ORR—a full two years before it went critical in March 1958.

When our crew made the first approach to taking the reactor to criticality, all the health physicists were suddenly called away to an incident at Y-12, and we had to temporarily interrupt our operations. On the second attempt, we successfully "went critical."

The ORR initially operated at 20 MW power, but the original cooling system was inadequate, and we had to lower the reactor power on hot days—another consequence of the Tennessee summertime. After a new, more efficient, cooling system was installed, the ORR's operating power was raised to 30 MW.

The ORR's operation was always smooth and dependable, with few unplanned interruptions or incidents. For this reason, and because of its many useful design features, it became a model for research reactors all over the world. Even today research reactors are being built that are the ORR's direct descendants. In December 1988, for example, I visited a reactor in Peru having many features that originated in the ORR."—*Jim A. Cox*

Jim Cox was assigned to Oak Ridge by the U.S. Army in 1944. When he was discharged in 1946, he became manager of radioisotope sales at what was then called the Clinton Laboratories (now ORNL). In 1950, Cox became head of the Reactor Operations Department, which operated the Graphite Reactor at the X-10 site. In 1952, Cox headed the operation of the Low Intensity Test Reactor (LITR) at ORNL, which was a "mock-up" for the Materials Testing Reactor built in Idaho (see main article). As director of the Operations Division, he was in charge of the ORR during most of its operating lifetime. Since retiring from ORNL in 1981, Cox stays busy doing consulting and "farming" at his home near Norris, Tennessee.

"My major recollections of the ORR center around the interesting research programs conducted there, the many enthusiastic and competent foreign visitors who joined us in this research, and the conscientious concern of the operations staff who made sure of the ORR's safety during our experiments.

Because the ORR was the major new research facility at ORNL when it became operational, this high-flux research reactor warranted (and got) the 'best' of the neutron research programs. Scientists in the Physics Division carried out experimental programs in both nuclear and solid state physics at the ORR, and we received tremendous support and assistance from personnel in other ORNL divisions in planning, designing, and constructing the elaborate—and often custom-designed and custom-built—mechanical and electronic equipment. The engineers and craftsmen who worked with us produced top-notch results. There was always great satisfaction when a new experimental apparatus was installed at one of the ORR's beam holes and the research data began to pour out!

As soon as the ORR's potential for excellent neutron-beam experiments became known, we began receiving requests from scientists all over the world who wanted to join us in taking advantage of the ORR's neutron flux, which was the best available at the time for research purposes.

I was responsible for an interesting experiment at the ORR's beam hole No. 6, using a 'fast-chopper' that rotated at speeds up to 12,000 rpm to produce microsecond bursts of neutrons and a long (180-m) flight path for time-of-flight neutron spectrometry. There was concern about damage that might occur if the chopper failed, even though it was enclosed in a shield of 6-inch-thick armor plate from an old battleship. The operations crew would routinely make around-the-clock equipment checks, and whenever they heard 'strange noises coming from behind the shield,' I received a phone call—sometimes to my home in the middle of the night. The chopper operated safely, however; and there were never any catastrophes."—*Jack E. Harvey*

Jack Harvey received a Ph.D. degree in physics from the Massachusetts Institute of Technology in 1950 and subsequently worked for five years at the Brookhaven National Laboratory doing neutron physics research. In 1955 he was invited to join the Physics Division of ORNL to help set up a time-of-flight neutron spectrometer at the new ORR. The equipment installation was completed in January 1959 and was producing data within a month. Harvey led this first group conducting neutron-beam research at the ORR, and he is still a leader in neutron physics research at ORNL today. In 1965 Harvey became codirector of the Oak Ridge Electron Linear Accelerator (ORELA) and, since 1969, has focused his research in that area.

Take a Number

By. V. R. R. Uppuluri

Monotonic Parts of Random Number Sequences

Sequences of random numbers usually have sets of consecutive numbers that are increasing or decreasing; each set is called a monotonic part of a sequence.

Consider a sequence of random numbers between 0 and 1, such as 0.89, 0.723, 0.413, and 0.6532. The first three numbers in the sequence are monotonically decreasing, so the length of the monotonic part of the sequence is said to be 3. Similarly, in the sequence 0.13, 0.2584, 0.429, 0.73645, and 0.24, the first four numbers are monotonically increasing. So the length of the monotonic part is 4.

In any sequence of random numbers between 0 and 1, the length of the monotonic part may be 1, 2, 3, 4, . . . However, the average length of the monotonic part is equal to ~2.4366, or $2e - 3$ (where e is the base of the natural logarithms).

Differences of Squares

Many numbers may be expressed in terms of differences of squares. For example, $3 = 2^2 - 1^2$; $4 = 2^2 - 0^2$; and $5 = 3^2 - 2^2$. However, 6 cannot be expressed as the difference of two squares of non-negative integers.

In general, it can be proved that the set of numbers in the form

$$4k + 2,$$

where $k = 0, 1, 2 \ldots$ cannot be expressed as a difference of the squares of non-negative integers.

However, numbers of the form $4k$, $4k + 1$, and $4k + 3$ can always be expressed as the difference of two squares of non-negative integers, because

$$n = (\frac{n}{4} + 1)^2 - (\frac{n}{4} + 1)^2 ,$$

and

$$n = (\frac{n+1}{2})^2 - (\frac{n-1}{2})^2 .$$

Isotope Materials for Research

By W. Scott Aaron

This evaporation apparatus was used at IRML for preparing $^{248}CmF_3$ deposits on thin carbon foil. The substrates were used as accelerator targets in 1985 for West German experiments that synthesized element 109, the heaviest element discovered so far. The thorium ion source used in these experiments was also made by IRML staff.

Without the support of the quiet, competent, ground control team, the Apollo VII astronauts might never have taken those first dramatic steps on the moon. In the same way, many important research developments of the last two decades might not have happened without the background support provided by the small, highly specialized staff and facilities of the Isotope Research Materials Laboratory (IRML) operated by ORNL's Chemical Technology Division.

The IRML, which is one of the most diversified isotope materials processing facilities in the world, has provided research materials used in a number of recent important scientific developments. For example, IRML staff produced both the ion source material and the thin-film accelerator targets used by the German research team in 1985 for high-resolution measurements on the synthesis of the heaviest known element, element 109,which the team first discovered in 1982. Other IRML products have been used to help fuse ceramic and metal parts for better high-temperature engines, develop a promethium laser for satellite-to-submarine communications, and generate neutral particle beams that may have "Star Wars" defense applications.

Since 1961, when the IRML was established in the former Isotopes Division, it has been a preparation center for custom-ordered materials enriched in various isotopes to meet special research needs. Customers for these isotope sources include ORNL researchers and groups from other national laboratories, foreign and domestic universities, research institutes, and private industry.

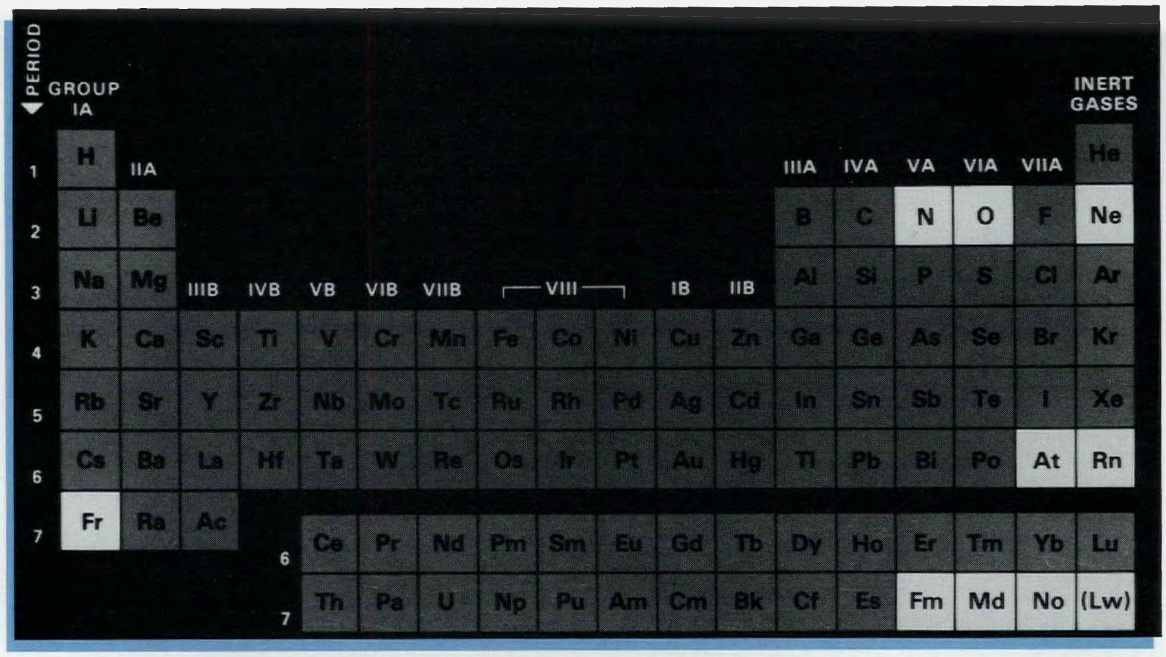
The periodic table on page 60 highlights the diversity of IRML's materials processing experience; we have prepared the isotopes of all the shaded elements as research materials in some form (e.g., thin films, foils, ceramic parts, various metal shapes). The IRML staff has extensive experience and unique facilities for performing vacuum, metallurgical, and ceramic processing of enriched isotopes into usable forms to meet specialized research requirements.

Research applications for radioactive isotopes have increased rapidly during the past few years. Isotopes are especially useful to scientists, including medical researchers, because they can be easily detected and measured, even as they move through a biological system such as a tree or a human body. Environmental scientists use isotopes to unravel the complex processes involved in pollutant interactions with soil, water, and air. Medical researchers use isotopes to study, diagnose, and even treat some types of cancer that are not amenable to other treatments. Nuclear physicists use isotopes both as sources for high-energy ion particles and as targets for the particle beams—exploring the fundamental nature of atoms and the nucleus and the mysterious forces that bind them. Isotopes also have a host of industrial uses.

Most of the IRML products have nuclear physics applications. For example, we prepare both the isotope sources used to generate high-energy particle beams in accelerators, and the targets for these beams. Some of our products are used in neutron dosimeters that allow physicists to map the neutron intensities of reactor cores and gather other important information on reactor core performance.

Other isotope sources are prepared at IRML for use by industrial customers. For example, we prepare a neutron source containing plutonium-238 and beryllium that is used by the U.S. and Canadian iron ore mining industry for quality control of their pellet products.

Preliminary work with customers is under way concerning the development of two new sources for medical treatment. One of these would enclose very small quantities of a stable enriched samarium isotope in the smallest capsules possible and then irradiate them to activate the samarium for treating brain tumors. The second development project seeks to prepare sealed americium-241 (^{241}Am) sources for intracavity radiation therapy.



IRML has prepared research material samples of most elements and their respective isotopes (shaded squares).

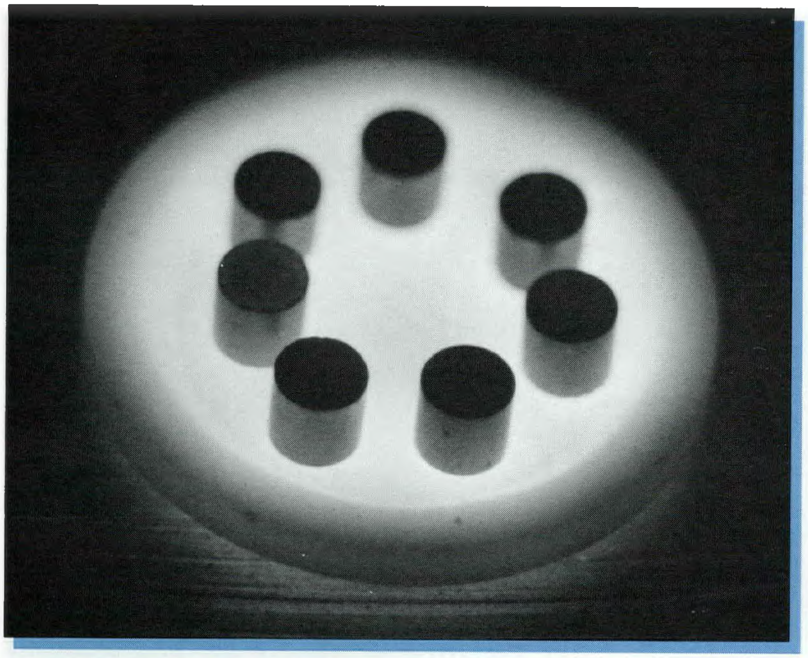
Because the ^{241}Am has lower gamma energies (60 keV) than the radioisotopes of cesium and radium currently used for this therapy [^{137}Cs (83 keV mean to 2450 keV maximum), and ^{226}Ra (662 keV)] it would offer greater safety for medical personnel, more flexibility in shielding, and more localized irradiation, causing less trauma to the patient. IRML also prepares high-energy gamma radiation sources that are used for calibrating radiation detectors—and a long list of additional custom-fabricated isotope sources for research and industrial needs.

Isotopes are found in nature, of course, and can also be produced by irradiating materials in a nuclear reactor or by bombarding materials with energetic charged particles in an accelerator. Unfortunately, these isotopes are seldom in a form that can be used in research or industry. The IRML staff processes the raw isotopes from a variety of materials into custom-made forms that will suit the specialized research needs.

Many of the materials processed at IRML have been prepared at the ORNL Calutron Facilities (at the Oak Ridge Y-12 Plant). The Calutron separates naturally occurring elements into their component isotopes, thereby producing a product that is "enriched" in the needed isotope. The stable enriched isotope materials thus prepared range in value from a few cents to hundreds of dollars per milligram, depending on their rarity and the current demand.

On a few occasions when ORNL supplies were depleted, isotope materials enriched by the Soviet Union have been supplied by customers for processing at IRML. Actinide materials (those enriched in isotopes of elements 89 through 103—actinium through lawrencium) are obtained from a variety of sources, including ORNL's High Flux Isotope Reactor and other DOE reactors. Tritium has been supplied by the Department of Energy's defense reactors at the Savannah River Plant.

Besides preparing and selling custom-ordered research materials, the IRML staff works to develop better isotope processing methods and new or improved research materials that will make more efficient use of the valuable isotopes or that will allow researchers to work effectively with even smaller quantities. The capabilities developed through isotopes processing have led the IRML staff to work on a number of other programmatic activities, such as high-level waste solidification, high-pressure gaseous and aqueous



These fuel pellets, hot-pressed by the IRML staff from ^{244}Cm oxide powder, are inducing fluorescence in the thorium oxide disk beneath them. Along with other fuel pellets and dosimeters produced at IRML, these were used in joint U.S./U.K. experiments at the fast breeder reactor located in Dounray, Scotland.

hydrogen isotope separation processes, and particle-beam neutralizer foil development. The IRML staff also perform a wide variety of specialized materials processing services for other ORNL and Energy Systems R&D programs, on a time-charge basis.

Vacuum Processing

One of the first, and still a major, product of IRML is thin-film accelerator targets for nuclear physics research. Most of this research involves accelerating beams of ionic or subatomic projectiles (the beam) to bombard extremely thin films of well-characterized nuclei (the target). Investigating the interactions between the target and the beam reveals important information to the nuclear physicist about the structure and behavior of the atomic nucleus. In many cases, the target is one of the critical factors in these experiments. Without high-quality, well-characterized targets, the sophisticated and expensive instrumentation of the large accelerators is of little or no use.

Evaporation. IRML uses a wide variety of vacuum processing techniques to prepare these thin-film accelerator targets and other film and coating preparations. One of the simplest techniques for producing thin films is vacuum evaporation. Metals or compounds—primarily oxides—containing the isotopes needed for the film are heated in vacuum to temperatures high enough to make them "boil," or evaporate. The atoms or molecules of the evaporated material will then condense to coat all cooler surfaces in the path of the vaporized hot source material (see photograph on p. 59). Refractory metal [tantalum (Ta) and tungsten (W)] wires or crucibles that are coated with or contain the isotope or other source material can be heated by various means to accomplish the evaporation most efficiently. We might use electrical resistance heating, induction heating or electron bombardment of the crucibles, or electron-beam-gun evaporation.

The electron-beam guns are the workhorses of IRML's evaporation efforts because they can focus large quantities of power (10 kW) on small areas (1 cm^2 or less), instantly heating the evaporant materials to white heat and quickly evaporating even refractory materials such as tungsten and the oxides of thorium, uranium, and plutonium (ThO_2, UO_2, and PuO_2). Electron-beam evaporation is also used by IRML to produce diffusion barrier coatings of zirconium dioxide (ZrO_2), magnesium oxide (MgO), or iridium (Ir) on metal parts to prevent unwanted interactions between these materials during subsequent metals processing steps. Other uses include applications of thermographic rare earth oxide phosphors to turbine blades for testing jet engines. Various other materials are applied by this technique as a type of "intermediate glue" that allows ceramic and metal components to be brazed together for

The face of Lee Zevenbergen is easily seen through this extremely thin IRML-made aluminum particle beam neutralizer foil.

the development of improved ceramic or adiabatic diesel engines. All of these are services performed by the IRML for other Energy Systems organizations at Oak Ridge.

In 1982, a group of German researchers used high-energy particle beams in an accelerator to synthesize element 109, the heaviest element yet discovered. However, to make more complete and higher-resolution measurements of their findings, they needed improved target materials. IRML was commissioned in 1985 to develop these targets, and in fact, we prepared both the target material and the ion beam source material used for this research.

Twenty-six targets of various thicknesses were prepared for the German experiments, which were conducted at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt. For each target, we converted about 2 mg of expensive ($130,000/mg) ^{248}Cm from the nitrate or chloride to fluoride, then evaporated deposits of the curium fluoride ($^{248}CmF_3$) to form a thin film on thin carbon foil backing. The German researchers also used a thorium metal ion source prepared by IRML to generate the heavy-ion beam used to bombard the ^{248}Cm target.

Particle-beam neutralizer foils—materials that convert a beam of charged particles (ions) into neutral particles (atoms)—are an excellent example of how IRML's thin-film expertise and equipment can be applied to nonisotope materials. In 1986, physicist Bill McCulla, of Los Alamos

National Laboratory, asked IRML to fabricate some thin metal foil neutralizers for his research related to developments for the Strategic Defense Initiative (SDI) Program. The requested aluminum (Al) foils were to be only ~300 Å thick—thin enough that a face can be seen through them (see photograph on p. 62). In addition, these films needed to be much larger than our usual products—an area of 7.6-cm diam was first needed, then 25 cm × 25 cm, and eventually even larger areas.

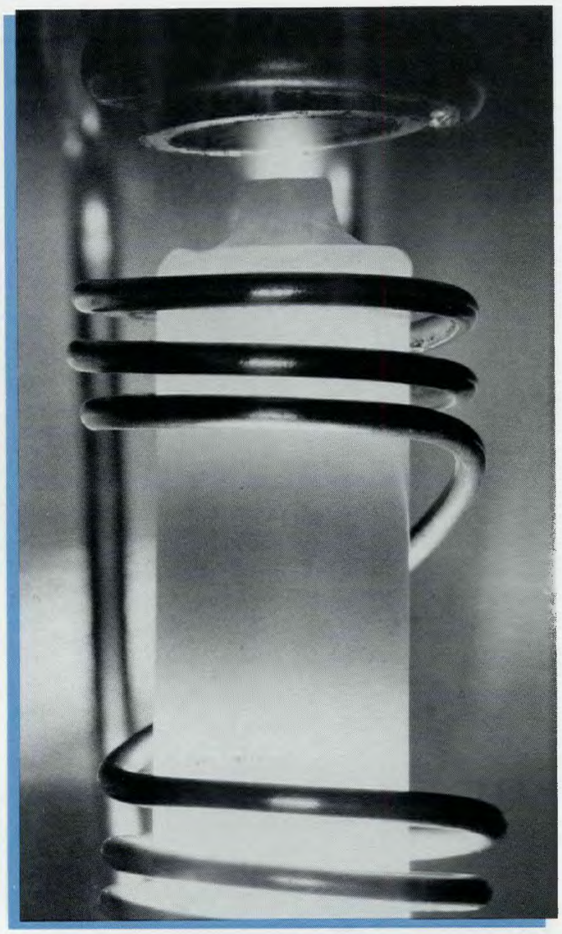
Dave Galbraith of IRML is shown loading an ion source into a heater inside a high-vacuum chamber. He is preparing the gallium liquid metal ion source for research in the Physics Division.

Although most of us in IRML considered meeting this request impossible, we started development work and, almost three years ahead of schedule, were producing the needed particle-beam neutralizer foils, supported by an extremely thin nickel (Ni) mesh having more than 90% open area! We have since produced foils of Al, boron (B), carbon (C), and titanium (Ti) at sizes up to 7.6 cm-diam, Al and C at 25 cm × 25 cm, and Al foils covering significantly larger areas.

The largest Al foils are produced using techniques much like those used for making accelerator targets. A glass plate is coated with a layer of water-soluble parting agent, and the thin metal film is deposited on top by flash evaporation from a large, resistance-heated ring filament inside a high vacuum chamber. The plate is then placed in a large tank (some call it the IRML hot tub), and water is slowly added. As the water rises, it dissolves the parting agent, and the released film of metal foil floats on the water surface. After the foil is completely released from the glass plate, it is moved to the opposite end of the tank and the water is drained, allowing the film to drape onto a nickel-mesh frame assembly to yield the final neutralizer foil. Lee A. Zevenberger of the IRML staff was awarded a Martin Marietta Energy Systems Technical Achievement Award for this work in 1987.

Although these foils are very thin, they are surprisingly strong. In addition to surviving a test of 6 h in a 50-MeV hydrogen ion (H^-) beam, with a current of 15 milliamps per cm^2 pulsed at 1–3 Hz with no visible or microscopic damage, the foils have also survived well in simulated space shuttle launches. Despite our initial doubts, and the early reservations of major aerospace corporations involved in the SDI programs, these foils appear to offer a durable, lightweight, compact means of producing large neutral particle beams in a space environment.

A pyrochemical reduction/ distillation process, carried out in a vacuum, is used at IRML to convert oxides of some isotopes to high-purity metals. Here calcium metal vapor can be seen distilling out of a tantalum crucible.



Sputtering. Another process used by IRML to produce thin films is called sputtering; it produces a "vapor" of the source isotopes using very little heat. In sputtering, energetic ions, usually of argon (Ar), are used to bombard a source material surface, scattering or "sputtering" individual or clusters of atoms or molecules from the source to form a thin coating on adjacent surfaces.

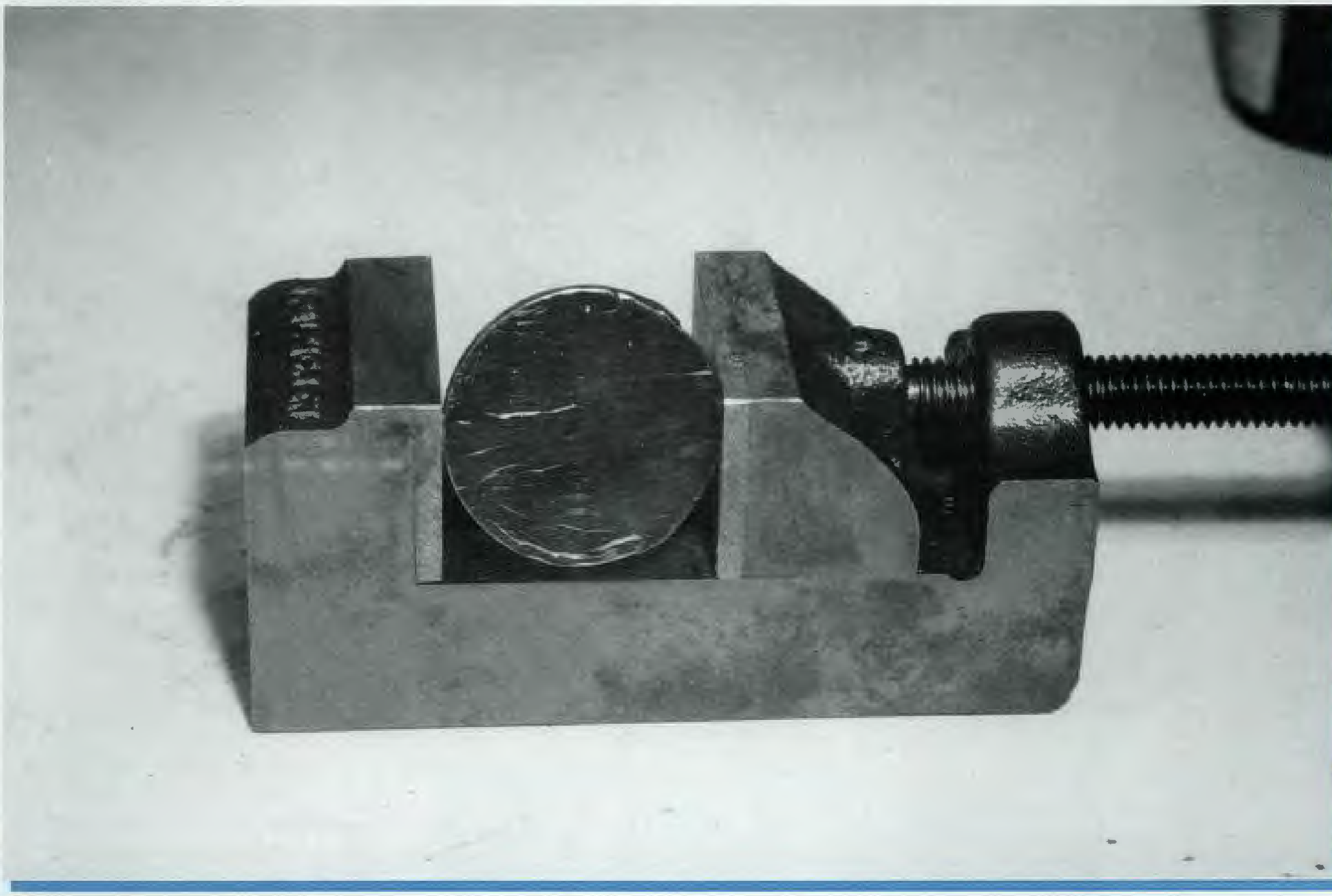
For small sputtering applications, a well-focused ion beam is shot into a high-vacuum chamber, producing thin films from as little as 5 mg of material sputtered from a 50-mg pellet. This production efficiency is very important since, in many cases, only a small amount of the enriched isotope source material is available. The low temperature allows the product material being coated to be placed very near the isotope source, achieving far greater material deposition efficiency than is possible with evaporation techniques.

For larger sputtering applications, ion plasmas are generated using a radiofrequency field in a low-pressure Ar atmosphere. The Ar ions are first directed against the components to be coated, to clean them by dislodging any surface impurities. The field is then reversed, directing the Ar plasma toward the source material, sputtering it to form a thin coating on the clean components. The sputtered material particles collide frequently with the Ar ions in the radiofrequency field, altering particle trajectories and allowing the coatings to be applied around corners, over irregular surfaces, and even into holes in the components. Because the plasma is generated by a radiofrequency field, both conductive and nonconductive materials (such as ceramics) can be sputtered to produce thin films and coatings.

Other Techniques. An unusual type of vacuum processing is sometimes used by IRML personnel to prepare thin-film coatings of californium-252 (^{252}Cf). An electroplated mother source of up to 15 μg of ^{252}Cf on a metal backing is installed in a vacuum system inside a glovebox, and the component to be coated is positioned above it. Once the chamber is evacuated, the radioactive decay of the ^{252}Cf causes self-sputtering and produces a thin coating of ^{252}Cf on the product component without requiring any external heat or energy.

IRML also operates a large vacuum system that makes tritium targets for accelerator experiments. These targets are generally bombarded with deuterium beams in a customer's accelerator to produce energetic 14-MeV neutrons for fusion materials studies or other neutron-irradiation damage research. In this preparation process, titanium (Ti) is evaporated onto copper (Cu) or other metal backings, which are then heated under vacuum. The system is then backfilled with tritium, which reacts with the Ti to form solid titanium tritide targets, ranging from 1-cm diam to 50-cm diam.

A different type of tritium preparation, known as the "tritium trick," is used to prepare the



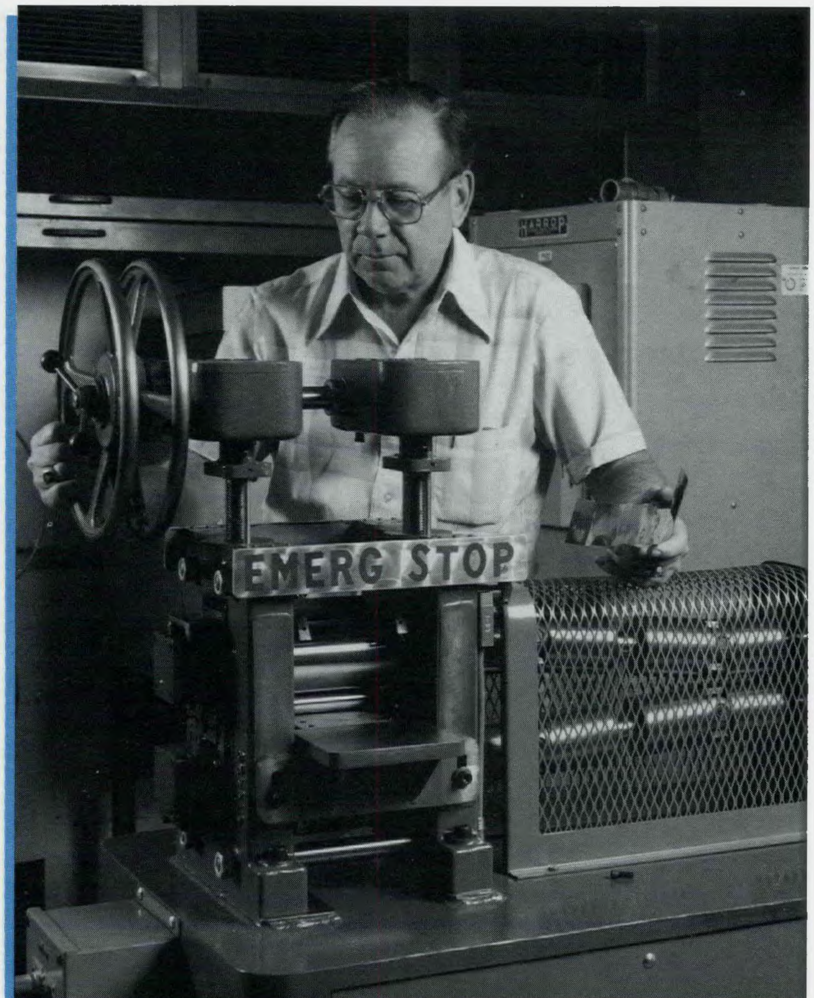
metallurgical samples required for studies of helium (He) embrittlement in candidate materials for fusion energy devices. Tritium (^3H), which has two neutrons and one proton, is diffused into the metal samples and allowed to decay to He (two protons and one neutron), then the excess mobile ^3H is removed, leaving behind only the newly formed He.

This method, which introduces controlled amounts of He into metal samples, has major advantages over all other techniques for introducing He into metals. Because almost all of the nondecayed tritium can be removed from these samples, they can be handled in normal metallurgical facilities, whereas samples prepared by the competing method of reactor irradiation become radioactive and must be handled and examined inside hot cells. In another competing preparation method, the He is driven into the metal samples by accelerators, but this process is quite expensive and introduces He into only the shallow surface layers of the metal.

Finally, one of the major vacuum processing techniques used by IRML is the reduction/distillation technique for pyrochemical preparation of high-purity metals of the Group IIA and rare earth elements and several actinides. This process involves mixing the desired oxide with a metal reductant such as lanthanum (La) or Th. When the mixture is heated in vacuum, the oxide is reduced to metal by the reductant and, with further heating, the product metal is distilled and collected as high-purity metal. Many millions of dollars worth of isotopes have been prepared by this process (see photograph on opposing page).

This disk of ^{239}Pu, resembling a silver dollar, was prepared at IRML by arc melting and drop casting.

Kermit Campbell is shown rolling thin metal foils on one of the IRML's several precision rolling mills.



Metallurgical Processing

Metallurgical processing is used extensively at IRML to prepare research materials from stable and actinide-enriched isotopes. Most operations are small scale (milligrams to hundreds of grams) and performed with great precision. Arc melting is used to consolidate materials and prepare custom-order alloys. In some cases, a drop-casting option is used to cast ingots for further processing or as final parts. Using arc melting and casting, we have prepared metal disks of ^{239}Pu and other actinides that resemble silver dollars (see photograph on p. 65). These disks are being used at a New England university for making elastic and inelastic neutron scattering cross section measurements (see R. M. Moon's article on p. 86).

Rolling is a common metallurgical process for preparing thin metal foils. However, "thin" has a new definition in the foils rolled by IRML! For example, household aluminum foil is about 0.005 cm thick, and paper is typically 0.008 cm thick; however, foils rolled by IRML for use as accelerator targets can be in the range of only 0.00004 cm thick—nearly 100 times thinner than what is commonly considered to be a thin-rolled foil. Some of our products are probably among the world's thinnest rolled foil materials.

Even such a hard material as tungsten has been rolled by IRML staff to 0.00005-cm thickness for use as positron moderators by the Analytical Chemistry Division. Foils this thin are usually hot-rolled inside stainless steel sandwiches, which breaks down the metal before it is cold-rolled. Very reactive metals such as lithium (Li), and some of the Group IIA, rare earth, and actinide metals are rolled in inert gas atmospheres inside gloveboxes; at the thicknesses involved, they would disintegrate or catch fire almost immediately upon contact with air.

Other metallurgical processes used at IRML for preparing research materials include casting, vacuum hot pressing, cold pressing and sintering, wire swaging, and welding. It is no exaggeration

to say that our staff has used almost all metallurgical processes and has prepared research materials from almost every metallic element.

Ceramic Processing

Although materials prepared by metallurgical or vacuum processes are usually used for accelerator targets, IRML also prepares a wide variety of other research materials using ceramic processing techniques. Custom ceramic powders formulated to meet research requirements are routinely prepared by the urea precipitation process, then fabricated by cold pressing or extrusion, followed by sintering or by vacuum hot pressing.

A special ceramic technology was developed here 15 years ago by Tom Quinby and Ed Kobisk, who have both retired from the IRML staff. Their technology, which received an I·R 100 Award, is still routinely used for the preparation of <0.5-mm-diam ceramic wires. These are carefully characterized and then encapsulated in vanadium (V) cans for use by customers throughout the free world as in-core reactor neutron dosimeters.

In 1988, IRML completed a customized preparation project for the Solid State Division in which single crystals of calcium fluoride (CaF_2) containing various dopant levels of radioactive

These glowing crystals of calcium fluoride doped with ^{147}Pm, as well as ^{147}Pm-doped glasses that can be used in a promethium laser, were prepared by IRML in cooperation with ORNL's Solid State Division.

promethium-147 (^{147}Pm) were grown using the Bridgman crystal growth technique in an inert atmosphere. A variety of ^{147}Pm-doped glasses were also prepared in this effort. These have been supplied to Lawrence Livermore National Laboratory for its development of a promethium laser that could be used for satellite-to-submarine communications.

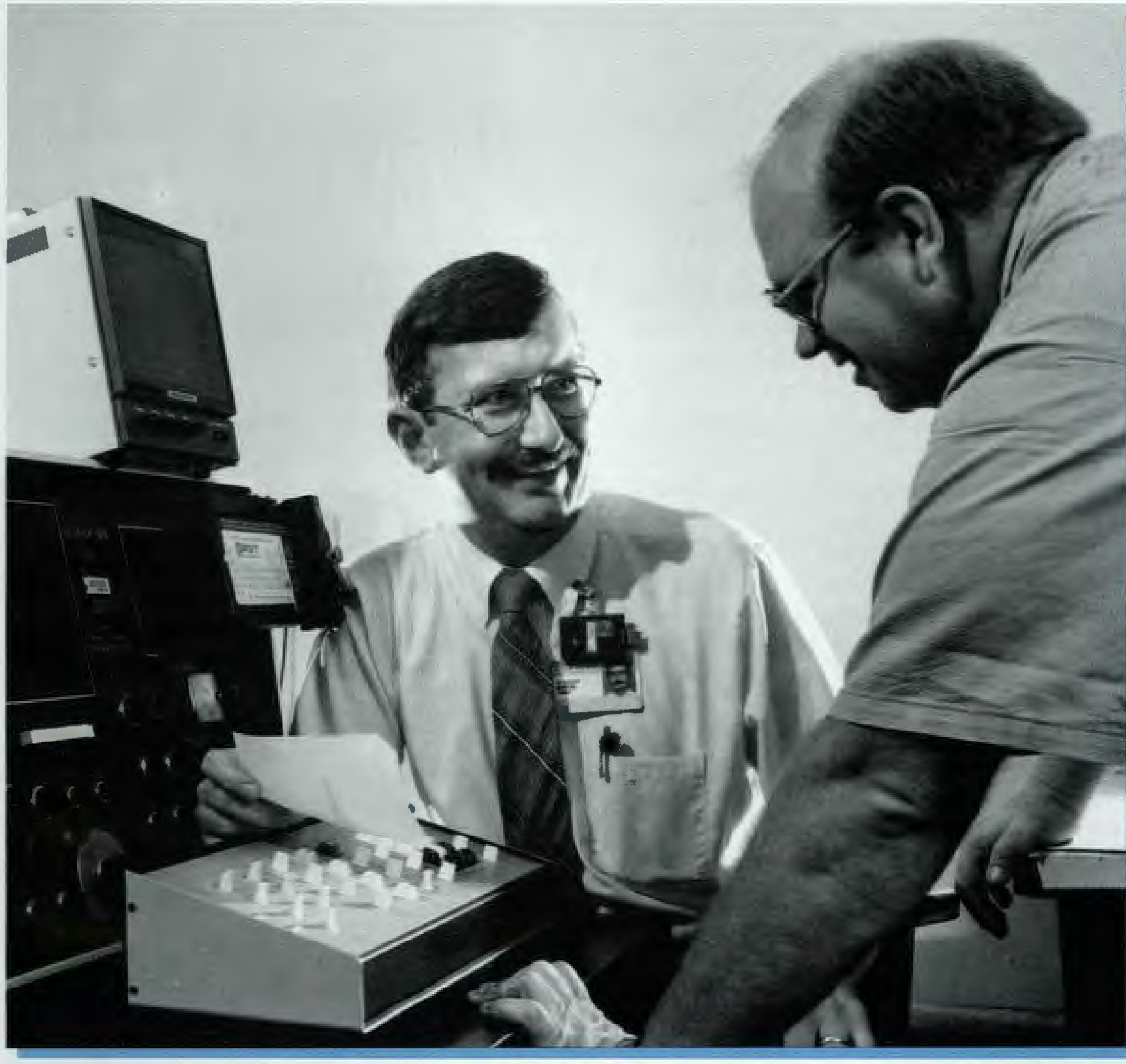
Miscellaneous Activities

At IRML, we routinely carry out chemical conversions to meet specific customer demands. For example, we may reduce oxide sources to metal products, convert oxides to fluorides, or fluorides to metals. For a current preparation project, we are developing a process to convert molybdenum fluoride (MoF_6) to Mo powder, at the request of a group at the Oak Ridge Gaseous Diffusion Plant. We also perform electro-deposition of metal and oxide thin films for various applications. A limited number of sealed, highly radioactive sources, such as ^{244}Cm-^{13}C gamma sources and ^{238}Pu-Be (beryllium) neutron sources are prepared for special purposes.

Along with these miscellaneous activities, IRML maintains a wide variety of analytical capabilities for in-house use, including optical and scanning electron microscopy, radiography, microgravimetric techniques, and alpha and beta/gamma radiation measuring. Preliminary plans are being made to revive IRML's X-ray diffraction capabilities for analyzing materials containing actinide metals.

A Cooperative Effort

A tremendous cooperative effort is required to complete these exacting and unique preparations. To be successful in preparing and characterizing the customized and sometimes exotic materials needed to suit customers' needs, IRML must, at one time or another, interact with virtually every ORNL division. The IRML staff has also, at one time or another, performed needed services for almost every ORNL division, as well as for hundreds of other researchers from around the world. Each year the staff performs 500 to 1000 preparations for between 400 and 500 different customers. Challenges and frustrations are faced daily by the IRML "ground control team," and they are proud of their role in providing valuable basic support and materials for the scientific advances of yesterday, today, and tomorrow. ornl



Scott Aaron (left), group leader of the IRML, and staff member Steve Richardson are pleased with results of a scanning electron microscope examination of an isotope material sample.

Biographical Sketch

W. Scott Aaron, group leader of the Isotope Research Materials Laboratory (IRML) in the Chemical Technology Division, came to ORNL in 1976, after obtaining his M.S. degree in metallurgy from Pennsylvania State University. For several years his responsibilities included special projects and the R&D group in IRML, which was then part of the Solid State Division.The IRML became part of the Operations Division in 1982 and was moved to the Chemical Technology Division in 1988. Aaron became leader of the IRML group in 1986. He is author of 39 publications, holds one U.S. patent, and is active in the International Nuclear Target Development Society. He received a Union Carbide Corporation Community Service Award in 1983 for his work with the Marlow Volunteer Fire Department.

Nuclear Healing

By Luci Bell

> *"By 1971, about 15 radioisotopes in some 30 chemical forms were approved by the AEC for medical use. . . . ORNL's production of radioisotopes certainly ranks among the most significant contributions to peaceful uses of nuclear energy."*

The terms "nuclear" and "healing" are seldom linked in the public's consciousness. However, radioisotopes—elements that undergo radioactive nuclear decay—have been used in the healing arts for more than 50 years and are responsible for many of the modern medical advances that we now take almost for granted. Using radioisotopes, doctors are able to probe the hidden recesses of the human body without scalpel or pain. They can observe the intricate functioning of internal organs, detecting and treating diseases in the very earliest stages—often before clinical symptoms would allow diagnosis.

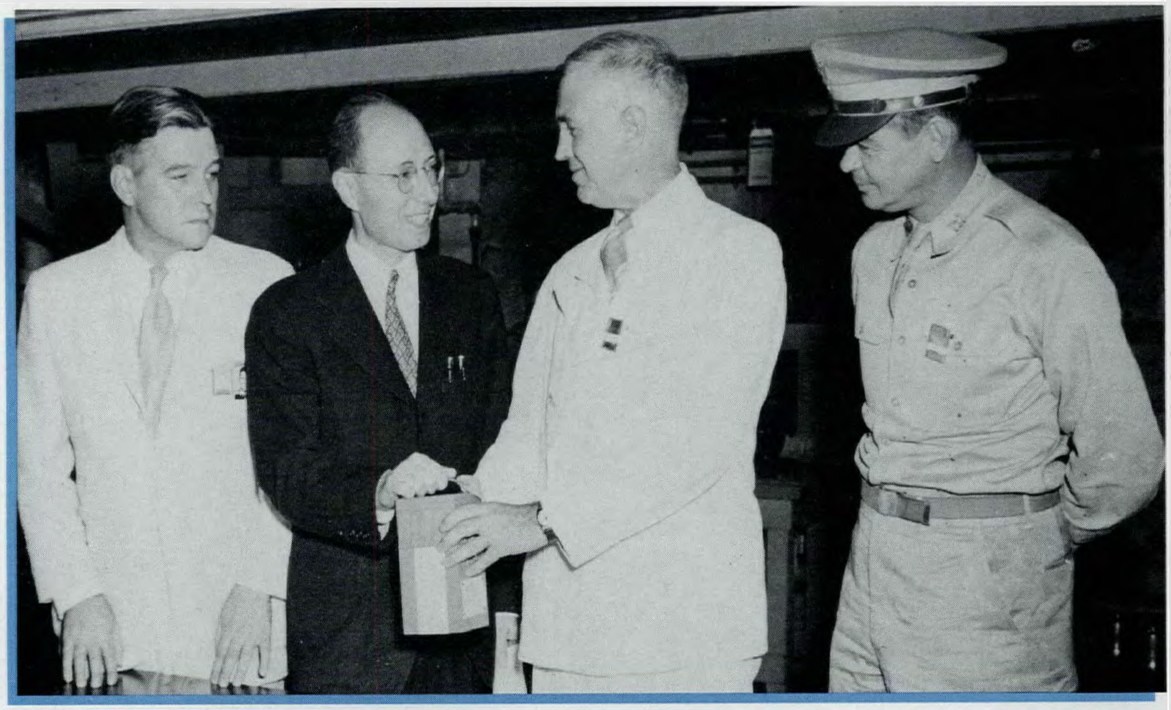
The first shipment of a reactor-produced medical radioisotope, carbon-14, was from ORNL's Graphite Reactor in 1946 to the Barnard Free Skin and Cancer Hospital in St. Louis, Missouri (see photo). Since that time, the medical and commercial uses of radioisotopes have multiplied beyond anyone's wildest imaginings during those early days. ORNL has produced, packaged, and delivered numerous radioisotopes for industrial, agricultural, research, and space applications, as well as tens of thousands of shipments for nuclear medical uses. ORNL's production of radioisotopes certainly ranks among the most significant contributions to peaceful uses of nuclear energy.

The Department of Energy's Isotopes Distribution Program (IDP) at ORNL, which is now part of the Chemical Technology Division, operates at no cost to the government. This is made possible because revenue from sales of the isotopes produced and distributed offset the funding used to support these operations. For the past five years, the revenue generated by IDP sales and activities has averaged nearly $14 million annually.

Although this funding arrangement sounds ideal, it has—over the long run—helped build a legacy of problems for ORNL's isotopes production facilities. The isotope sales revenue is designated specifically for production and distribution activities, and no programmatic funding or sales revenue has been provided for upkeep or improvement of the isotopes production facilities. As a result, many of them are in disrepair and have been closed for safety considerations; other facilities, though meeting safety standards, are out of date and lacking the best and most modern isotope production techniques and equipment. Research to develop and improve the isotope production schemes and facilities is urgently needed, if the production rate is to continue to meet the user demands for these important isotopes. Initially the program provided only small amounts of radioactive materials for research applications. As uses for the isotopes developed, however, our production capability increased until, through the 1950s, ORNL was the nation's major supplier of radioisotopes for both research and commercial use. We continue to be the major supplier—and in some cases, the *only* Western supplier—of some of these research materials.

Glenn T. Seaborg, the eminent nuclear scientist, is well known for his leadership role in the Manhattan Project and his discovery of plutonium and other transuranic elements (for which he shared a Nobel Prize in 1951). Seaborg also served as Chairman of the Atomic Energy Commission (AEC) from 1961 to 1971, an era when radioisotope production and usage were growing rapidly. In a recent issue of the ORNL-produced newsletter *Isotope News,* Seaborg writes that "One of the most significant developments in radioisotope processing during that decade was the recovery of megacurie quantities of fission products in the ORNL Fission Products Development Laboratory. By 1971, about 15 radioisotopes in some 30 chemical forms were approved by the AEC for medical use." Seaborg's article details some of the most common medical uses of radioisotopes and points out their application in X-ray fluorescence and their "outstanding success" in radiation sterilization of medical supplies, stating that "Both technical and economical advantages are afforded by this process through (a) elimination of the damaging


EMERGENCY
RUSH
SHIPMENT
THIS PACKAGE CONTAINS
Synthetic Radioisotopes
SHIPPING INSTRUCTIONS
Information for Customs Officials
This Package Contains Radioisotopes
Shipment authorized by United States Atomic Energy Commission.
Package is sealed for protection of health. Must NOT be opened for inspection.
This is to certify that the contents of this package are properly described by name and are packed and marked and are in proper condition for transportation according to the regulations prescribed by the Interstate Commerce Commission and the Civil Aeronautics Board
OAK RIDGE NATIONAL LABORATORY



The first radioisotope for medical use—1 millicurie of carbon-14—was shipped in August 1946 from ORNL to the Barnard Free Skin and Cancer Hospital in St. Louis. To mark this first peacetime use of a radioisotope, prominent officials gathered in front of the loading face of the Oak Ridge Graphite Reactor. From left, Prescott Sandidge, assistant executive director, Clinton Laboratories (now ORNL); Eugene P. Wigner, research director, Clinton Laboratories; E. V. Cowdry, research director of the Barnard Free Skin and Cancer Hospital, and Colonel E. E. Kirkpatrick, deputy district engineer in charge of the Clinton Engineer Works.

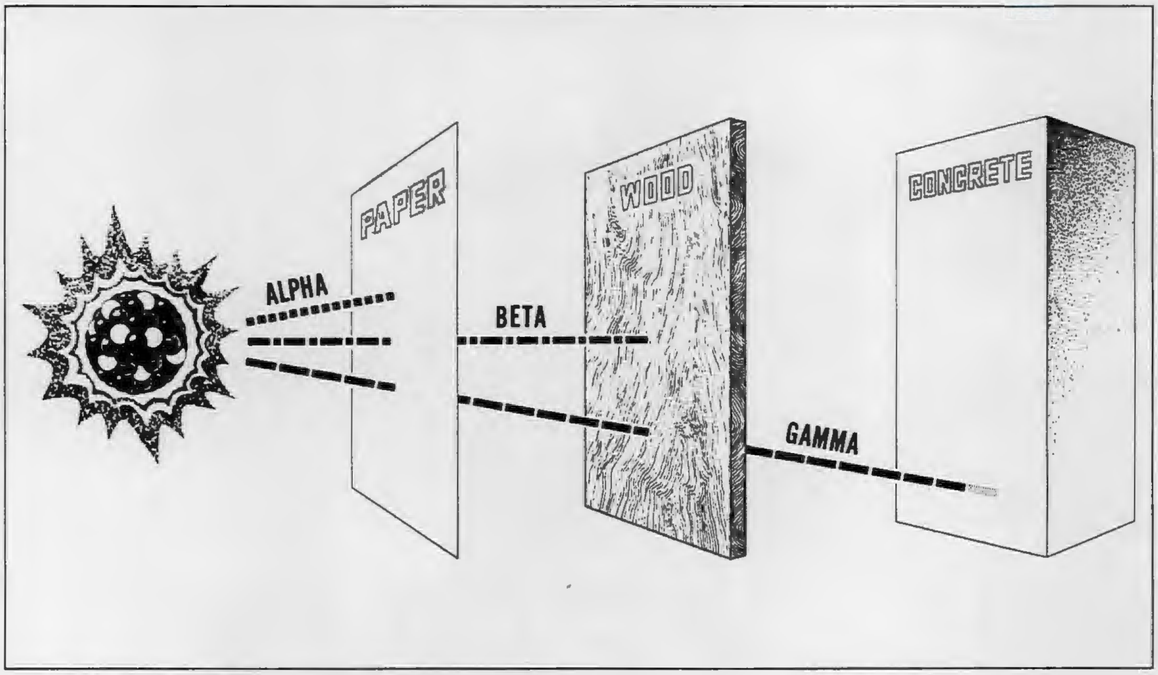
effects of heat, (b) sterilization in the final container, (c) greater reliability, and (d) elimination of residual sterilization gas."

Beginning in 1954, the IDP also began distributing enriched stable isotopes, which are used by customers to produce radioisotopes on an as-needed basis. Many of these products are supplied by other government laboratories or agencies and enriched by the Chemical Technology Division's calutron facilities, located at the Y-12 site, before being distributed through the IDP. As private commercial production of radioisotopes has increased, government has withdrawn from production, except for the isotopes that private sources do not supply. Currently, the IDP provides more than 300 different isotope products, including almost every element, to a wide and varied international market. A significant number of these products are targeted for health care uses. An estimated 40,000 medical procedures using radioisotopes are performed each day in the United States alone, and about half of the patients admitted to U.S. hospitals are diagnosed or treated using radioisotopes.The estimated value of radiopharmaceutical "sales" in the United States is about $250 million per year. Many of these radioisotope products (and related services, such as isotope purification and special product formulation) are available from the DOE national laboratories and marketed through the IDP.

Versatile Medical Tools

Why are radioisotopes such useful and versatile medical tools? As the nucleus of a radioactive element decays, or returns to a more stable form, it emits radiation in the form of energy or highly energetic particles. Gamma radiation (similar in wavelength and energy to X rays) has the greatest penetrating power and can pass through the human body, but is stopped by about four feet of concrete. Of the nuclear decay particles, a beta particle (electron or positron) is less penetrating and can be stopped by a thin metal sheet. Beta particles are thus especially useful for therapeutic applications, because their lower energy minimizes damage to nontargeted tissues inside the body. An alpha particle has even lower energy and can be stopped by a sheet of paper. Each particular radioisotope

More than 300 isotope products not available from commercial sources have been packaged and distributed by ORNL's facilities. Many of these products are used in medical research and treatment.



Radioisotopes are useful medical tools because of their predictable alpha, beta, and gamma radioactive decay emissions; their known penetrating powers; and their ability to be metabolized and detected in normal body processes.

decays by emitting a characteristic radiation spectrum, whose energy and penetrating power can be precisely measured.

The second characteristic that makes radioisotopes so useful is their predictable process of radioactive decay. The half-life, or time required for half the atoms of a radioactive element to undergo decay to a more stable form, is accurately known for all elements. These half-lives range from fractions of a second to millions of years, but some elements have half-lives in the range of hours and days, making them useful for diagnosing and treating diseases without causing extensive tissue damage for the patient.

Finally, some radioisotopes can be incorporated into body tissues or the circulatory system for imaging or treatment procedures because they have the same chemical properties as the nonradioactive form of the element. For example, one of the earliest nuclear medicine successes was in the use of radioactive iodine-131 to image and treat cancers of the human thyroid gland. When a few radioactive iodine atoms are ingested by a patient, they are metabolized in the body and accumulate in the thyroid gland in the same way that nonradioactive iodine does. The radioactive iodine (or other radioisotope) emits a carefully calculated and controlled radiation dose that does not harm the patient as it destroys the thyroid tumor. When gamma-emitting radioisotopes accumulate in a body organ such as this, or when they circulate in the blood moving through a body organ, the emitted radiation can be detected by an external imaging device, allowing a physician or research scientist to trace their movement through the body and "see" the organ in which they accumulate. Hence these radioisotopes are often called radiotracers.

Because the type of radioactive decay emission, the energy and penetrating power of that emission, the half-life, and the chemical properties of the radioisotope are known quantities, researchers or physicians can often "order" a radioisotope product having just the right properties for a particular diagnostic or treatment application. If the element does not naturally concentrate in the organ or body system being investigated (as radioiodine does in the thyroid gland), a radioisotope may be chemically attached to a compound that will carry it to the right location.

This procedure, called labeling, has greatly expanded the medical applications of radioisotopes and is the basis for the development of numerous therapeutic radiopharmaceuticals. A variety of tissue-specific agents for the heart, lungs, brain, kidneys, liver, and other body organs have been developed for nuclear medicine applications. One of the most exciting current areas of medical research involves labeling monoclonal antibodies that seek out and attach to particular types of body cells (such as cancer cells), destroying them selectively via this targeted radioactivity. Radiopharmaceuticals incorporating monoclonal antibodies are proving useful for cancer diagnosis (location of the tumor), therapy (destruction of the malignant cells), and patient management (monitoring treatment progress).

Medical Radioisotopes

While space does not permit a listing of all the radioisotopes used in medical applications, those discussed here are among the most important.

Technetium-99*m*. This is probably the most widely used radioisotope for diagnosis; its 6-h half-life and chemical adaptability make it a safe and useful agent for examining the brain, heart, blood, lungs, liver, kidneys, thyroid, spleen, bone, and other tissues. For example, doctors can view a patient's skeleton and detect various skeletal abnormalities or diseases such as osteoporosis by injecting ^{99m}Tc in a chemical form that concentrates in the bones. In a different chemical form, the technetium isotope serves as a blood-flow marker; it can be injected into the patient's bloodstream during exercise on a treadmill, allowing doctors to detect early heart disease. Beginning in 1990, limited quantities of a "sister" radioisotope, ^{96}Tc, will be produced by special order at the Brookhaven National Laboratory. With a half-life of 4.3 days, this isotope can be used for in vitro metabolic and kinetic studies when use of the short-lived ^{99m}Tc would be impractical.

Thallium-201. It is one of the most important medical isotopes used in the western world for heart imaging. Physicians use it to measure blood flow (perfusion) through the heart muscle, which can indicate diseased or defective muscle areas. Although this isotope is not produced directly at ORNL, its parent or source material is enriched thallium-203, a stable isotope whose principal source in the free world is ORNL.

Iodine-131. One of the earliest radioisotopes used in nuclear medicine, ^{131}I has also been one of the most widely used in organ function studies and for radiopharmaceutical therapy. Because iodine concentrates in the thyroid gland, it is ideal for diagnosis and treatment of thyroid tumors. This was its primary use for many years, but direct radioiodination of antibodies has allowed its use for other in vivo metabolic studies. ORNL's Nuclear Medicine Group of the Health and Safety Research Division has developed a new radiolabeled agent, iodophenylmaleimide, based on a maleimide protein labeling technique developed by P. C. Srivastava that allows the radioactive iodine to bind more stably to a benzene (phenyl) ring than in other such agents. The new compound binds covalently with an antibody under mild conditions and allows labeling with either ^{131}I or ^{123}I. A patent has been granted for this technology, and Martin Marietta Energy Systems, Inc., has signed a licensing agreement with DuPont to study applications of this protein-labeling agent for cancer research.

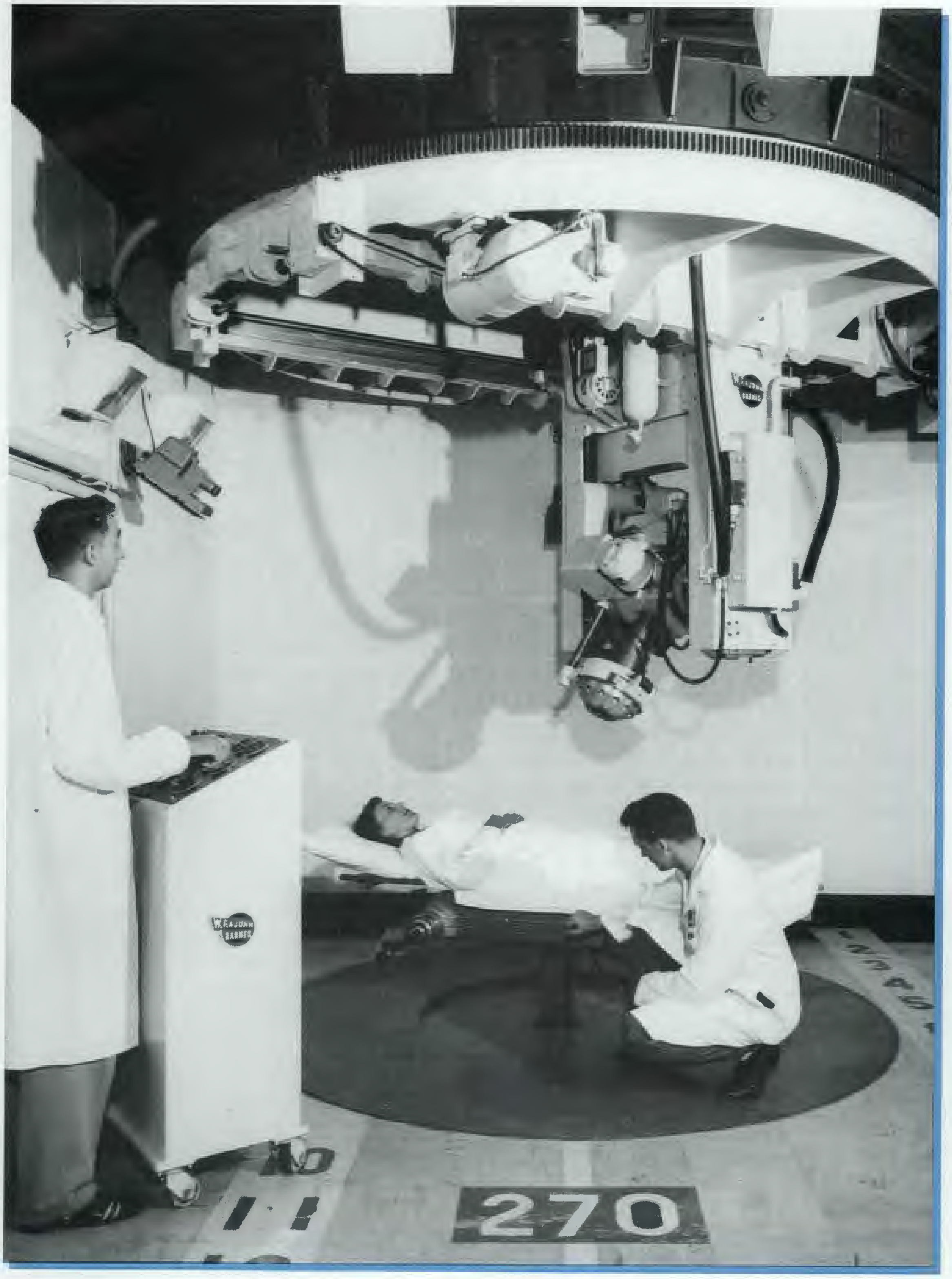
ORNL's Contributions

ORNL played a major role in developing the technology of radioisotope production used throughout the world. Because of the radioisotopes produced here, Oak Ridge became a center for research on radioisotope characteristics and applications. The Oak Ridge Institute of Nuclear Studies (now the Oak Ridge Associated Universities) operated a School of Radioisotope Technology during the 1950s, which attracted physicians, radiologists, physicists, and biologists from all over the world and helped to spread the knowledge about radioisotope applications to numerous hospitals and research institutions. Under the leadership of Art Rupp, who headed the isotopes production facilities, ORNL

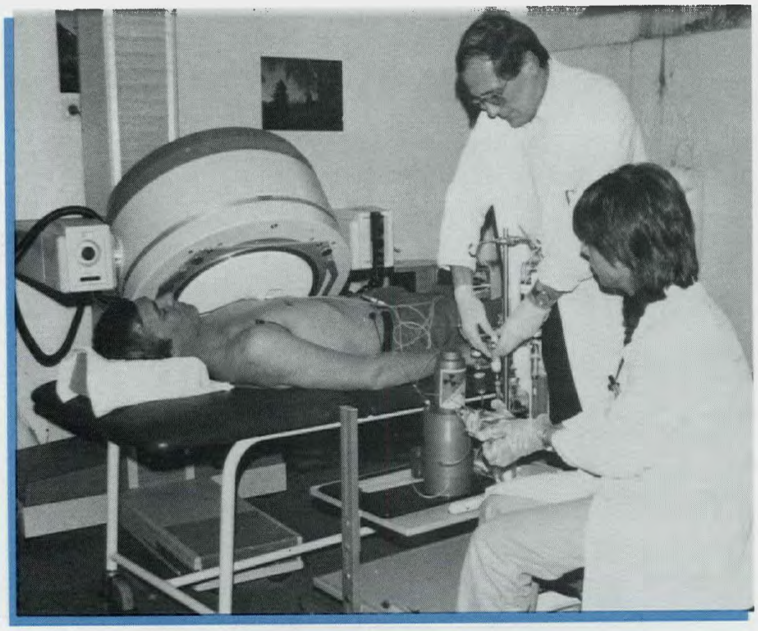
ORNL has played a major role in developing the technology of radioisotope production and processing.

produced and processed a large number of radioisotopes for medical applications. These were then chemically and biologically tested in animal and patient studies at ORAU in a very successful long-term research collaboration. ORNL researcher P. R. Bell and other staff members of the former Instrumentations Division helped develop the radioisotope scanners that have revolutionized cancer diagnosis and therapy by making cancer detection and treatment possible at a much earlier stage of development. ORAU's Medical Division, then headed by Marshall Brucer, pioneered in developing successful medical applications for many of these radioisotopes. Some of the important medical isotopes produced, studied, and developed for medical applications at ORNL and ORAU are listed here.

Gallium-67. Now commercially produced and distributed, this isotope was one of the first to prove successful for broad-spectrum tumor localization studies. In the early 1960s, ^{68}Ga was supplied by ORNL for use as a bone-scanning agent at the ORAU clinical research facilities in Oak Ridge. Because of its short half-life (68 min), a stable carrier isotope had to be added to obtain a good bone scan within 2 to 4 hours. In an effort to avoid this problem, ORAU researchers decided to try ^{67}Ga, which has a 76-h half-life and would allow scanning over a 2-day period. ^{67}Ga was successful in imaging cancerous bone lesions, as



"ORNL researcher P. R. Bell and other staff members of the former Instrumentations Division helped develop the radioisotope scanners that have revolutionized cancer diagnosis and therapy by making cancer detection and treatment possible at a much earlier stage of development."



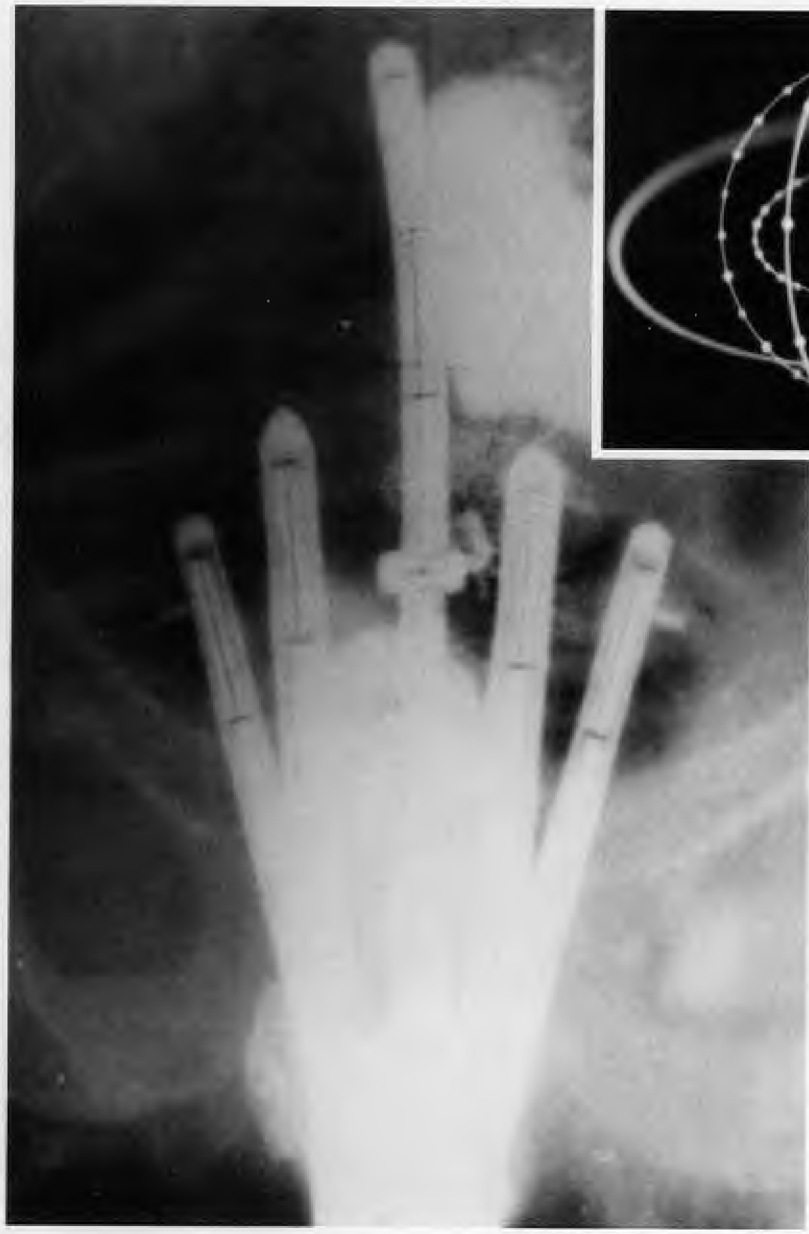
The osmium-191–iridium-191*m* generator system developed at ORNL is set up for intravenous administration of the radioisotope to evaluate a patient's cardiac function.

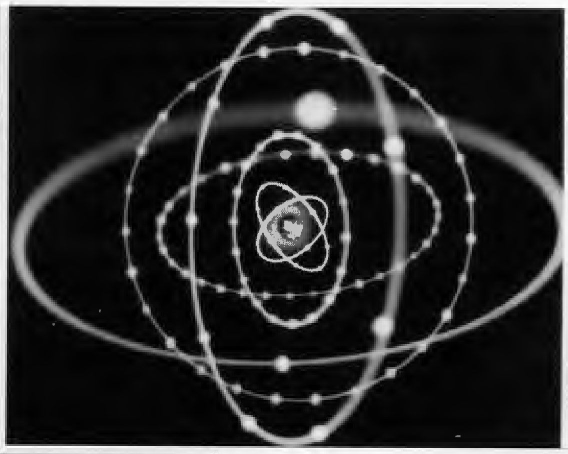
expected, but the patient scans at ORAU also showed dark image areas outside the skeletal area. Further studies revealed consistent uptake of ^{67}Ga by soft-tissue tumors as well as bone, which subsequently led to its widespread adoption as a medical agent for diagnosis of localized soft tumors. For many years, this radioisotope was produced mainly at the large cyclotron facilities on the Y-12 site, then sold to commercial companies for packaging and distribution to medical institutions. Although its tumor-uptake mechanism is still poorly understood, ^{67}Ga remains the "gold standard" for scanning diagnosis of soft-tissue tumors and bone lesions.

Osmium-191. Formerly produced in ORNL's High Flux Isotope Reactor, this radioisotope decays to produce a short-lived daughter product, iridium-191*m*, which emits a very low dose of gamma radiation. Injected into a patient's bloodstream, this radionuclide is particularly useful for evaluating heart function in adults. It may well replace the commonly used ^{99m}Tc for this procedure, which is performed on about 500,000 patients a year in the United States. Russ Knapp and his colleagues in ORNL's Nuclear Medicine Group have developed a safer and more efficient bedside generator system for ^{191}Os use with heart patients (see *ORNL Review*, p. 28, Vol. 21, No.1, 1987). The ORNL-developed generator provides better separation and greater yield of the short-lived ^{191m}Ir daughter from the ^{191}Os source. The new generator is covered by a patent awarded in 1986—one of the first patent waivers requested by Martin Marietta Energy Systems. The generator system has been tested by patient studies in Belgium and is now being further evaluated through clinical tests at U.S. hospitals.

Californium-252. A neutron-emitting transplutonium isotope, ^{252}Cf has a sufficiently long half-life (2.6 years) for long-term clinical application and a specific radiation activity high enough to be useful for cancer therapy (2.3×10^9 neutrons per second). The DOE Office of Basic Energy Sciences is solely responsible for ^{252}Cf production and processing. Its production, by the irradiation of curium targets in the HFIR, has been interrupted since the HFIR's 1986 shutdown, and both researchers and cancer patients are concerned that the available stockpiles may be depleted before the HFIR is returned to operation.

In one treatment protocol, tubes containing ^{252}Cf are inserted into a patient's uterus and vaginal canal, destroying cervical cancer cells without causing significant radiation damage to the surrounding delicate tissues (see X-ray image on facing page). Researchers at the University of Kentucky, Lexington, have developed this ^{252}Cf treatment protocol that results in a significantly higher 5-year cure rate for this type of cancer than with conventional therapy (see *ORNL Review*, p. 67, Vol. 21, No. 2, 1988). Methods are also being investigated for using this radionuclide to treat brain and melanoma/sarcoma body surface cancers.





This X-ray of a female pelvis shows stainless steel tubes containing californium-252 that have been inserted into the uterus and vaginal canal to irradiate the surrounding cancerous tissue. The treatment protocol, developed at the University of Kentucky in Lexington, results in a significantly higher 5-year cure rate than conventional therapy.

Inset: The entire world supply of this extremely heavy man-made element, californium-252 (artist concept), was produced, and is currently stored, in ORNL's High Flux Isotope Reactor.

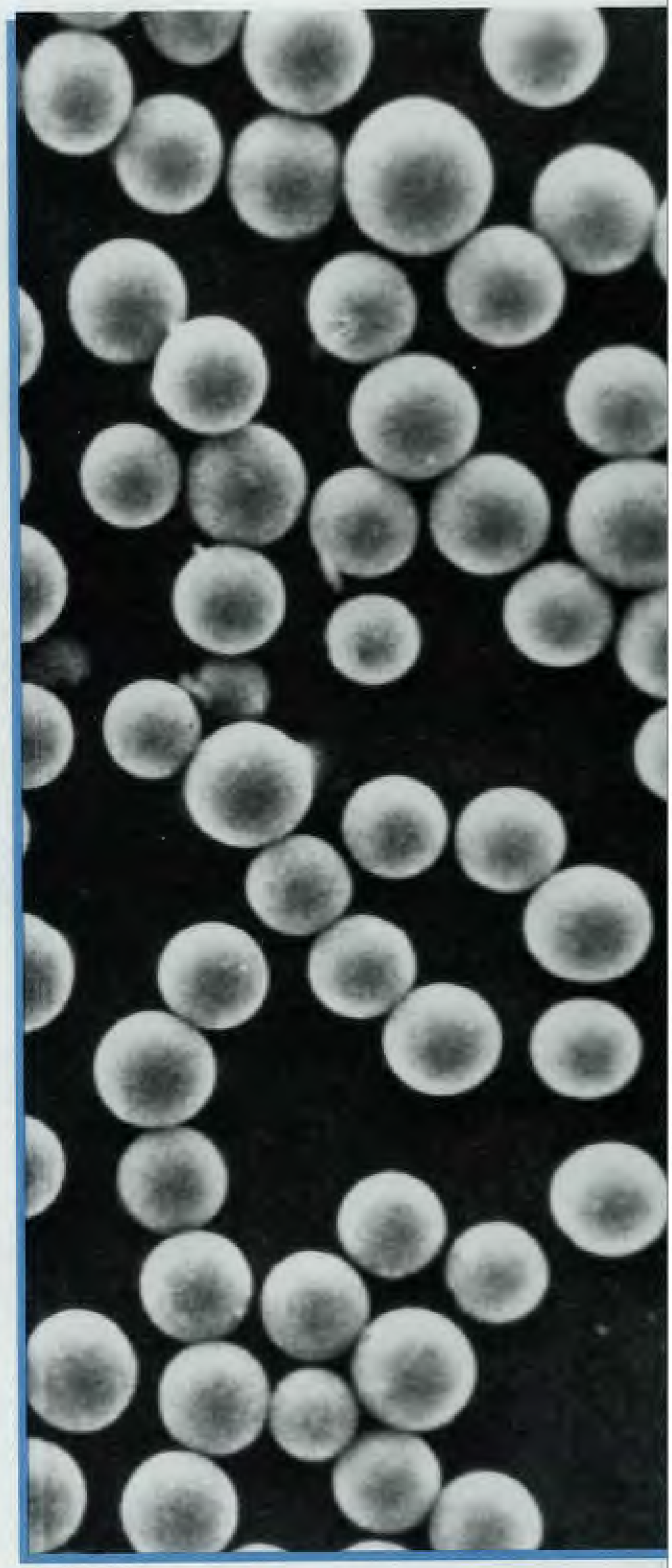
Gadolinium-153. This radioisotope decays with a unique emission of two gammas rays of different energies (97 and 107 keV), which allows medical practitioners to make density measurements by comparing the relative absorption of these rays as they pass through materials. The major medical application for ^{153}Gd has been in making bone density measurements in patients having osteoporosis—loss of bone minerals.

Production of this radioisotope began at ORNL in the late 1960s, primarily to supply the National Aeronautics and Space Administration's need for an accurate atmospheric density measuring device in the Mars space probe. Neutron irradiation of natural europium-151 oxide starting material in the HFIR was a source of multicurie quantities of the ^{153}Gd. Because several undesirable europium isotopes are also produced during this irradiation, the irradiated targets must be processed, first by an electrochemical process that separates the bulk of the undesirable isotopes, then by a high-pressure ion exchange step (developed by ORNL's Nuclear Medicine Group) that gives a final ^{153}Gd purity of 99.999%.

The use of unique hot-cell processing equipment and glovebox manipulators designed at ORNL enabled us to supply both NASA's needs and the nuclear medicine demands that also developed because of the isotope's suitable half-life (242 days) and activity (~30 Ci/g of Gd_2O_3). Through 1983, the demand for ^{153}Gd averaged about 30 Ci per year, but by 1986 the radioisotope had gained widespread medical usage in dual-photon absorptiometry for determining bone mineral content in osteoporosis patients. At that time, ORNL had outstanding orders for 1500 Ci of the radioisotope and had to revise the target design and radiochemical processing procedures to meet these needs.

Although no other domestic source of the ^{153}Gd has become available, in 1988 a British commercial firm began producing the isotope in significant quantities at prices that ORNL, with its out-of-date hot-cell processing facilities and

These yttrium-90–labeled resin microspheres are used in liver cancer therapy research.

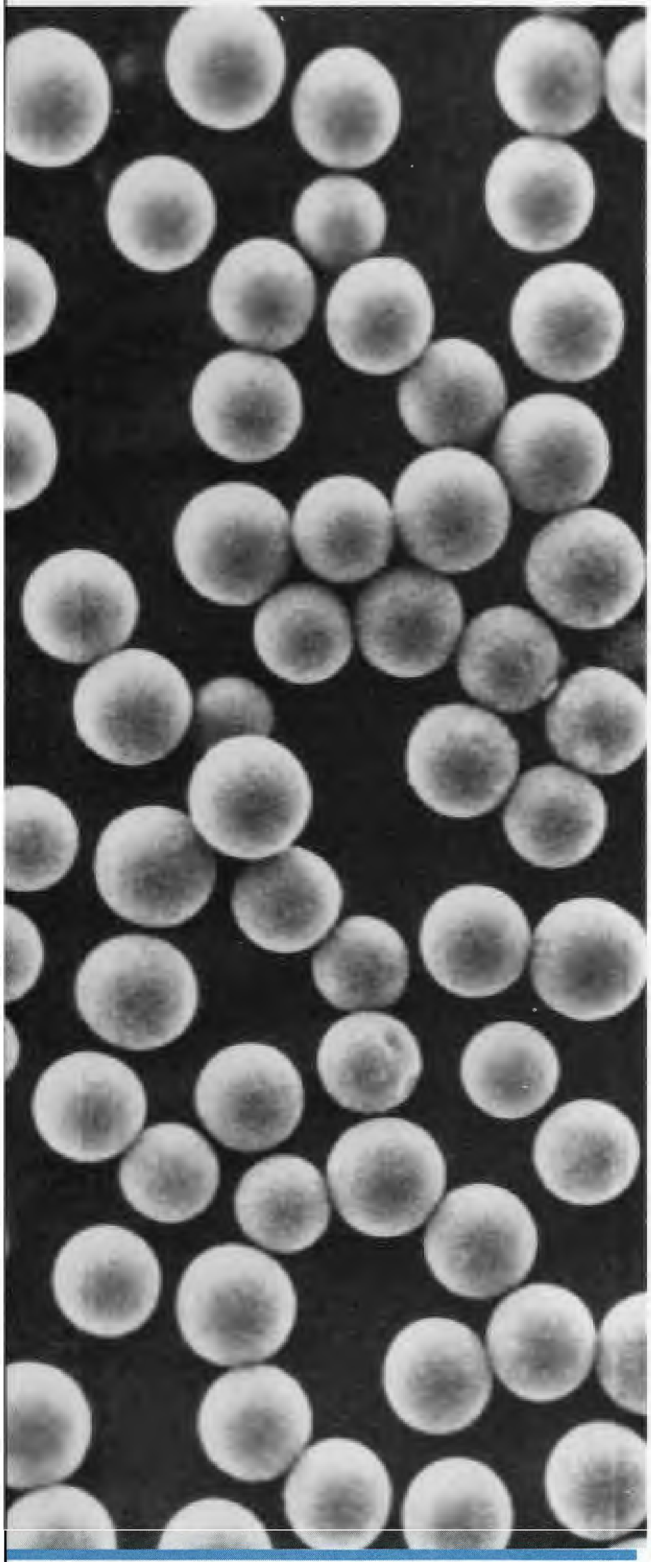


the DOE's full cost-recovery requirement, cannot match. In addition, the use of the dual-photon absorptiometry technique for monitoring osteoporisis has not been authorized for Medicare reimbursement, so physicians are increasingly reluctant to use it. These factors, plus the HFIR's unavailability for target irradiation since its shutdown in 1986, have led the IDP to announce that ^{153}Gd can no longer be made available to its customers.

Palladium-103. This radioisotope is currently produced at ORNL from target materials irradiated at the University of Missouri Research Reactor. Of intermediate activity (8 to 9 Ci, 17-day half-life), the ^{103}Pd is first processed to remove unwanted activation products and then plated out onto minute cylindrical graphite pellets, through an electrolytic process. ORNL's customer for this radioisotope is a Georgia-based company that loads the small ^{103}Pd pellets into slightly larger titanium tubes that are then laser-welded to form small seeds. Medical customers place the tiny radioactive seeds into slender metal "needles" that are injected directly into prostate cancers. The short-range "Auger" electron radiation from the ^{103}Pd destroys the surrounding cancer cells without causing undue trauma to the patient's normal tissues.

Yttrium-90. With its 2.25-MeV pure beta radiation, this radioisotope is increasingly being studied for its potential use in cancer therapy. It is produced exclusively at ORNL by chemical separation from strontium-90, a fission by-product supplied from the Waste Encapsulation Storage Facility at Hanford, Washington.

Jim Wike of the Chemical Technology Division, who heads the team responsible for ^{90}Y processing and distribution, says group members must begin "milking" the ^{90}Sr "cow" (by remote operation in a hot cell) early each Monday morning (2 to 5 a.m.). The early start is necessary to allow adequate time for the extensive quality control measures of sampling and testing, as well as the elaborate packaging



and paperwork required prior to shipment. The ^{90}Y has only a 63.4-h half-life, so it must be shipped out to the end users as expeditiously as possible.

Wike and his colleagues separate the ^{90}Y radioisotope by solvent extraction, process it to enure that it is "carrier-free" (i.e., of high purity and free of the ^{90}Sr), and incorporate it into resin microspheres that are used in liver cancer research and treatment. In vivo use of ^{90}Y requires that ^{90}Sr contamination levels be kept below 10 μCi per curie of ^{90}Y. The highly purified isotope is also supplied to several medical institutions that use it to label monoclonal antibodies, the new "leading edge" in nuclear medicine.

Isotopes Production and Services

ORNL is not licensed for the distribution of radioactive pharmaceuticals, but we have for many years supplied radioisotopes to radiopharmaceutical manufacturers and to research institutions for medical uses. These products are most often sold to commercial customers, but some are available on a loan or lease basis to research institutions approved by DOE.

For more than 30 years, ORNL produced a variety of medically important radionuclides in the 86-inch cyclotron facility, until it was shut down in 1983. The HFIR also represents an important source of biomedical radionuclides, although its temporary shutdown since 1986 has made it necessary for customers to seek alternative sources when these are available. For example, the Brookhaven High Flux Beam Reactor, which performs irradiations for research and development but not for commercial purposes, helped ORNL during the HFIR's shutdown by supplying radioisotopes for the Nuclear Medicine Group's research projects until that reactor, too, was temporarily closed down by DOE in December 1988. With both of these high-flux reactors out of service, the only significant operating U.S. source for some of the medical radioisotopes is currently the University of Missouri Research Reactor.

Compliance with federal, state, and local regulations is critical in the packaging and shipment of radioisotope products.

When the Advanced Neutron Source (ANS) becomes available at ORNL in the late 1990s, its higher flux will provide a powerful radioisotope production capability. The ANS will also allow significant conservation of the enriched stable isotopes that are used for radioisotope production. If we assume that radioisotope "burnup" is not a problem and that thermal neutron flux is the predominant factor, the radioisotope production capacity of the ANS could be several times that of the HFIR. Thus, at the ANS, much smaller amounts of the enriched target materials will be required to produce the same quantities of radioisotopes.

In addition to producing radioisotopes and stable isotopes, ORNL provides a variety of related services. The stable isotopes sold through the IDP are electromagnetically enriched in calutron facilities at the Oak Ridge Y-12 Plant site prior to sale. Other handling services include the measuring, packaging, and documentation required for safely transporting the radioisotope materials. ORNL maintains a variety of "special form" shipping containers designed to meet various shipping regulations and, in addition, can construct, load, and test shipping containers designed by customers to meet a particular need.

ORNL also fabricates radioisotopes into encapsulated sources, in cases where this service is not provided by the private sector. For example, ORNL fabricates all cesium-137 sources of greater than 1400-Ci activity (which are sometimes used to sterilize medical instruments or supplies) and may provide cesium-137 sources of less than 1400 Ci, if the buyer states that the sources are for resale.

Other services related to radioisotopes are provided at ORNL, if these are not available from private U.S. industries. For example, special product forms can be fabricated to meet particular commercial or research needs (see article on the IRML, p. 58); purification or chemical and/or physical conversion processes can be conducted to meet special product requirements; and reactor irradiation services or special analyses can be provided. Each request for these services must be individually approved by DOE to ensure that government facilities are not competing with private industry.

Biomedical Radioisotope Technology Development

A small, but well-recognized, biomedical radioisotope technology development and research effort is conducted at ORNL by the Nuclear Medicine Group of the Health and Safety Research Division. Headed by Russ Knapp, this group is involved in designing and testing new radiopharmaceuticals and in developing and testing radionuclide generator systems for clinical use. Preclinical animal testing of newly developed agents are usually conducted at ORNL, and clinical evaluation is often done through collaborative arrangements with physicians and research hospitals in the United States and European countries such as Belgium or the Federal Republic of Germany (see article on p. 28, *ORNL Review*, Vol. 21, No. 1, 1988). A superior generator system developed by Knapp and his colleagues in the Nuclear Medicine group and the maleimide protein labeling technique of Srivastava (discussed earlier) have been patented and are part of ORNL's successful record of technology transfer. The labeling technique has already been licensed to a leading pharmaceutical company.

In addition to developing clinical radionuclide generators, the Nuclear Medicine Group prepares specialized radioisotope-labeled therapeutic agents such as ^{195m}Pt-labeled *cis*-dichloroammine platinum(II), which is useful for evaluating the pharmacokinetic properties, tissue distribution, and excretion of this antitumor compound and for monitoring effective plasma levels to maintain optimal therapy dosage. The ^{195m}Pt is the only practical radionuclide of platinum for biological research use, and Knapp says there is currently widespread interest in using this radiolabeled agent to monitor the uptake of *cis*-DDP in certain types of brain tumors (gliomas) by single-photon computerized tomography (SPECT). The preparation of the compound has been complicated by the HFIR's shutdown, necessitating new radioisotope production arrangements and changes in the radiochemical synthesis.

Other radioisotope technology development projects of the Nuclear Medicine Group include optimization of copper-67 production via the neutron irradiation of enriched zinc-67. The copper-67 is of interest for radiolabeling tumor-specific antibodies and other therapeutic agents. This project, as well as research on the radionuclides samarium-145 and samarium-153, also awaits the HFIR's return to operation, because reactor production provides much higher-specific-activity and carrier-free materials—important considerations for radioisotopes in therapeutic applications.

"The medical uses of radio-isotopes continue to proliferate."

New Medical Horizons

The medical uses of radioisotopes continue to proliferate. New and exciting technologies in the field are being developed, such as the applications of radiolabeled monoclonal and polyclonal antibodies and the new imaging technologies that utilize radioisotopes. Many scientists in the field believe nuclear medicine is only now entering its most important era. Henry N. Wagner, Jr., professor of medicine, radiology, and environmental health sciences at the Johns Hopkins Medical Institutions, and past president of the Society of Nuclear Medicine, believes nuclear medicine will play a major role in translating the new genetic knowledge into practical therapeutic applications. "Nuclear medicine has created the discipline of in vivo chemistry in living human beings and can provide a chemical bridge between genotype and behavioral phenotype," he says, adding that "Nuclear imaging can revolutionize in vivo chemistry in the coming decade."

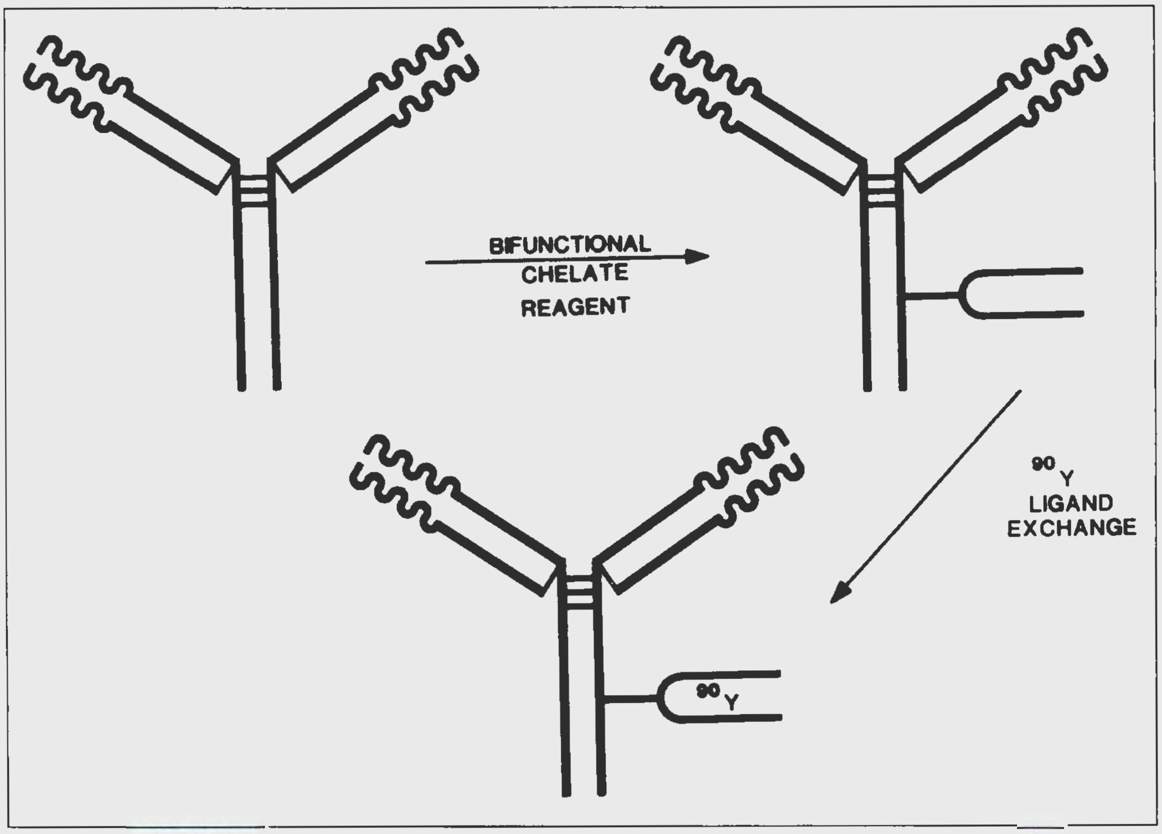
The advent of radionuclide-based SPECT and positron-emission tomography (PET) as

"Among the newest and most exciting developments in nuclear medical diagnosis and treatment are the uses of bifunctional chelates to label monoclonal antibodies with radio-isotopes."

important diagnostic imaging tools is stimulating another new surge of research activity to develop the appropriate radiopharmaceutical imaging agents. These advanced imaging technologies are already yielding important new information about brain chemistry, for example, that will improve the treatment of epilepsy, Alzheimer's disease, Parkinson's disease, and chemical addictions. ORNL's Nuclear Medicine Group is involved in this research area, particularly in the development of radioiodinated compounds to evaluate cerebral neuron receptor populations by SPECT.

Among the newest and most exciting developments in nuclear medical diagnosis and treatment are the uses of bifunctional chelates to label monoclonal antibodies with radioisotopes. ORNL supplies ^{90}Y to several research institutions that are using these labeled monoclonal antibodies to study new approaches to breast, colon, prostate, and melanoma cancer treatment.
The antibodies are unique proteins designed by scientists to "seek out" complementary proteins called antigens that are produced in the body by cancer cells. The radiolabeled antibodies to tumor-associated antigens are considered by many physicians to be the long-sought "magic bullets" for cancer diagnosis and treatment. They can be designed to recognize and concentrate in the cells of a specific type of cancer, allowing the isotope's radiation activity to pinpoint the cancer's location and, in therapeutic applications with high-energy radionuclides, to produce the maximum treatment benefit with minimal toxicity to the patient.

Lee Washburn, Jim Crook, and their colleagues at ORAU have developed a technique that uses the chelate-conjugated monoclonal antibodies labeled with ^{90}Y for treating colo-rectal cancers. Animal studies conducted by the ORAU team have shown tumor volume reductions of 87% after 14 days of administering the radiolabeled antibodies.



Preliminary clinical evaluations of the therapy are now under way at the Thompson Cancer Survival Center in Knoxville.

Researchers are also using monoclonal antibodies labeled with ^{90}Y in a promising new technique for reducing patient rejection of organ transplants. Physicians have discovered that, in patients treated with the labeled antibodies prior to transplant, the body's natural antigens that would stimulate rejection of the transplanted organ's "foreign" tissue are destroyed. The patient's new antigens, produced by the body after transplantation is completed, seem less able to recognize the transplanted tissue as foreign; hence, in many cases, the organ is not rejected. Although still in the investigative stages, this method offers hope for a much higher percentage of successful organ transplants than has been possible in the past.

As the HFIR resumes operation, and particularly as the ANS facility becomes a reality at ORNL, our scientists will again have a plentiful supply of radioisotopes and be able to continue contributing to and, in many cases, leading the progress in nuclear healing. ornl

Nuclear Electricity First Produced at ORNL

The first known production of electricity from nuclear energy occurred on August 23, 1948, at ORNL's Graphite Reactor, although it is commonly believed that the first demonstration of nuclear electricity generation took place in December 1951 at the Experimental Breeder Reactor–1 in Idaho. Here, Logan Emlet of ORNL oils a small steam engine, driven by steam produced by nuclear fission at the Graphite Reactor, which supplied sufficient electricity to light a tiny flashlight bulb. On March 1, 1961, Emlet became a vice president of Union Carbide Nuclear Company, which operated ORNL for the Atomic Energy Commission.

Neutron Scattering at Research Reactors

By Ralph M. Moon

Ernie Wollan (left) and Cliff Shull conducted some of the first research in neutron diffractometry, using this instrument in 1945 at the Graphite Reactor.

In the very early days of neutron scattering research, Oak Ridge National Laboratory played an important, almost dominant, role. Ernie Wollan set up a neutron diffractometer at the X-10 Graphite Reactor in 1945. He was joined by Cliff Shull in 1946, and they began a productive collaboration that laid the groundwork for almost all subsequent experimental work in neutron scattering. They were well prepared: Wollan had done a thesis on the scattering of X rays by gases under Arthur Compton at the University of Chicago, and Shull had been a graduate student at New York University when O. Halpern and M. H. Johnson worked out their definitive theory of the magnetic scattering of neutrons. By 1951 Wollan and Shull had published the nuclear scattering lengths of more than 60 elements and isotopes, demonstrated the existence of antiferromagnetism and ferrimagnetism, reported fundamental results on ferromagnetic materials, and established neutron diffraction as a quantitative, valuable experimental technique.

The neutron scattering program at ORNL has been continuous since those early days. We have enjoyed a succession of reactor sources, each having a significantly higher neutron flux than its predecessor: the Graphite Reactor—10^{12} cm^{-2}s^{-1} (a million million neutrons per square centimeter per second), the Oak Ridge Research Reactor (ORR)—3×10^{14} cm^{-2}s^{-1}, and the High Flux Isotope Reactor (HFIR)—10^{15} cm^{-2}s^{-1}. The proposed Advanced Neutron Source (ANS), which is designed to have a neutron flux of ~7×10^{15} cm^{-2}s^{-1}, will be the first ORNL reactor whose primary mission is neutron scattering.

The complexity and difficulty of the experiments attempted at ORNL have increased with the source flux. At the Graphite Reactor and the ORR, the emphasis was on elastic scattering. Our first inelastic measurements were at the ORR, and there was a strong effort on this type of experiment at the HFIR. The first polarization analysis measurements were performed at the HFIR, and we expect this technique to reach full fruition at the ANS.

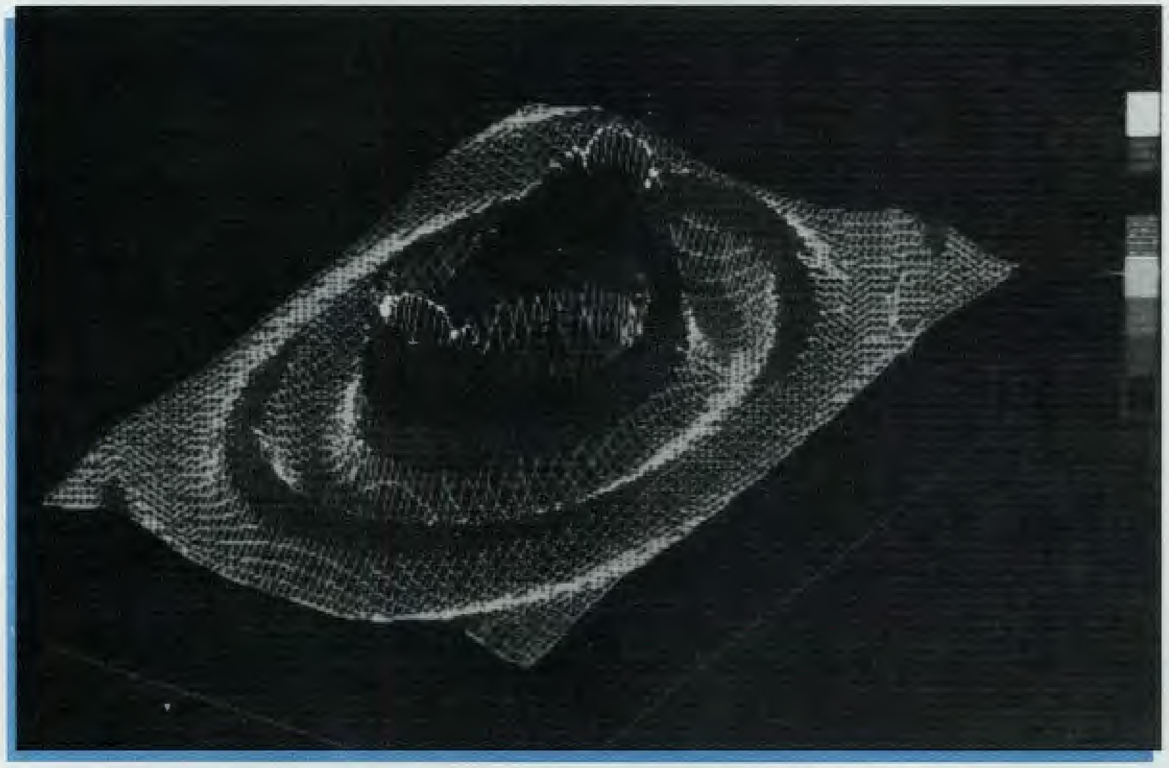
The worldwide growth in the complexity and diversity of neutron scattering is much more dramatic than on the strictly local scene. Much of this growth must be attributed to the success of the Institut Laue-Langevin (ILL) in Grenoble, France, where intense neutron beams, innovative instrumentation, and institutional policies have combined to create a mecca for neutron scientists. Most of the instruments at the ILL were planned by physicists but now are used by chemists, biologists, polymer scientists, and metallurgists on research problems the planners had never envisioned. We anticipate a further flowering of the sciences here when the ANS is fully operational.

The applications of neutron scattering are derived from a few fundamental properties of the neutron which, for certain types of experiments, give neutrons a unique advantage over X rays, electrons, and other probes used to investigate the nature of liquids and solids. The only disadvantage in the use of neutrons is their high cost, compared to photons or electrons, and their relative scarcity. These factors dictate that neutrons be used only for those problems in which their unique properties give them clear advantages over other probes. This constraint still leaves wide fields of research in many scientific disciplines open for the use of neutron scattering.

Condensed Matter Physics

The best current example of the value of neutron scattering is in the characterization of high-temperature superconductors. The number and position of oxygen atoms in these materials are closely linked to their superconducting properties. Because of the relatively large nuclear


SCALE OF 64
REGULATED H.V. SUPPLY



Neutron scattering, used to verify this calculated structure factor of a magnetically saturated ferrofluid, is often more effective than X rays, electrons, or other atomic probes in deriving fundamental material properties (see cover and inside-cover caption for complete color-coded structure factor image and explanation).

scattering length of oxygen, the Bragg intensities in neutron diffraction are much more sensitive to the oxygen atoms than are the corresponding intensities in X-ray diffraction. Accordingly, neutron diffraction has played a crucial role in determining important structural details of these materials. Also, the magnetic scattering of neutrons has helped determine the long-range order of magnetic moments on the copper sites and the character of the magnetic excitations in these materials.

The study of magnetic materials has always been an important application of neutron scattering. The relative orientation of atomic magnetic moments and the periodicity of the magnetic structures are revealed by the intensities and location of elastic (Bragg) peaks that appear in the diffraction pattern when a material undergoes magnetic ordering. For antiferromagnetic materials, neutron diffraction is the best method for determining magnetic structures. The magnetic intensities also contain information on the shape and size of the electronic magnetic moment distribution in a single atom.

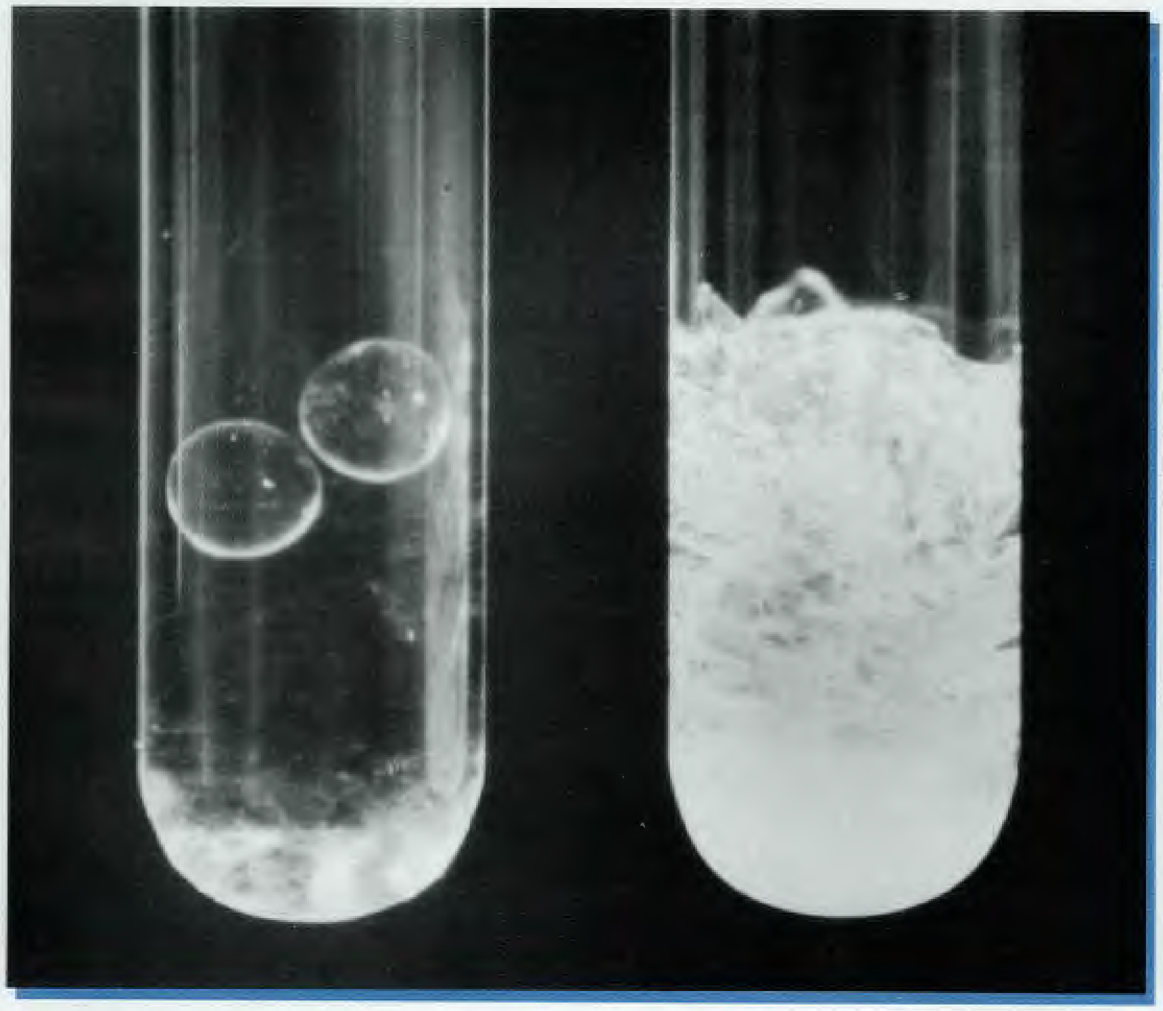
The theory of phase transitions has been a central part of condensed-matter physics in recent years. A fruitful testing method for theories of phase transitions has been the observation of critical magnetic scattering of neutrons near the transition temperature and the growth of long-range magnetic order below the transition temperature, as revealed by Bragg scattering of neutrons from antiferromagnets.

The interatomic forces responsible for magnetic order (exchange interactions) can be deduced from measurements of inelastic magnetic scattering of neutrons. Similarly, the interatomic (electrostatic) forces responsible for the mechanical and acoustic properties of matter can be determined through inelastic nuclear scattering of neutrons.

Biology Studies

The applications of neutron scattering to biology are closely associated with the scattering properties of hydrogen and deuterium. In electron density maps prepared by X-ray crystallographic studies of biological molecules, the hydrogen atoms are not visible. Because most of these molecules contain more hydrogen atoms than all other atomic species combined, this is an important omission. In fact, the arrangement and exchange of hydrogen atoms and water in biological molecules can often provide a key to understanding biological processes and properties. Naturally biologists would like to have a better tool for tracking hydrogen exchange in these molecules. Biologists originally entered the neutron field because high-resolution neutron diffraction studies make it possible to determine the hydrogen positions in protein structures. The neutron data are used in conjunction with, not in place of, the X-ray data to allow a complete structural determination.

Neutrons are also used in low-resolution studies to determine the location and shape of molecular components in some large structures. These low-resolution studies became possible with the development of small-angle neutron scattering (SANS) instruments, which were initially used in Europe but now also play an important role in U.S. research. Two new technological developments came together to promote the growth of SANS: large-area, position-sensitive detectors and dedicated



These tubes provide an optical analog of the neutron contrast variation technique. Both tubes contain borosilicate beads with ground pyrex fibers and solvent. In the tube on the left, the refractive index of the solvent matches that of the pyrex fibers, making the fibers invisible. On the right, the refractive index of the solvent is different from that of the beads and fibers; light scattering from the fibers is dominant, so our eyes are unable to detect the beads and solvent.

computers, which make possible the acquisition, organization, and analysis of large amounts of data. These instruments can be used to measure the size and shape of objects ranging in size from roughly 10 to 2000 Å. (The position-sensitive detectors used are based on a development by Manfred Kopp, formerly of ORNL's Instrumentation and Controls Division.)

The pattern produced by a SANS analysis is determined by variations in the neutron scattering length density, which for a molecule is simply the sum of neutron scattering lengths for all the atoms divided by the molecular volume.

The important feature for biological studies is that the scattering length for hydrogen is -0.37×10^{-12} cm, while for deuterium it is $+0.67 \times 10^{-12}$ cm. Therefore, the scattering length density of water can be varied from -0.55×10^{10} per cm^2 to 6.36×10^{10} per cm^2 by mixing H_2O and D_2O. These numbers bracket the scattering length densities for most biological materials, so that it is possible to make any particular material "invisible" in a SANS experiment by dissolving it in water with the appropriate H_2O:D_2O ratio (see illustrative photograph on p. 89).

The advantage of this "contrast variation" technique is that it can be applied productively to the study of objects that contain two different chemical species having different scattering length densities. By matching the scattering length density of the solvent to that of species A, the shape and size of species B can be determined without interference. Similarly, by changing the D_2O concentration in the solvent so that species B is invisible, the shape and size of species A can be deduced. This technique has been used, for example, in studies on nucleosomes, viruses, and transfer RNA.

It is also possible to use selective deuteration (substituting the deuterium isotope for ordinary hydrogen) in the material under study to label specific structural subunits and thereby determine the position of these labeled subunits in the larger structure. Important studies of lipids in membrane bilayers and of the positions of proteins in ribosomes are done using this method.

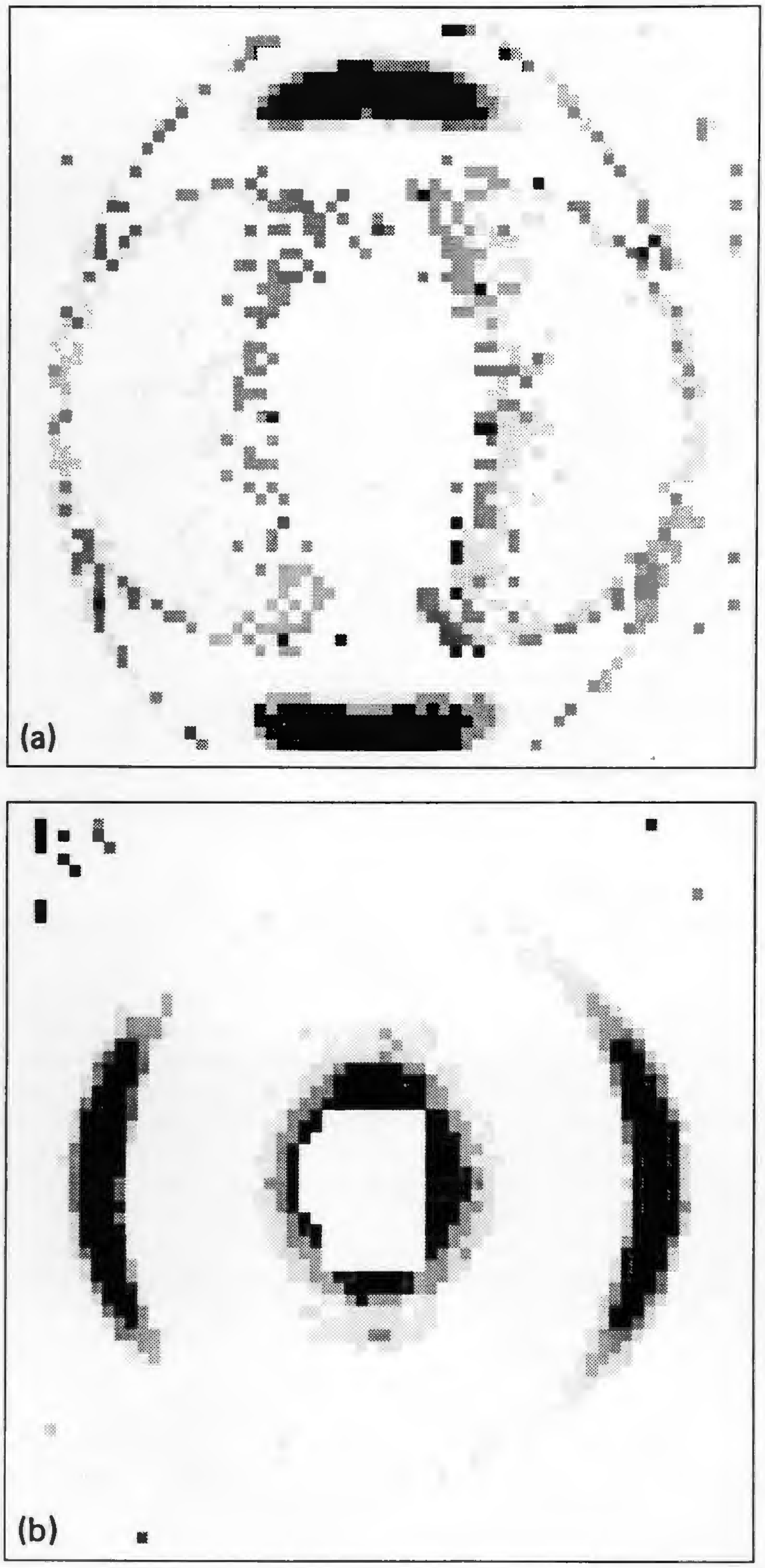
Chemistry Research

The first chemical application of neutron scattering was by crystallographers who used neutron diffraction to locate light atoms, particularly hydrogen, in a wide variety of structures. Much of this work requires single-crystal samples, but in recent years diffraction from powder samples has become a useful technique for moderately complex structures. A contributing factor to the growth of powder techniques has been the success of more sophisticated data analysis methods. With the current generation of high-resolution neutron powder diffractometers, refinement of structures with up to 100 adjustable parameters can be achieved.

Submicrometer or colloidal systems have long been an area of industrial importance, and most research has traditionally concentrated on the macroscopic behavior of these systems. In recent years the SANS technique has been remarkably useful in studying their microscopic properties. Not only can details of the intraparticle structure be studied, but interparticle correlations in position are revealed. In fact, these systems form three-dimensionally ordered arrays of particles.

Surfactant solutions form a rich variety of submicrometer structures that vary with temperature and concentration. These include spherical and cylindrical micelles; lamellar, cubical, and hexagonal structures; and liquid-crystalline phases. Advances in liquid theory have made possible a quantitative description of scattering from spherical micelles or colloids in concentrated solution.

A SANS pattern from a single anisotropic particle will itself be anisotropic—showing different intensities in different directions. However, scattering from a collection of randomly oriented anisotropic particles (cylindrical shapes, for example) will be isotropic—showing the same intensity in all directions. To obtain a scattering pattern that reveals the shape of the individual particle, the experimenter needs a method to line up all the



Small-angle neutron scattering (SANS) intensity patterns for tobacco mosaic virus suspended in a ferrofluid. A magnetic field was applied in the left-to-right direction, and the virus intensity is indicated by shading from white (minimum) to black. Dark areas in (a) indicate interparticle correlations, as the particles arrange themselves in an ordered structure. In (b), the detector has been moved much closer to the sample, so the pattern is for a different range of scattering angle. Dark areas in (b) are associated with the internal structure of the magnetically aligned virus particles.

cylinder axes so they are pointing in the same direction. Two methods are now available to do this alignment. A shear field set up in a viscous fluid by a rotating sample container has been used to align cylindrical micelles suspended in the fluid. Also, application of a magnetic field to a combined suspension of spherical magnetic particles (a ferrofluid) and tobacco mosaic virus particles has resulted in alignment of the non-magnetic virus particles (see figures on p. 91).

Catalytic materials are also being investigated with various neutron scattering techniques. Powder diffraction is being used to study the structure of zeolites, and inelastic scattering is being used to study proton siting and mobility as the zeolite temperature approaches that used in chemical processing. Inelastic studies have also been performed on molecular species absorbed on fine particles of platinum and nickel.

Chemical spectroscopy through inelastic neutron scattering is a rapidly growing field in Europe, largely because of the good energy resolution available on some of the ILL spectrometers. Rotational energy levels in solids, diffusion, and relaxation phenomena are particular focuses of this work. A motivating factor behind some of this work is the need to understand the behavior of hydrogen absorbed in metals for applications in energy storage devices.

Polymer Analyses

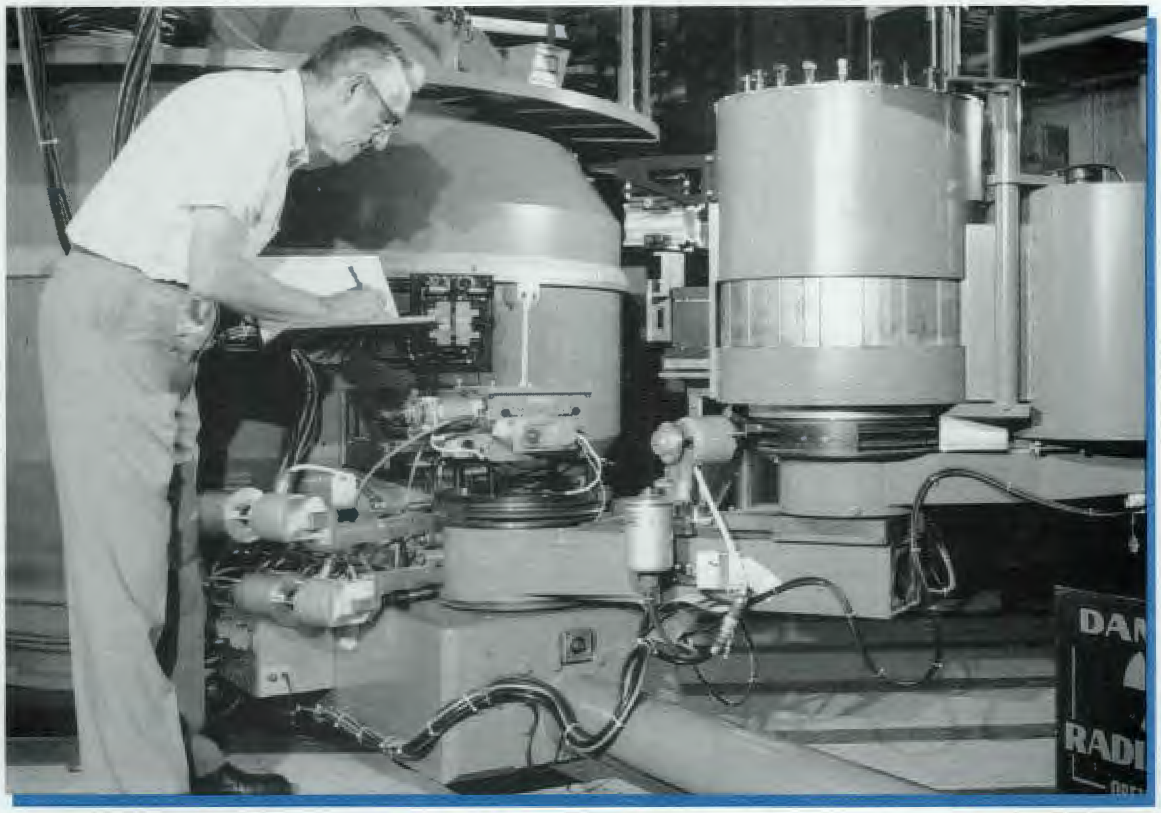
The SANS technique, coupled with selective deuteration and contrast variation, is also extremely important in a wide variety of polymer experiments. Polymer scientists constitute the largest group using the SANS facilities in the United States. One of the earliest and most important applications was the confirmation of a major theoretical model for the polymer chain configuration in bulk, amorphous material. Small amounts of deuterated polymer were added to a matrix of the same, but fully hydrogenated, polymer; in this way the single-molecule structure factor was measured and found to be in agreement with that of the model.

The state of miscibility in polymer blends (a mixture of two different polymers) can be characterized by SANS, and this information has been particularly valuable in view of the current interest in producing new materials from blends of available polymers. Before the development of the SANS technique, the methods used to investigate the compatibility of polymers in blends could indicate macroscopic segregation but could not detect fine-grained separation at the level of molecular segments. The SANS data from blends in which a fraction of one polymer species has been labeled with deuterium will reveal the polymer compatibility at the segmental level.

Block copolymers contain two or more chemical subchains within a single polymer chain. These subchains can separate into microphases as a result of mutual incompatibility of the different parts of the molecule. Such microphase regions are compact, each containing parts of many molecules and giving a colloidal-type structure having a characteristic dimension of about 100 Å. SANS studies have revealed the structure of these microphase regions, along with the individual chain dimensions within the microdomains.

Materials Science

There are great, although still largely unrealized, opportunities for application of neutron scattering to materials science. Many of these opportunities stem from the penetrating power of neutrons, which permits observations of bulk rather than surface properties of microstructure and defects and allows scattering studies to be performed on samples within furnaces, cryostats, and pressure cells. The study of changes in microstructure during the processing of alloys and ceramics is perceived as an area of great potential. Another developing area is real-time studies of structural responses to external perturbations such as temperature, stress, electrical fields, and magnetic fields. Either periodic or stepwise perturbations can be applied. The penetrating power of neutrons allows bulk, nondestructive studies to be made of manufactured components. For example, the texture (preferred orientation of grains) and residual stress can be measured as a function of distance below a surface.



Ralph Moon at the HB-3 triple-axis neutron spectrometer at the High Flux Isotope Reactor.

Plans and Predictions

The future of neutron scattering in the United States is closely tied to the ANS. For most experiments, the higher source flux at the ANS, coupled with improved neutron delivery systems, will increase the effective neutron flux at the sample position by at least a factor of 10, compared to the HFIR. When combined with more, and improved, neutron scattering instruments, the scientific productivity of the ANS should be about 30 times greater than that of the HFIR.

It is impossible to anticipate the specific research topics to be investigated at the ANS, but we can make a guaranteed prediction that good neutron scattering facilities will be required to understand the structure and dynamics of the new materials of the 21st century.

Biographical Sketch

Ralph Moon was born in Bombay, India, but grew up in Kansas City, Missouri. He joined the ORNL Physics Division in 1963, after obtaining a Ph.D. degree in solid state physics from the Massachusetts Institute of Technology. Since 1964, he has been a member of the Solid State Division and is currently head of its Neutron Scattering Section. His major research activities have involved the use of neutron scattering techniques for the study of magnetic materials.

A Neutron Scattering Primer

In *neutron scattering* experiments at a reactor, a beam of neutrons, all moving in the same direction with the same velocity or energy, is allowed to strike a sample. Generally, most of the neutrons will pass through the sample with no interaction with the atoms or molecules within the sample. Some of the neutrons will have an interaction, and they will be scattered from the incident beam direction.

The scattered neutrons may emerge from the sample with the same velocity or energy as the beam (*elastic scattering*) or with a change in energy (*inelastic scattering*). Experimenters count the number of neutrons leaving the sample as a function of the angle from the incident beam direction and as a function of the final neutron energy. From these data they can deduce fundamental information on the structure and dynamics of the sample. *Structure* refers to the relative position of atoms within the sample; this information is contained in the elastic scattering. *Dynamics* refers to the relative motion of atoms within the sample, and this information is determined from the inelastic scattering measurements.

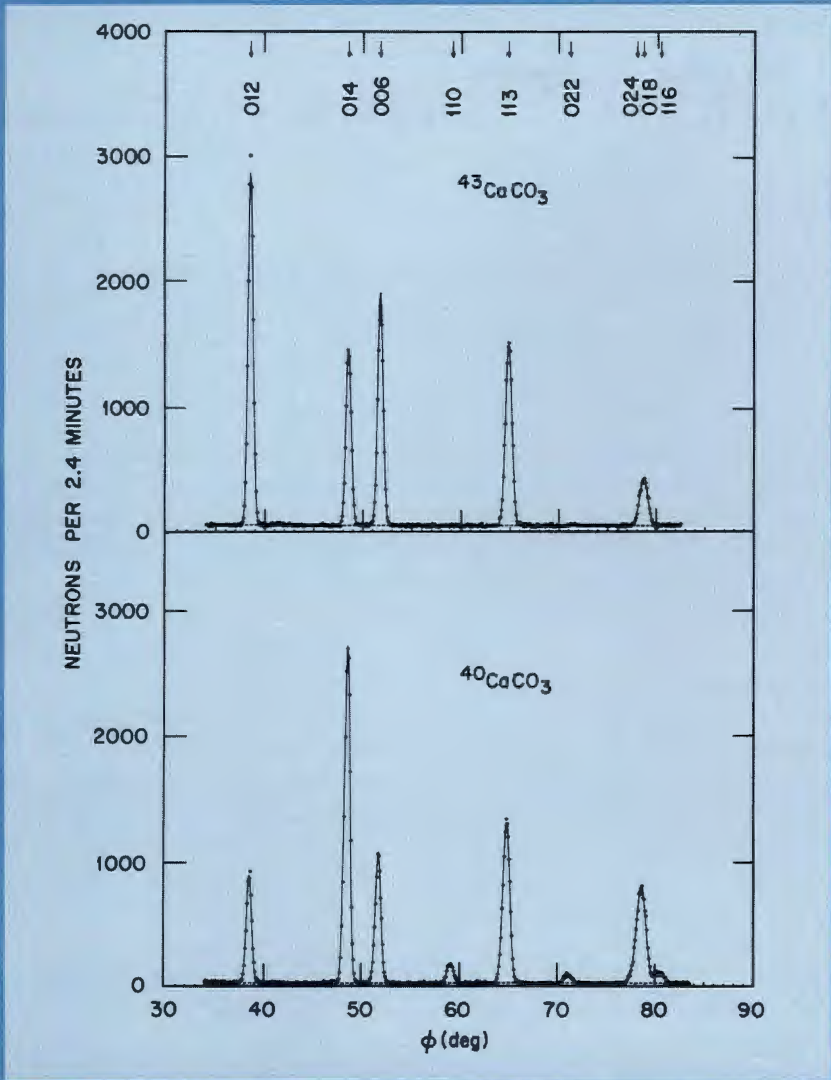
In neutron scattering interactions between an atom and a neutron, the atom exerts a force on the neutron which changes the neutron trajectory. There are two important interactions in neutron scattering. One is a *nuclear interaction* between the neutron and the nucleus of the atom, whose measurement is called the *nuclear scattering length* (ranging roughly between 10^{-12} cm and 10^{-13} cm). Each element, and each isotope of a given element, has a different nuclear scattering length (as illustrated by the neutron scattering data shown here for carbonates of two different calcium isotopes).

The other important interaction—the *magnetic interaction*—is similar to what you feel when holding two small bar magnets close together. Because the electron clouds in some atoms have a net magnetic moment (like a *very* small bar magnet) and every neutron also has a characteristic magnetic moment, there is a magnetic interaction, as well as a nuclear interaction, when a neutron passes very near a magnetic atom. The strength of this interaction is proportional to the magnitude of the atomic magnetic moment and is measured by a quantity called the *magnetic scattering length* (also roughly 10^{-12} cm).

Scattering research to investigate the behavior of solids and liquids can be performed with various kinds of beams; light, X rays, neutrons, and electrons are the most common. All of these techniques are valuable, and each can give information not easily obtained with the others. Each of these beams has a characteristic energy and corresponding particle wavelength. For structural studies it is desirable to have the wavelength comparable to the distance between atoms in the sample, and for dynamics studies it is desirable to have the energy of the particles in the beam comparable to the energy of motion of the atoms in the sample.

Neutrons possess certain unique properties that make them especially valuable for studying the fundamental behavior of materials. Only neutrons have the right wavelength and energy for studies of both structure and dynamics. In addition, because of the neutron's magnetic interaction, neutron scattering research has revolutionized our understanding of magnetic materials.

Another very noteworthy property of the neutron is its ability to locate and let us "see" hydrogen atoms. This property is especially important because so many compounds in living tissues are made of long-chain molecules having many hydrogen atoms in complex arrangements. The scattering of X rays by hydrogen is very weak, making this method less attractive for locating hydrogen in the presence of other atoms. Neutrons, however, strongly interact with hydrogen atoms, making neutron scattering the method of choice for studying biological samples and polymers.



Neutron diffraction patterns showing Bragg intensity peaks for isotopic samples of calcite powder. The change in the diffraction pattern is caused by the different neutron scattering lengths for ^{40}Ca and ^{43}Ca.

Neutrons penetrate most materials quite easily. Typical penetration depths are measured in centimeters for neutrons and in micrometers for X rays. An important consequence is that neutrons can be used to probe well below the surface of manufactured structural components in a nondestructive manner. For example, neutron scattering can be used to generate three-dimensional maps of the residual stress near welds in oil pipeline sections. This strong penetrating power also makes it easy to use neutron beams for analyses both inside and outside of cryostats, furnaces, and pressure cells. For example, many of the most interesting magnetic phenomena occur at very low temperatures but, fortunately, the aluminum thermos bottles used as cryostats to keep samples cold are almost completely transparent to neutrons.

Several specialized measuring instruments have been developed to meet various requirements in neutron scattering research. For example, in analyses of crystalline materials, the elastically scattered neutrons are observed at only at a limited number of angles from the direction of the incident beam. This phenomenon, called *diffraction* or *Bragg scattering*, enables researchers to measure the angles and the number of neutrons scattered at each angle (*Bragg intensities*), and to make deductions about the structure of the sample material from these measurements. A neutron diffractometer, designed to make such measurements, simply counts all the neutrons at a particular angle without doing any energy analysis. A more complicated instrument called a *neutron spectrometer* also measures the energy of the scattered neutrons.

For some experiments it is desirable to produce a *polarized beam*—an incident beam in which all the neutrons have their magnetic moments lined up in the same direction. A *polarization analysis spectrometer* determines the magnetic moment alignment of the scattered neutrons in a polarized beam. Such instruments are useful, for example, in analyses of ferromagnetic materials.

The Advanced Neutron Source: An Update

By Colin West

Computer-generated drawing of the reflector tank assembly for the proposed Advanced Neutron Source (ANS) reactor.

Within nine years, the Advanced Neutron Source (ANS), ORNL's proposed new research reactor facility, should be built and operating. The ANS is planned to meet the national need for an intense, steady-state source of neutrons for research and will enable the United States to recapture the world leadership it once held in neutron-scattering experiments (see Bell's article on the Oak Ridge Research Reactor, p. 30).

In 1989, the ANS Project entered the conceptual design phase, and in 1990 ~$95 million of detailed design and safety analysis work is expected to begin. On this schedule, construction work would begin late in calendar year 1993 and the new reactor could become operational in 1998.

In addition to its usefulness in materials science studies, the ANS will have many other scientific applications. The user facility built around the new research reactor at ORNL will be invaluable for fundamental nuclear physics investigations, chemical analyses, and testing for radiation effects on various structural materials and fuels to be used in fusion or fission reactors. The various applications for neutrons are discussed in other articles of this issue. The ANS will also produce isotopes important to medical research, diagnosis, and treatment at the same production level as the High Flux Isotope Reactor (HFIR).

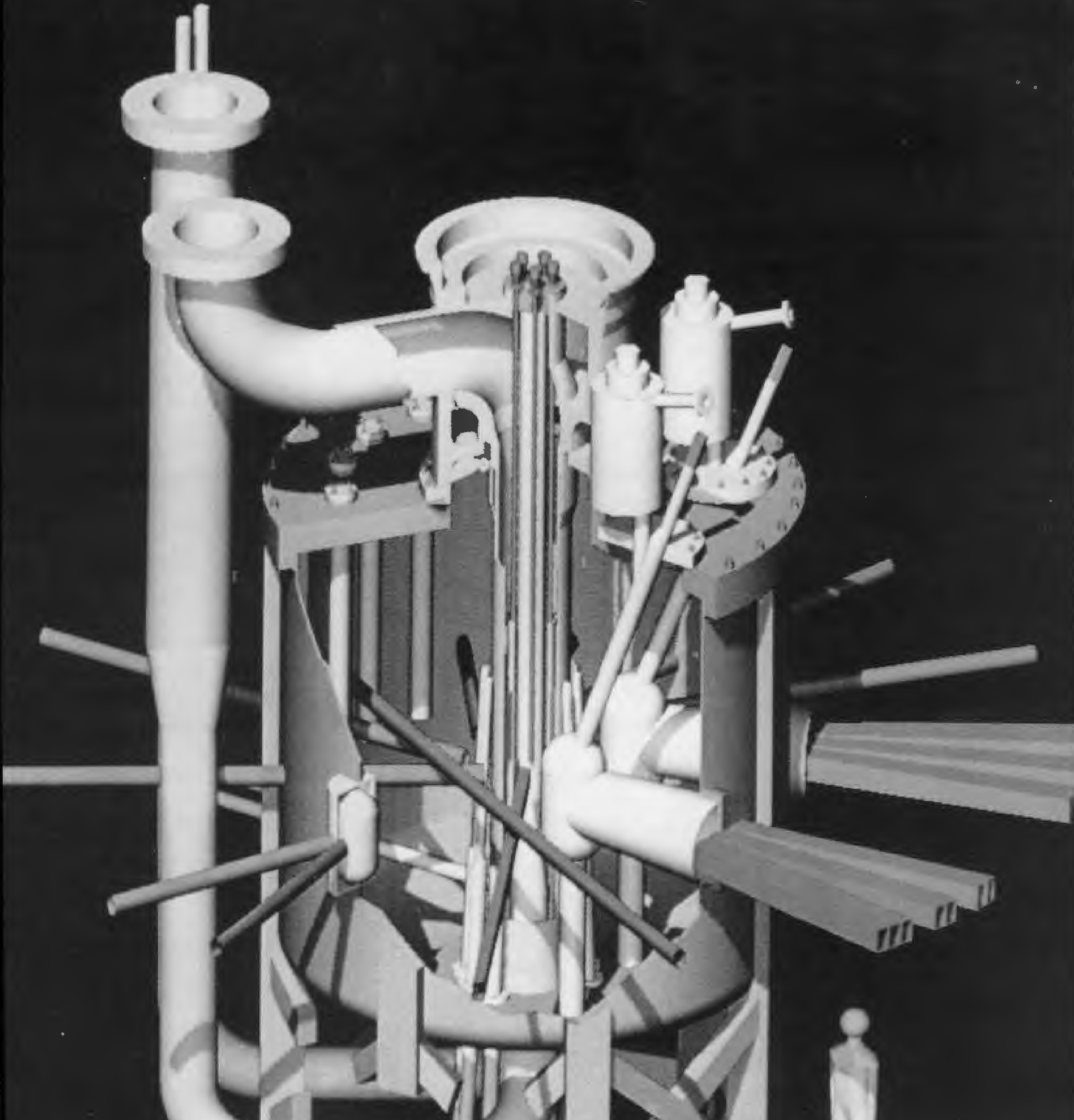
New Core Designed

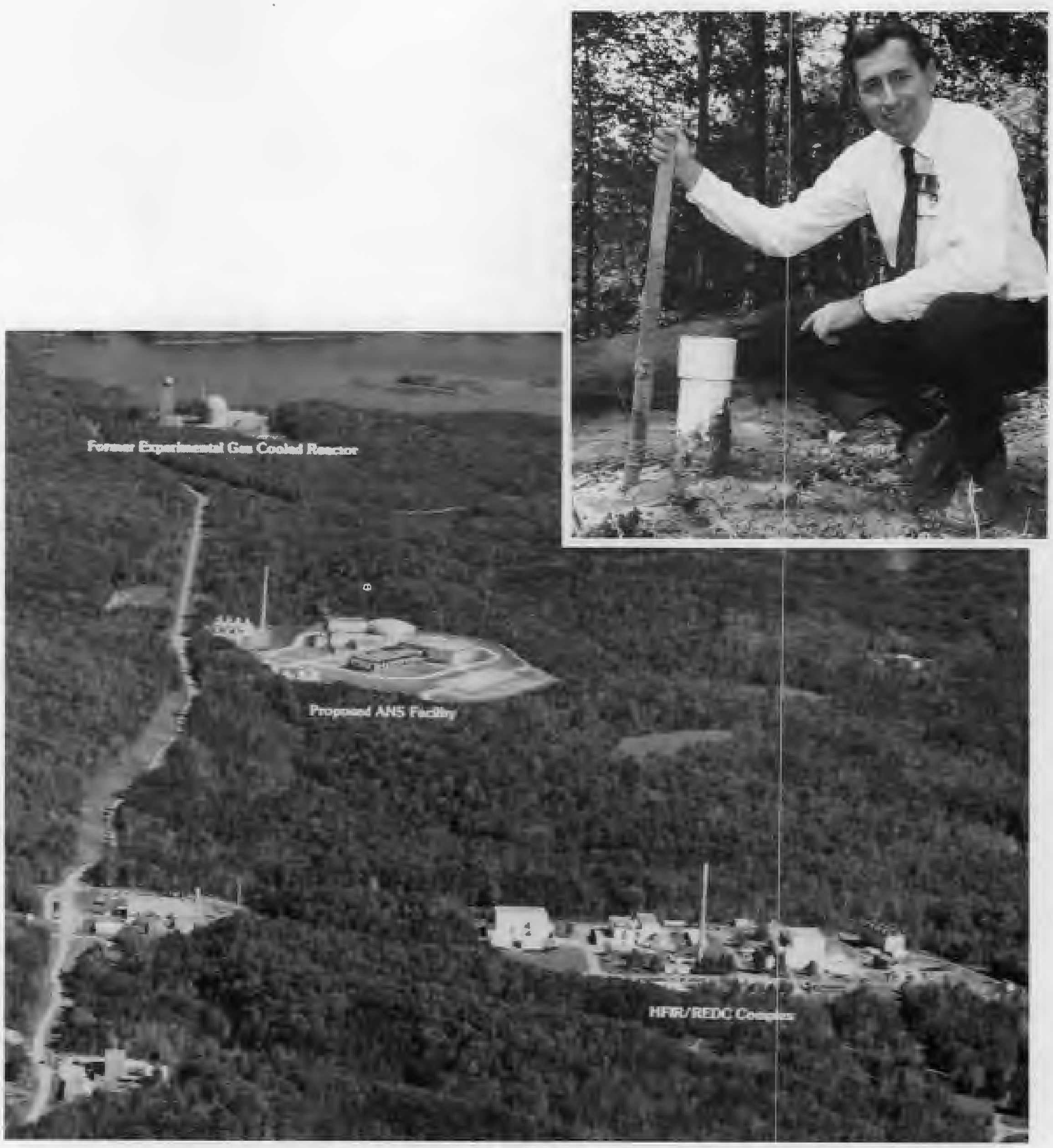
Research and design work for the ANS (formerly called the Center for Neutron Research) has made progress in the three years since the *Review* first reported on the project (Vol. 19, No. 1, 1986). The reactor core adopted as a reference for beginning conceptual design uses less uranium fuel and has a lower heat flux within the core (an important safety advantage) and has lower pressure in the coolant system than the earlier designs. The new core concept was developed by a strong team from several ORNL divisions (Engineering Physics and Mathematics, Instrumentation and Controls, Chemical Technology, Metals and Ceramics, Solid State, and Engineering Technology), as well as the Engineering Organization of Martin Marietta Energy Systems, Inc., and staff members of the Idaho National Engineering Laboratory (INEL).

The new core design, which combines ideas and proposals from Oak Ridge and INEL, is similar to that of the HFIR core in that it contains two concentric annular elements of thin, aluminum-clad fuel plates. In the HFIR core, these elements are nested one within the other, but in the ANS core, they will be separated vertically, one element above the other.

The core's fuel elements will be cooled by heavy water (D_2O) and surrounded by a large reflector tank containing additional D_2O (see computer drawing on facing page). Neutrons released by the nuclear fission reaction in the relatively small core will escape into the reflector tank, where they will be slowed down by repeated collisions with the heavy-water nuclei (mainly the deuterium). Some of the neutrons will be reflected back into the core by the collisions and will maintain the nuclear chain reaction in the fuel elements.

Tubes penetrating the reflector tank will allow beams of the unreflected neutrons to be channeled into experimental areas surrounding the reactor for use in neutron scattering experiments. D_2O, rather than ordinary water (H_2O), is used as a coolant in the ANS because the deuterium does not slow the neutrons as quickly and does not absorb so many of them, making more neutrons available to the beam tubes in the reflector. In the HFIR, which is primarily an isotopes production reactor, the opposite is true; the designers wanted to keep as many neutrons as possible inside the core region,





This computer-enhanced photograph shows the location of the preferred ANS site on the Oak Ridge Reservation. Inset: Doug Selby of the ANS staff marks the location of the site's deepest core drilling operation, performed in September 1989 to assess geological suitability for the reactor.

where various elements are irradiated by slow neutrons to produce medically and scientifically important isotopes. Therefore, the HFIR is cooled by light water.

Because the ANS is a national project, with ORNL designated by DOE as the lead laboratory, the project team includes staff from DOE, four of the national laboratories, American and foreign universities, and private industrial firms. We are working together on reactor design, safety analyses, balance of plant design (e.g., buildings, utilities, and cooling circuits), and defining the R&D needed to address unresolved technical issues. John Hayter of the Solid State Division is leading a substantial effort to define the research instrumentation that will be installed at the completed facility. Hayter's program also includes R&D work at ORNL and other institutions to design new and improved instruments that will optimize the use of the very high neutron flux that will be available from the new reactor.

Preliminary Site Selected

Another activity completed during the past year was the preliminary selection of a site for the new ANS facility. In this effort, led by Phil Thompson of Energy Systems Engineering, the entire DOE reservation at Oak Ridge was studied. Areas that failed to meet minimum requirements were rejected (e.g., those that are too steep, lie within a floodplain, include historic sites, or have unsuitable base rock), leaving four areas potentially suitable for the ANS. These areas were ranked on the basis of proximity to support facilities or utilities, absence of known endangered flora or fauna, and the amount of site modification that would be required.

The site selected from among these final four is in Melton Valley, near the HFIR and the Radiochemical Engineering Development Center (see photograph on facing page). The project team's next step has been to investigate the site by field survey and core drilling. The site selection process involved extensive input from several ORNL divisions, Energy Systems Engineering, DOE's Oak Ridge Operations, and Science Applications International Corporation. Should the detailed investigation for the site's Environmental Impact Statement (EIS) reveal unexpected problems at the selected site, then an area in Western Bear Creek Valley (one of the remaining potentially suitable sites) will be reconsidered.

Safety Analysis Under Way

The ANS Project team has made important strides toward ensuring that the final ANS design is as safe as possible. The safety analysis program, led by Mike Harrington of the ANS Project Office, has been very active, with work under way in the Engineering Technology, Engineering Physics and Mathematics, and Instrumentation and Controls divisions at ORNL, as well as at INEL and Brookhaven National Laboratory.

Research reactors such as the ANS have some inherent safety advantages over typical power reactors. In particular, the amount of radioactive fission products in the core will be much lower because of the lower thermal power level of the ANS (300 MW vs 3000 MW for a typical power reactor), the smaller fuel inventory (15 kg of uranium-235 vs 2000 kg) and the shorter core life (2 weeks vs 2 years).

Despite the lower power level, the ANS will have a containment dome as large as a typical power reactor. This large space is needed to accommodate experiments, and it also makes plenty of volume available to absorb any accidental energy release. In fact, because the ANS has a smaller core, the total energy stored there will be much lower than that of an average power reactor system. Another important safety point is that the cooling water in the ANS will be at a lower temperature than that in a power reactor, which must produce high-pressure steam for the turbines. In the event of a pipe leak or break in the power reactor systems, the high-temperature water can turn almost instantly into vapor, putting a substantial pressure load on the containment. In the ANS, the cooling water leaving the core at an average temperature of about 85°C, well below the boiling point, cannot flash into steam. In addition, several other design features of the ANS offer significant safety advantages—for example, the upward flow of coolant in the core enables thermosyphon cooling and the forced cooling to work in the same direction.

In the early stages of the ANS Project, the largest part of our effort has been devoted to the R&D needed to resolve issues raised by the design and safety analysis teams. This work, led by Doug Selby of the ANS Project Office, involves a wide range of disciplines and organizations. "Core physics" (i.e., calculations of the nuclear reactions within and around the core, the neutron flux available for experiments, the heat generation rates, and other aspects of core performance) has been handled by staff members of ORNL's Engineering Physics and Mathematics Division and INEL. Development and testing of the nuclear fuel, a uranium silicide compound highly enriched in uranium-235, is a collaborative effort involving Argonne National Laboratory, the fuel manufacturer (Babcock and Wilcox), and ORNL's Metals and Ceramics and Engineering Technology divisions.

The behavior of the aluminum cladding around the fuel and the flow of cooling water through the core are being studied by staff from ORNL's Engineering Technology and Chemical Technology divisons and from INEL. A highlight of this work was the 1988 startup of a high-pressure, heated-water loop designed to measure the corrosion of aluminum and other effects under the extremes of heat loading and coolant velocity expected for the ANS fuel. This loop was the culmination of a successful construction project led by Bill Montgomery, at that time a member of the Engineering Technology Division.

Other areas of research include development of a "cold source" (a container of liquid deuterium maintained at very low temperature to slow some of the neutrons to the extremely low energies needed for particular research applications) and the instrumentation and control system for the reactor. These areas are under investigation by the Engineering Physics and Mathematics Division, Energy Systems Engineering, and the Instrumentation and Controls Division.

Project Requests Design Funds

At a major DOE review in April 1989, the project proposed funding of $94 million over a 3-year period for the ANS to begin detailed design work, cost estimating, and safety studies. The review team recommended that DOE request these funds from Congress, to begin in fiscal year 1991. If approved, this new phase of the work will start in October 1990 and will form the justification and basis for a funding request to Congress to begin construction in October 1993. DOE recognizes the scientific importance of the new facility, but we must demonstrate that the project is well planned by means of credible cost and schedule estimates and a defensible technical approach.

The scientific staff throughout the Laboratory have responded, as always, with their best efforts to support the ANS Project. Under the leadership of the Energy Systems Engineering staff, individual researchers at ORNL, and our subcontractors have helped to define the R&D work to be done over a 5-year period, the resources needed to do the work, and the timetable on which results might be completed. All of these data, prepared in fine detail and combined into an overall planning document, provide powerful justification supporting our budget request. At this point, we are pleased with the sound foundation laid for the ANS and optimistic about future progress toward making this needed research facility a reality. ornl

At the preferred ANS site, Colin West, project director (fourth from left), and Ken Darnell of ERC/EDGe examine core samples. Gathered here are representatives of the ANS staff, DOE, and the Geologic Associates Division of ERC/EDGe, the company contracted to do the core drilling.

Biographical Sketch

Colin West received his Ph.D. degree in physics from the University of Liverpool in England and first worked for the United Kingdom Atomic Energy Authority. He came to ORNL in 1977 to work for the Program Planning and Analysis Office. West transferred to the Engineering Technology Division in 1981 and became director of the Advanced Neutron Source Project in 1986. He is author or coauthor of three books and more than 80 additional technical publications.

ORNL and the Modular HTGR

By F. J. Homan

Malcolm Peters adjusts gas flow in the Core Conduction Cooldown Furnace, designed to simulate conditions during a core conduction cooldown accident in an operating MHTGR. Irradiated fuel will be heated in this furnace (which will be located in a hot cell) to temperatures beyond those expected from decay heat following reactor shutdown.

In the United States, the high-temperature gas-cooled reactor (HTGR) has had a checkered history. Support for its development has waxed and waned over 35 years. Today the HTGR, in modular form, is back in favor because of its safety characteristics and operational efficiency. Plans are now to develop this reactor type for use in the next generation of U.S. commercial nuclear power plants and for the production of tritium for the nuclear weapons program.

The HTGR has been under development since the mid-1950s when it was conceived in San Diego, California, by a company now called General Atomics (GA). Parallel development of HTGR technology was conducted by the United States (Peach Bottom Reactor and Fort St. Vrain Reactor), the Organization for Economic Cooperation and Development [OECD] (the Dragon Reactor in Great Britain), and the Federal Republic of Germany (the AVR and THTR). Both the U.S. and German programs continue today, but the OECD program was discontinued in the late 1970s when the Dragon Reactor was shut down. Japan, a relative newcomer in the HTGR arena, is moving aggressively toward construction of a new model called the High-Temperature Test Reactor (HTTR).

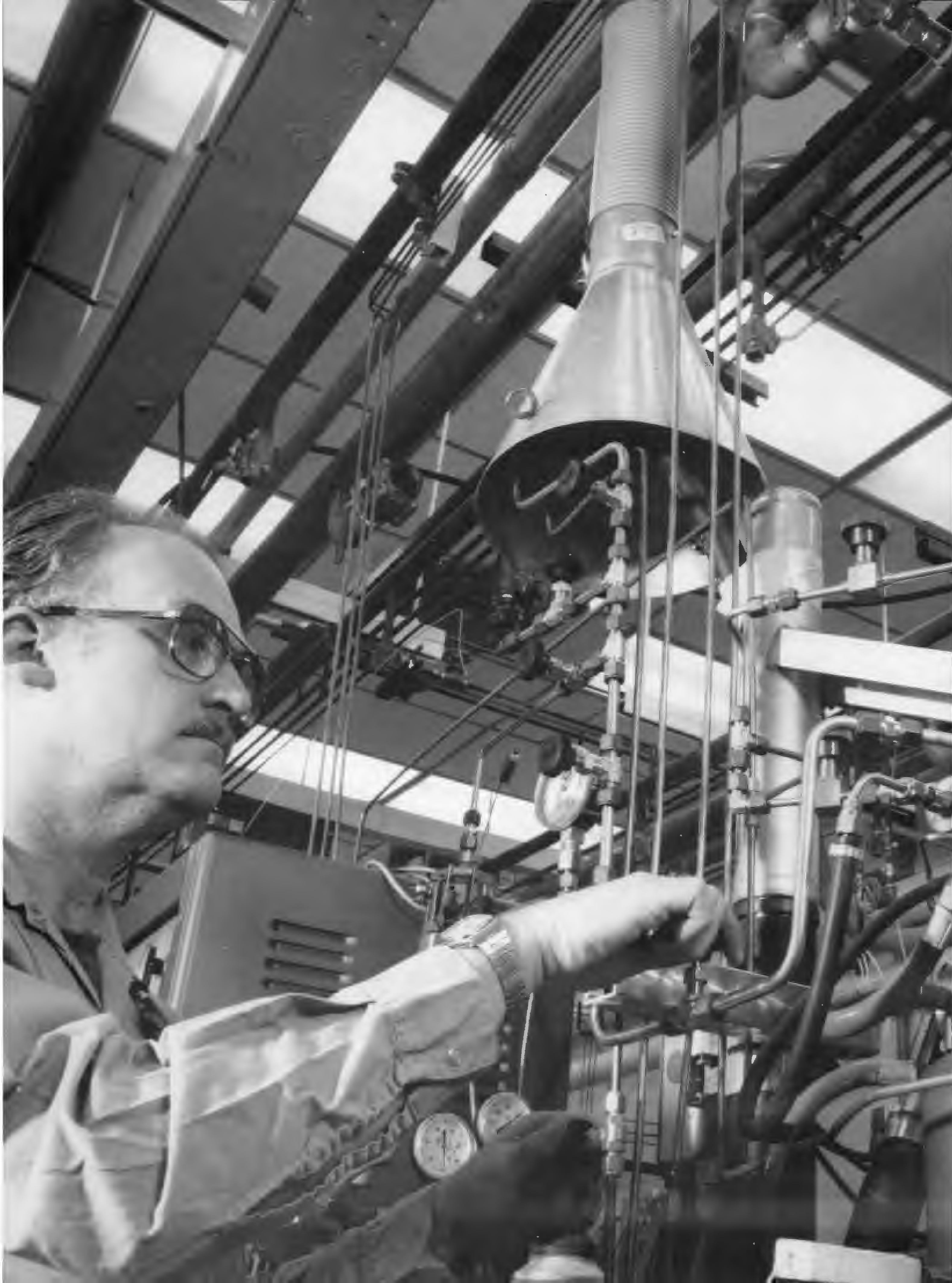
Each national program has recognized the unique advantages of the HTGR over other reactor systems under development for electricity production. The advantages include the inert single-phase coolant (helium gas), the all-ceramic core, and the low power density (compared with water- and liquid-metal-cooled reactors). These features lead to increased safety margins and higher operating temperatures, resulting in higher thermal efficiency and the potential for advanced applications such as direct-cycle electricity and process heat production.

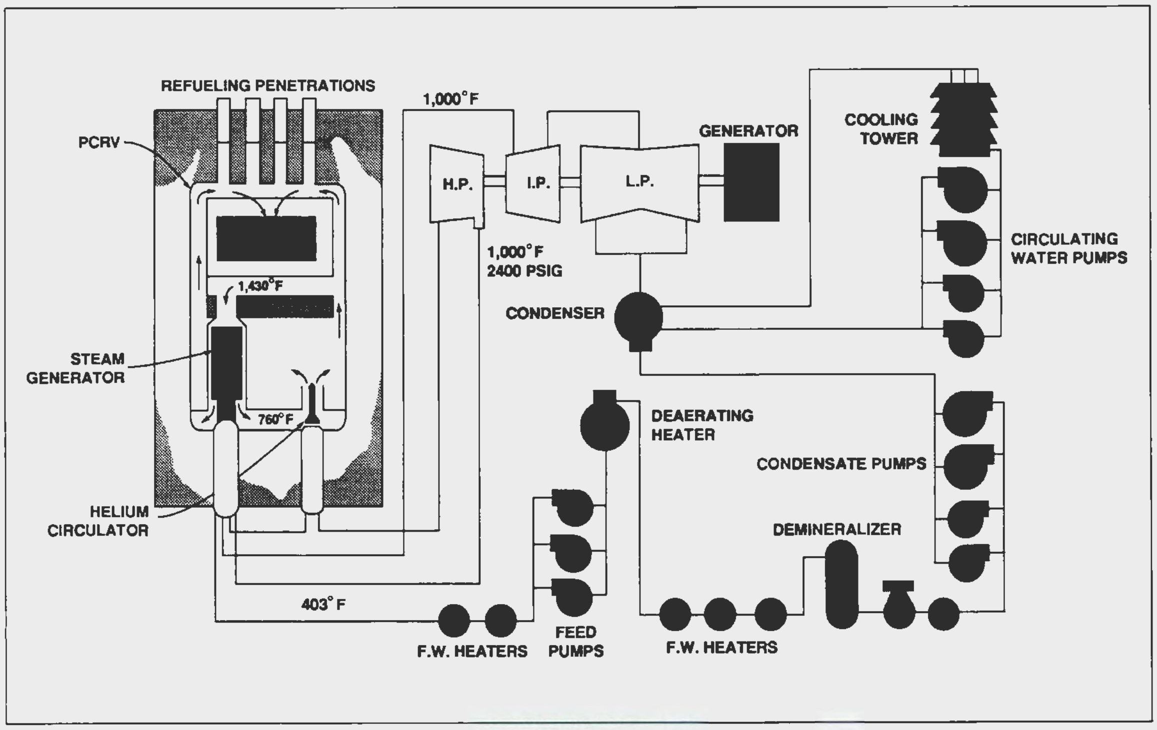
HTGR Evolution

The HTGR within the U.S. civilian reactor program strategy has evolved in several stages. The U.S. Atomic Energy Commission's (AEC's) plan in the late 1960s was to develop commercial breeder reactors to serve as "fuel factories" for the light-water reactors (LWRs) already commercially deployed. LWRs operate on the "low-enriched uranium" (LEU) fuel cycle, with a conversion ratio of about 0.6 (see sidebar). Breeder reactor designs developed in the late 1970s were expected to produce breeding ratios from about 1.07 to 1.3. The AEC planners envisioned "energy parks" with clusters of breeder and converter reactors and ancillary fuel fabrication and reprocessing facilities. Surplus fuel from the breeders was to be used as "make-up" fuel for the converters (the HTGR was then considered an "advanced converter").

Operating with the highly enriched uranium (HEU) fuel cycle and using thorium-232 (^{232}Th) as the fertile material, early HTGRs were expected to have conversion ratios approaching 0.82 (for every ten units of ^{233}U or ^{235}U consumed, eight units of ^{233}U would be bred). Advanced HTGR designs were expected to "break even"—that is, have a conversion ratio of 1.0. AEC planners in the 1960s expected several hundred large converter reactors to be in place by 1990, with significant commercial deployment of breeder reactors delayed to beyond the year 2000. This situation was expected to rapidly deplete inexpensive sources of uranium, making the HTGR, with its superior uranium utilization relative to LWRs, look very attractive. Once the breeder economy was in place (after 2000), AEC planners expected the HTGR to move into advanced applications.

Because of events of the 1970s, the ambitious plans of the 1960s fell short. The economic downturn of the early 1970s caused deferral or cancellation of the aggressive construction scheduled by many electric utilities. Licensing delays and cost overruns made new nuclear plants much less attractive to utility executives than the first generation of "turnkey" plants constructed in the late 1950s and 1960s.





Schematic of Fort Saint Vrain Reactor, a nominal 330-MWe HTGR designed by GA and operated by Public Service of Colorado. It was shut down in 1989.

The change in market conditions was particularly hard on the HTGR. In 1976, GA had expressions of interest for 16 large HTGRs, with orders for 10 reactors. By the end of the decade, all these orders had been cancelled. Orders for LWRs also stopped. The concern over the availability of low-cost uranium resources for the growing nuclear economy began to relax. This eliminated one of the major advantages of the HTGR. U.S. government concerns over worldwide proliferation of nuclear weapons made the HEU fuel cycle unattractive. Test reactors all over the world were pressured into adopting LEU fuel. The HTGR program, then sponsored by the AEC's successor agency, the Energy Research and Development Administration (ERDA), was redirected from HEU to LEU fuel. Recycle of LEU fuel from the HTGR is much less attractive, in terms of both cost and performance. By 1977 ERDA's HTGR fuel recycle program had been cancelled. The "window of opportunity" for the HTGR appeared to be closed.

In 1979 nuclear utility executives were shocked to learn from the Three Mile Island accident that errors by reactor operators licensed by the Nuclear Regulatory Commission (another AEC successor) could turn a $4 billion asset into a $2 billion liability in a matter of minutes. The Chernobyl accident of 1986 raised additional questions about the safety of traditional nuclear reactor operation. Safety and investment protection replaced construction economics and uranium utilization as the key parameters for judging the quality of nuclear plants.

In response to the new pressures facing nuclear energy, the national HTGR program changed directions through plant redesign. Formerly, the flagship of the HTGR program had been the 2240-MWt plant. Additional design studies had considered plants in the 3000- to 4000-MWt range. In 1987 the Department of Energy (ERDA's successor) shifted its emphasis from such large units to the Modular HTGR (MHTGR).

The MHTGR station concept consists of four modules, each 350 MWt (138 MWe). The annular MHTGR core is a long, slender configuration that permits rejection of decay heat by conduction and thermal radiation to a reactor cavity cooling system (RCCS) in the event of coolant loss. The RCCS operates without pumps, valves, fans, or any other mechanical system that might fail. Heat is rejected to the atmosphere through natural convection. Even if the RCCS becomes disabled, decay heat can be discharged to the ground to keep the core from overheating.

This revolutionary design has invoked a new concept in reactors—"passive safety." Designs employing passive safety measures make use of natural physical laws to protect the plant and the public, instead of requiring elaborate, redundant, mechanical safety systems.

Improved safety is just one benefit of the MHTGR; it is also expected to be easier to operate, standardize, license, and build. Unique design features will be incorporated to ensure higher availability and a longer plant life. The small size of the modular units also permits better adaptability to changes in the demand for electricity. The MHTGR station, rated at 1400 MWt (552 MWe), is only about 43% the size of the standard LWR plant adopted in the United States, Europe, and Japan.

Mike Kania (at keyboard) and Chuck Baldwin check the status of the core-conduction cooldown furnace.

Critics express concern that MHTGR capital costs will be higher than standard HTGR costs because of the smaller scale. However, MHTGR proponents expect the economics of scale to be offset by savings from shop fabricability of components; the elimination of expensive, complex, and redundant safety systems; and standardization that should simplify the licensing process and increase the probability of maintaining a realistic construction schedule, thereby avoiding cost overruns from interest on capital.

During the past 12 years, the HTGR program struggled. DOE frequently did not request funding for the program. Design and technology work proceeded at a bare subsistence level during this period. Even so, GA, ORNL, and the nuclear utility industry worked aggressively to keep DOE and the Congress informed about the advantages of the HTGR.

Today interest in the concept has revived. DOE has selected the MHTGR as one of the reactors to be developed for producing special nuclear materials needed in the nuclear weapons program. In response to the concern over global warming, several bills have been introduced in Congress directing DOE to develop new, safe forms of energy production that do not burn fossil fuels. LWR and liquid-metal–cooled reactor (LMR) advocates are also developing modular designs having passive safety features. Like the phoenix, the HTGR concept of the early 1970s is rising from the ashes in new form for the new age.

ORNL's Contributions

ORNL began technology development for the HTGR concept in the late 1950s with AEC sponsorship for irradiation testing of coated-particle fuels in the Oak Ridge Research Reactor (see article on p. 36). Fuel testing and examination have continued to the present. In the late 1960s and 1970s, ORNL's role expanded to include many other aspects of fuel and materials characterization and development. In addition to the HTGR technology development program, ORNL also managed the HTGR fuel recycle program—also known as the Thorium Utilization (ThU) program—and participated in the Gas-Cooled Fast Reactor (GCFR) program. Specific ORNL contributions over the past 30 years are summarized here, and our current areas of involvement are highlighted.

Irradiation testing of various particle fuel types. The irradiation testing program in the 1970s supported both the HTGR base technology and the ThU program. Fuel particles containing various combinations of uranium, oxygen, carbon, and thorium were tested—UO_2, UC_2, $(U,Th)O_2$ (with varying Th:U ratios), and UCO. Coated particles and fuel compacts were also fabricated and tested. ORNL has helped evaluate fuels for recycle application, for the LEU fuel cycle, and most recently for the MHTGR. The sol-gel process for fabricating dense HTGR fuel kernels was primarily developed at ORNL and is used today in all HTGR programs. ORNL's current focus is on irradiation testing of high-quality LEU UCO, the reference fuel for the MHTGR, under normal operating conditions and simulated accident conditions.

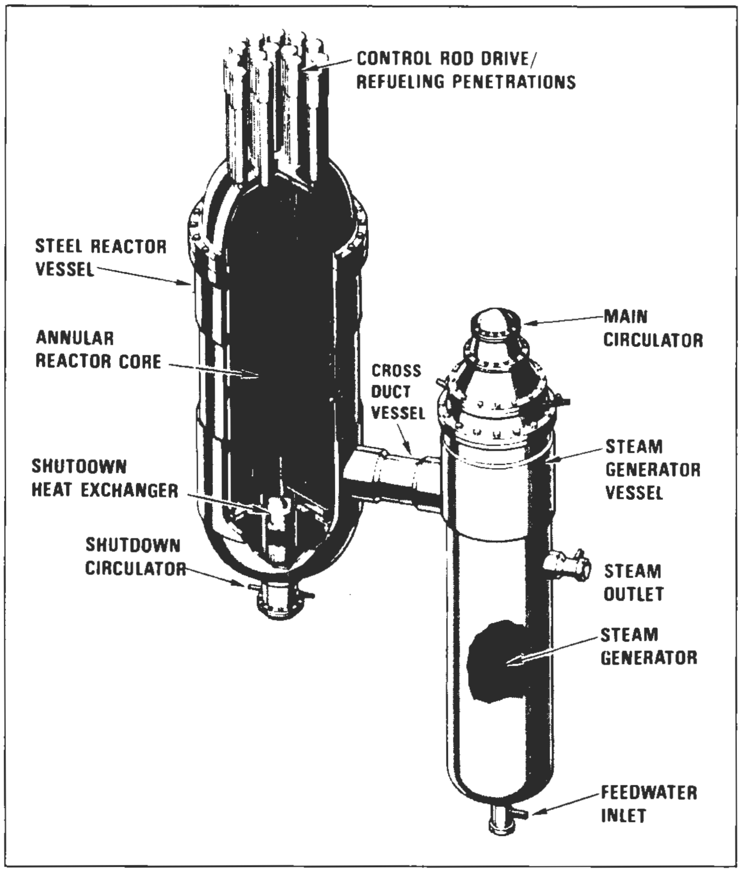
"ORNL analysts, in collaboration with GA and KFA counterparts, have quantified all the major failure mechanisms for coated particle fuels."

Postirradiation examination (PIE) of irradiated fuel. ORNL pioneered development of several procedures for examination of individual coated particles. These procedures include use of electron microprobes, scanning electron microscopes, gamma spectroscopy, and postirradiation gas analyzers. These techniques have been adopted by all national HTGR programs to identify failure mechanisms, and to provide statistically valid measurements of fission product retention. Currently, ORNL is performing PIE and data analysis on LEU fuels in support of the commercial MHTGR program.

Kernel and coating characterization and performance. ORNL analysts, in collaboration with GA and KFA [Kernforschungsanlage Jülich GmbH (Nuclear Research Center, Jülich, FRG)] counterparts, have quantified all the major failure mechanisms for coated particle fuels. These include thermal migration, corrosion of the coatings by rare earth fission products, penetration of the coating by the fission product palladium, pressure-induced failure, and coating matrix interaction. Coating microstructure effects on performance have also been quantified through work at ORNL in collaboration with other researchers worldwide. In the early 1980s ORNL and KFA researchers identified a pyrocarbon coating permeability problem that resulted in replacement of the Biso-coating design (with the Trico-coating design) for fuel particles within the U.S. program.

Fission product behavior studies. From thermodynamic considerations, ORNL scientists have predicted the phases present in oxide, carbide, and oxy-carbide fuel kernels as a function of initial composition and burnup. These predictions have been matched with qualitative metallographic examination results to develop fuel models explaining how these phases influence kernel and coating performance during irradiation. ORNL's current work focuses on measuring fission product release rates from failed particles; determining the chemical form of fission product species; studying the diffusion of metallic fission products through the matrix and fuel element graphite; and the plateout, lift-off, and wash-off of fission products in the primary circuit of the MHTGR.

Graphite characterization and testing. HTGR fuel elements, support structure, and reflector structure are made of graphite, but the properties and dimensions of graphite change because of irradiation. ORNL researchers have tested numerous grades of graphite, measured their mechanical and physical properties before and after irradiation, characterized the irradiation effects, and quantified the statistical variation in properties and quantified the statistical variation in properties within billets and between billets. U.S., German, and Japanese graphites have been studied. The HFIR is an ideal research tool for this type of work, because it is possible to reach full exposure in a few months (compared with 3 to 4 years in an operating HTGR). ORNL's current research aims to provide a full array of property and irradiation data for graphites of interest to MHTGR designers.



Schematic of the 350-MWt MHTGR plant designed by General Atomics.

heat-transport system, steam generator, control-rod cladding, and other reactor internals.

Alloy testing. Unlike the Large HTGR (LHTGR), the MHTGR design includes an LWR-type steel pressure vessel. In the 1970s ORNL and GA pioneered work on analysis of prestressed concrete reactor vessels (PCRV) for the LHTGR. The LHTGR program used a PCRV because steel pressure vessels could not be made large enough to accommodate the large core. With the MHTGR design, the core is much smaller in size (and thermal output) and can fit inside a steel vessel. Thus, the PCRV was no longer needed. Pressure vessels of the type designed for LWRs could be used instead. ORNL is now providing data on vessel steel performance at the temperatures, neutron exposure, and spectral conditions representative of the MHTGR. Data are also being generated for alloys to be used in the heat-transport system, steam generator, control-rod cladding, and other reactor internals.

Shielding analysis. ORNL pioneered the development of large neutron transport codes, which have been applied in the analysis of MHTGR shielding designs, to evaluate the neutron dose to the reactor vessel and other internals. ORNL has also done extensive experiments to validate the shielding design methodologies.

Reactor physics. Reactor analyses of both the pebble-bed and primatic core designs have been done at ORNL. During the past 20 years, ORNL has also evaluated performance characteristics of breeder and advanced converter concepts, annular vs cylindrical designs, large vs modular sizes, and both low-enriched and high-enriched fuels. Large-scale computer codes were enhanced with methods specifically developed for graphite, gas-cooled, heterogeneous-fueled reactor systems.

Advanced materials properties. Current work focuses on advanced, high-temperature alloys of interest for producing direct-cycle electricity and process heat. These alloys are not included in the MHTGR materials matrix.

Safety studies. A comprehensive HTGR safety program plan was developed at ORNL in the early 1970s. Current studies relate to programmatic review of HTGR safety and to safety-related work in international programs.

"ORNL should play a major role in the MHTGR technology development because of the Laboratory's 30 years of R&D experience in the commercial HTGR program."

International Cooperation

ORNL and KFA scientists have collaborated informally for over 25 years on design and technology issues associated with the four HTGRs constructed in the United States and Germany. Similar cooperation exists between commercial organizations in the two countries. In 1977 a formal "umbrella" agreement on GCR technology development was implemented. The original agreement included work on fuels, fission products, graphite, metals, and fuel recycle. The areas of cooperation have since been expanded to include physics experiments in the AVR at KFA, thermal hydraulics methods validation, and safety studies (recently, ORNL and German scientists showed that the AVR could undergo a loss-of-coolant accident without fuel damage).

In the mid-1980s a similar agreement was established between the United States and Japan. Currently DOE and the Japanese Atomic Energy Research Institute (JAERI) are cooperating in fission chamber testing, fuel development, graphite development, and metals characterization.

Agreements between the United States and United Kingdom include an exchange of graphite properties data. Through ORNL, DOE is currently subcontracting with the French Commissariat l'Energie Atomique (CEA) for a series of fission-product behavior studies in the COMEDIE Loop of the Siloe Reactor in Grenoble, France.

New MHTGR Development

Until recently, ORNL and GA have partitioned the responsibility for HTGR technology development, with each organization bringing special facilities and talents to the program. Beginning in 1986, a new arrangement was established for the DOE program, designating GA, coupled with Bechtel National Inc., Stone and Webster Engineering Corporation, and Combustion Engineering to be responsible for MHTGR design. ORNL's responsibility is technology development, and the technology requirements have been arrived at using the following approach:

- The utilities defined specific user requirements
- The NRC defined specific regulatory requirements
- The design team performed a disciplined functional analysis to focus user and regulatory requirements on specific design features
- Data from earlier work were used to develop the specific design features. Where data were not available, assumptions were used (based on LHTGR experience) and design data needs were formulated
- A technology development plan was developed from the design data needs. Specific experiments and analyses were proposed to respond to each data need.

In 1988 DOE selected the MHTGR as one of two technologies to be deployed for production of special nuclear materials (SNM). The New Production Reactors (NPR) Program plans to build a heavy water reactor capable of producing 100% of goal quantities of SNM at the Savannah River Plant, and an MHTGR capable of producing 50% of goal quantities at Idaho National Engineering Laboratory. Both reactors are expected to be producing SNM by the turn of the century. DOE expects the generic safety-related research and development for these two reactors to be performed at its national laboratories. Much of the MHTGR technology developed for the NPR will be shared with the commercial program.

ORNL should play a major role in the MHTGR technology development because of the Laboratory's 30 years of R&D experience in the civilian HTGR program. The decade of the 1990s should be an exciting one for MHTGR development at ORNL.

Coming to Terms with

Breeders and HTGRs

"Refabricating" new fuel elements for reactors.

As in other technical fields, the world of reactor technology sometimes speaks a language all its own. This brief discussion should help define and "translate" some of the terms commonly used by reactor engineers.

Conversion ratio is defined as the ratio of the amount of fuel "bred" divided by the amount of fuel "burned." For commercial light-water reactors, the starting fuel is about 3% uranium-235 (the fissile isotope), and 97% ^{238}U (the fertile isotope, because it can be used to breed new fuel). Plutonium-239 is "bred" through neutron capture in the fertile isotope. During reprocessing the ^{239}Pu can be recovered, along with the unburned ^{235}U, and remotely "refabricated" into new fuel elements that can be returned to the reactor. Thus, in a reactor having a conversion ratio of 0.6, 6 units of ^{239}Pu would be produced for every 10 units of ^{235}U consumed.

When the conversion ratio is >1.0, it is called the breeding ratio. Reactors having a ratio <1 are called "converters," and those having a ratio >1 are called "breeders." A breeder reactor that produces 11 units of ^{239}Pu for every 10 units of fissile isotope (^{235}U or ^{239}Pu) burned has a breeding ratio of 1.1. The surplus fissile material can be used to refuel converter reactors or to fuel additional breeders.

Makeup fuel is the difference between what is burned and what is bred. For example, an LWR with a conversion ratio of 0.6 would require ~4 units of makeup fuel for every 10 units of fissile fuel burned.

HTGRs designed to operate on the highly enriched uranium cycle would have high conversion ratios—mostly because of the use of ^{233}U as the fissile isotope. ^{233}U is the isotope bred from neutron capture in thorium-232. ^{233}U is a "premium" fuel compared with ^{235}U, because of the higher number of neutrons produced per fission reaction. HTGRs operating with low-enriched uranium (<20% ^{235}U compared with 93% ^{235}U) produce much less ^{233}U, and therefore have significantly lower conversion ratios. ornl

Biographical Sketch

F. J. Homan is director of Reactor Programs at Oak Ridge National Laboratory, with programmatic responsibility for the Liquid Metal Reactor, Gas-Cooled Reactor, Light Water Reactor, and New Production Reactor and related technology programs. He received a B.S. degree in metallurgical engineering from Cornell University in 1963 and has done graduate work at the University of Tennessee in nuclear engineering and management science. Since he joined the Metals and Ceramics Division of ORNL in 1967, Homan has held a number of positions, focusing principally on nuclear fuel cycle research and development and waste management.

PIUS-BWR: Concept for a Passively Safe Reactor

By Charles W. Forsberg

Charles Forsberg and his colleagues are studying new reactor safety and design concepts that should improve both the economics and public acceptance of nuclear energy production.

Scientific research is driven by a desire to know how the universe works. In contrast, engineering research is driven by need. The lack of engineering research on horse-drawn carts reflects the lack of need for better horse-drawn vehicles. For nuclear power, the needs are lower capital and operating costs, improved public acceptance of the technology, and the development of nuclear reactors that can be operated successfully and safely anywhere. Meeting these needs becomes more urgent as pressure mounts for nuclear power to play a role in controlling the "greenhouse effect" of carbon dioxide emissions threatening our planet.

Since the Three Mile Island (TMI) accident in 1979, a major goal of reactor designers has been to develop reactors with passively safe systems—that is, safety systems that have no moving parts and require no operator action. In the aftermath of the Chernobyl accident in 1986, passive safety received increased emphasis because of operator error in that accident. Several groups at ORNL, including myself and some colleagues in the Chemical Technology Division, are investigating new concepts for passively safe light-water reactors (LWRs).

One result of this work has been our invention at ORNL of a new reactor—the Process Inherent Ultimate Safety Boiling-Water Reactor (PIUS-BWR). It is one of several design concepts being considered, and its description can provide an understanding of some of the new directions in nuclear power research. The development of the PIUS-BWR concept also illustrates the necessity for an interdisciplinary approach to this type of research problem.

Why Develop A New Reactor Concept?

Our experience with the current generation of U.S. LWRs is mixed. The performance of the nuclear reactor cores within the power plants is good and nuclear fuel costs are low; however, questions have been raised about LWR safety, even though safe operation of LWRs is ensured by:

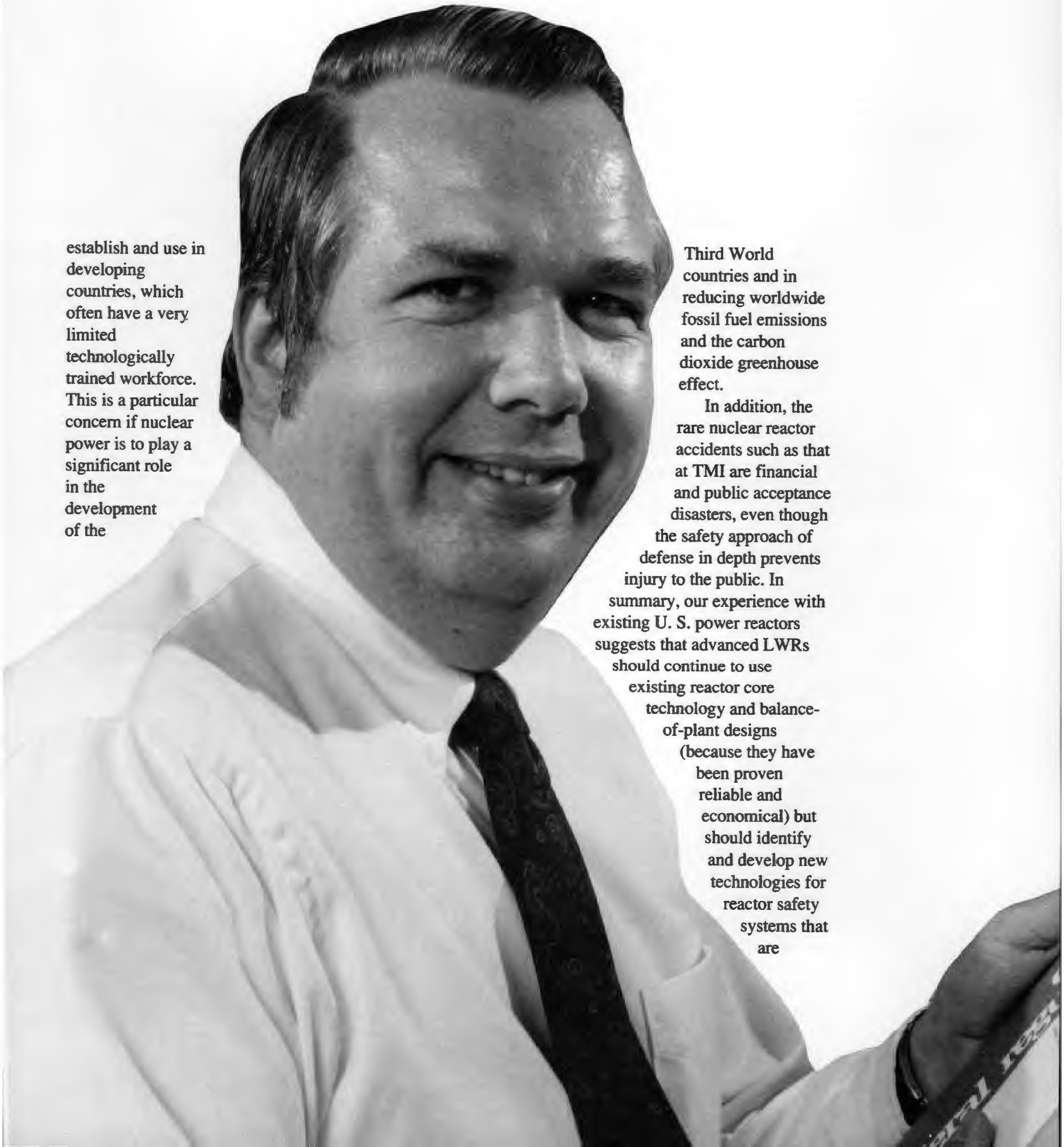
- use of multiple, independent safety systems having pumps, motors, valves, and diesel generators to provide power
- a "defense in depth" design strategy that provides multiple barriers to prevent radioactivity releases to the environment after an accident
- highly trained operating and maintenance crews.

This multiple-backup approach to safety (which is now being adopted by the Soviet Union) has protected the public, even during the TMI accident in which the reactor core melted. Unfortunately, the costs of this approach to safety have been very high.

Improving safety performance to prevent accidents (the current U.S. philosophy) is expensive. At present, the operating and fuel costs of the average U.S. nuclear power plant exceed those of the average coal-fired power station.

The multiple-backup approach to safety also requires complex management and regulatory systems that make nuclear power difficult to establish and use in developing countries, which often have a very limited technologically trained workforce. This is a particular concern if nuclear power is to play a significant role in the development of the Third World countries and in reducing worldwide fossil fuel emissions and the carbon dioxide greenhouse effect.

In addition, the rare nuclear reactor accidents such as that at TMI are financial and public acceptance disasters, even though the safety approach of defense in depth prevents injury to the public. In summary, our experience with existing U. S. power reactors suggests that advanced LWRs should continue to use existing reactor core technology and balance-of-plant designs (because they have been proven reliable and economical) but should identify and develop new technologies for reactor safety systems that are



inherently safe, simpler to operate, and more acceptable to the public. In short, keep what works well and change that which can be improved.

"For reactors of the future, we need a defined set of safety characteristics . . ."

PRIME Safety Goals

For reactors of the future, we need a defined set of safety characteristics that would allow siting of a nuclear power reactor anywhere. We can summarize these characteristics with the acronym PRIME (Passive safety, Resilient operation, Inherent safety, Malevolence resistance, and Extended time):

Passive safety. The reactor should be designed to use only passive safety systems. Because these have no moving parts such as motors, pumps, and valves, the potential for operator error and for many types of mechanical failures is essentially eliminated.

Resilient safety. The reactor safety systems must be resilient—that is, they should not interfere with normal operations or create incentives that could cause them to be bypassed or disabled by operating and maintenance staffs. Historically, the major chemical (Bhopal) and nuclear accidents (TMI and Chernobyl) have involved operator shutdown of safety systems for what were thought to be good reasons at the time.

Inherent safety. Whenever possible, inherent safety features should be incorporated in the design. Materials and structural configurations should be selected to eliminate some classes of accidents (such as those caused by chemical reactions) and their associated safety systems. There is an important distinction between inherent safety and passive safety. A concrete building filled with glass bottles to be recycled is *inherently safe* against fire because a fire cannot occur there. However, a wooden building containing water sprinklers and receiving water from a water tower is *passively safe* against fire; a fire is possible, but the passive safety system can put it out without the aid of motors, pumps, and other mechanical devices. Inherent safety implies no need for a safety system, for an accident is impossible. Because of its radioactivity, a reactor cannot be inherently safe; but it can be made inherently safe against some accidents.

Malevolence resistance. The reactor should be capable of passively withstanding deliberate human acts of sabotage (e.g., a short-term power plant takeover by terrorists or short-term assault with conventional munitions) without significant release of radionuclides to the environment. Plant security for public health and safety should depend primarily on passive, rather than active (guards, security checks, etc.), techniques. In practice, this design objective should also provide passive protection against operator errors and inaction. Because active security measures are a significant operating cost, this feature would be a major economic benefit.

Extended safety. The inherent and passive safety features of the reactor should be designed to ensure safety against major releases of radioactivity for an extended time (>1 week) after an accident or assault, without requiring human intervention.

The PIUS-BWR Concept

Using the PRIME safety goals listed here, we have developed the PIUS-BWR reactor concept. It is similar to current boiling-water reactors in the way electric power is produced (see figure on p. 114): water is fed to the reactor core, where it is heated to steam; the steam is sent to a turbine, which spins a generator that produces electricity; and the steam from the turbine is condensed to water, which is pumped back to the reactor.

However, the PIUS-BWR reactor safety systems are radically different from those of current reactors. The primary safety concern for water-cooled reactors is ensuring that cooling water is present in the core at all times to prevent a reactor core meltdown. The safe shutdown condition in an emergency situation for such a nuclear reactor core is in a large tank of borated water; the water cools the reactor core, and the dissolved boron prevents the reactor from operating.

Submerging a reactor in a large tank of water to ensure reactor core cooling was an idea originally conceived for research reactors, such as the now-closed Oak Ridge Research Reactor (see Bell's article on p. 36 for a history of this facility). The PIUS-BWR uses the same idea and includes an additional one-week supply of emergency cooling water in a tank inside the reactor pressure vessel.

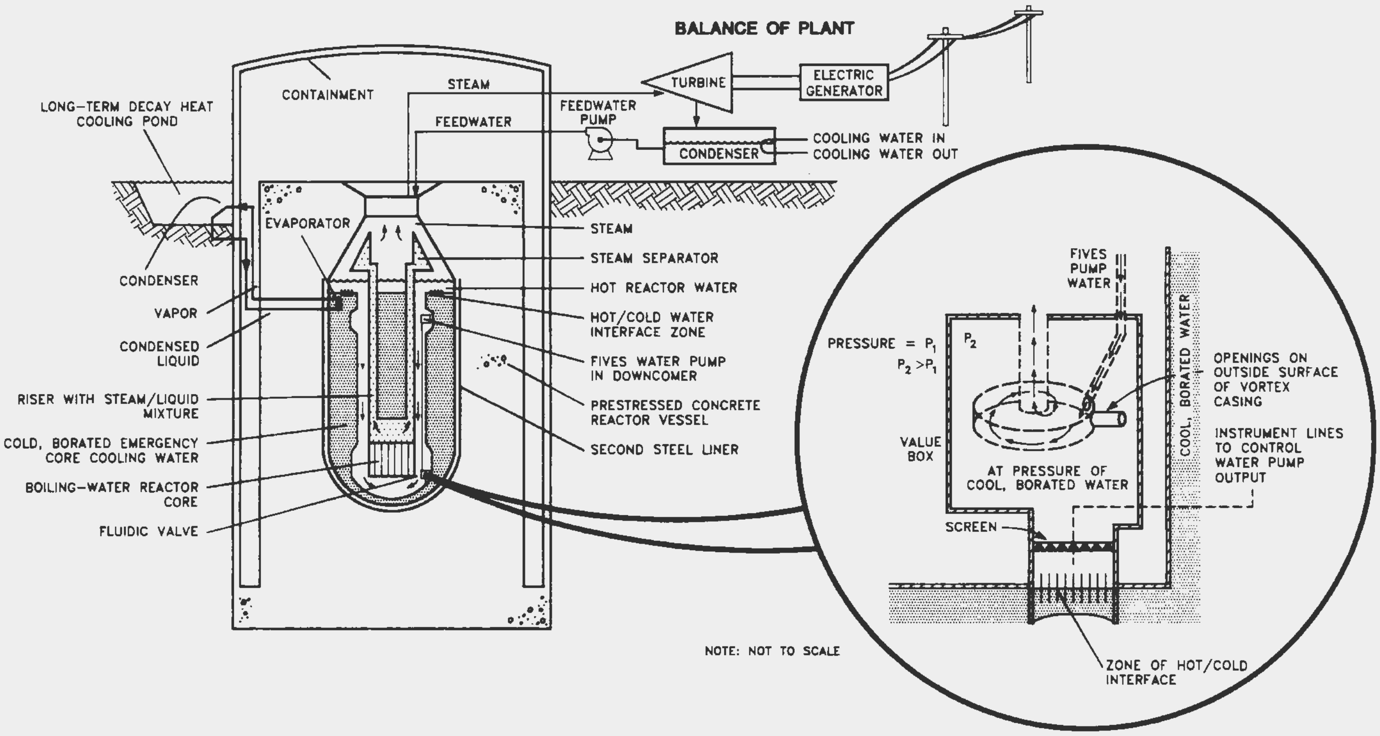
A reactor core sitting in a tank of cold, borated water produces no power, because boron absorbs the fissioning neutrons in the reactor core and stops reactor operation. The reactor needs clean water in the reactor core during normal operation, but the cold borated emergency cooling tank water must be able to reach the reactor core in the event of a clean water shortage. A conventional valve between the borated water and clean reactor water in the tank would serve this purpose, but such valves can fail in an emergency. What is needed is a valve that has no moving parts, yet will open automatically if the reactor core has a clean water shortage.

Such a valve may sound like an impossibility. However, we recognized that valves that cannot fail are needed, and are already being developed, for use in the chemical and oil industries, in nuclear fuel reprocessing plants, at offshore oil platforms, and in other critical industrial areas. Fortunately, research in Great Britain and elsewhere has found ways to build a valve from nonmoving or "fluidic," parts.

In our PIUS-BWR reactor concept (illustrated on p. 114), the pressure vessel is divided into two zones: one containing the reactor core, clean water for cooling the reactor, and other nuclear equipment, and a second zone containing the one-week supply of cold, borated emergency water. If the reactor core is short of water, the borated water enters the reactor core through the "fluidic valve," shuts down the reactor, and removes heat from the core by boiling the water (see schematic inset).

During normal operations, the cold borated water is in contact with the clean reactor water (primary coolant) at two locations. Near the top of the water tank, the two water zones are in direct contact through a hot/cold water interface; the cold, high-density, borated water is heavier and naturally stays below the low-density, clean, hot water. Near the bottom of the water tank, the fluidic valve separates the cold borated water from the clean hot reactor water. The valve remains closed as long as it receives high-pressure water from a water pump located above the reactor core in the clean water. If the reactor water is low or a power failure occurs, this pump fails. As a result, because no high-pressure water is keeping it closed, the fluidic valve opens, and the reactor core ceases to operate when it is flooded with the cool, borated water.

The central component of the passive safety system is the "vortex fluidic valve assembly" (schematic inset). This arrangement is similar to a conventional centrifugal pump having a blocked exit line. The incoming pump water is injected tangentially at high velocities into the vortex casing, causing the water to move in a strong circular motion. The centrifugal forces create higher water pressures (forces) near the outside surface of the vortex valve casing and lower pressures near the inside—the same effect experienced by amusement ride passengers forced back against their seats by the rapid circular movement. The valve's outside surface has holes (short lengths of tubing) that connect it to a zone of clean, higher-pressure reactor water, which, in turn, is in contact with the borated water zone at the bottom hot/cold water interface zone. The center of the vortex valve casing is connected to the reactor's clean primary coolant water below the reactor core and exhausts pump water to it. By adjusting the water-pump output, the pressure of the warmer clean coolant water zone inside the vortex valve can be made to match that of the cold borated water outside the fluidic valve. In this concept, the dynamic force of the moving water, rather than mechanically operated metal parts, prevents water flow through the valve during normal reactor and pump operations. If the pump fails to perform normally in maintaining this pressure, the valve automatically opens, allowing the cold borated water to flow into the core and shut down the reactor's operation.



The PIUS-BWR concept incorporates safety characteristics that would allow siting of this nuclear power reactor anywhere.

Besides the fluidic valve and the large tank of borated water, another safety feature incorporated in the PIUS-BWR design is a leak-free pressure vessel. Such a vessel is needed to overcome two complications: the borated water tank containing the reactor is large (13-m. diam and 25-m height for a 750 MWe power plant), and the water tank must be at a pressure of 6.9 MPa (1000 psi) to produce steam at this pressure for the power plant. Using some existing technologies, Swedish researchers have found ways to build large pressure vessels that maintain their integrity at high steam pressures.

The PIUS-BWR concept includes a prestressed concrete reactor vessel (PCRV) similar to those originally developed for the High-Temperature Gas-Cooled Reactor (HTGR) Program. Basically a reinforced concrete monolith held together by thousands of prestressed steel cables through the concrete, the PIUS-BWR reactor vessel also has multiple steel liners to prevent leaks. From inside to outside of the vessel, the wall is composed of a stainless steel liner, 1 m of reinforced concrete, a second embedded steel liner, and 7 to 8 m of concrete.

This pressure vessel design can withstand both serious accidents and assaults by terrorists using explosives. Because the vessel walls include multiple prestressed cables and rebar, the destruction of individual cables or rebar would not destroy vessel integrity. Similarly, the use of backup embedded steel liners buried under a meter of concrete ensures liner integrity and a leak-tight vessel even during violent events.

Many other innovative components are included in the PIUS-BWR concept. Most of these, like the devices previously described, are based on, or modified from applications in other industries—which is typical of advanced engineering research.

For the Future

Our research has identified and studied several new design concepts and approaches to reactor safety that should prove useful for improving both the economics and public acceptance of nuclear energy production. The PRIME safety criteria and other design goals thought to be impossible a decade ago now appear achievable. Our ORNL-developed PIUS-BWR concept is encouraging evidence that reactor designs more acceptable to the public are possible and that the current worldwide burst of innovative reactor research should lead to safer, more economical nuclear power plants for the future.

Biographical Sketch

Charles Forsberg joined the research staff of ORNL's Chemical Technology Division in 1975. He holds a B.S. degree in chemical engineering from the University of Minnesota and a Ph.D. degree in nuclear engineering from the Massachusetts Institute of Technology. In 1987, Forsberg became manager of the Developmental Light-Water Reactor Program, which is concerned with studying and evaluating new reactor design concepts. He is the author of more than 40 research publications.

Advanced Controls for Nuclear Facilities

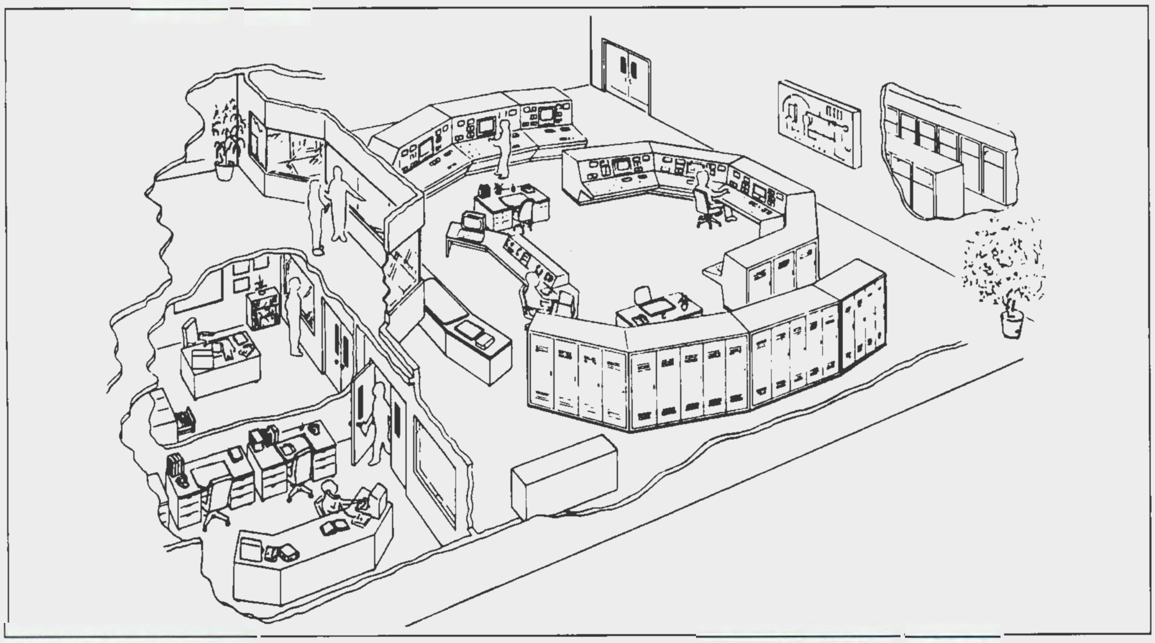
By Jim White

Most U.S. nuclear power plants today have more than 100 individual systems that are, for the most part, manually operated and controlled. Only a few of these systems have any degree of automation, and the technology used is now out-of-date, intolerant of human and instrumentation failures, and lacking the flexibility needed to adapt to changes in operating standards or procedures. The crucial tasks of managing the interactions among both automated and manual systems are left to the human operators. As a result, today's power plant control rooms are filled with alarms, strip chart recorders, dials, and gauges that must be monitored.

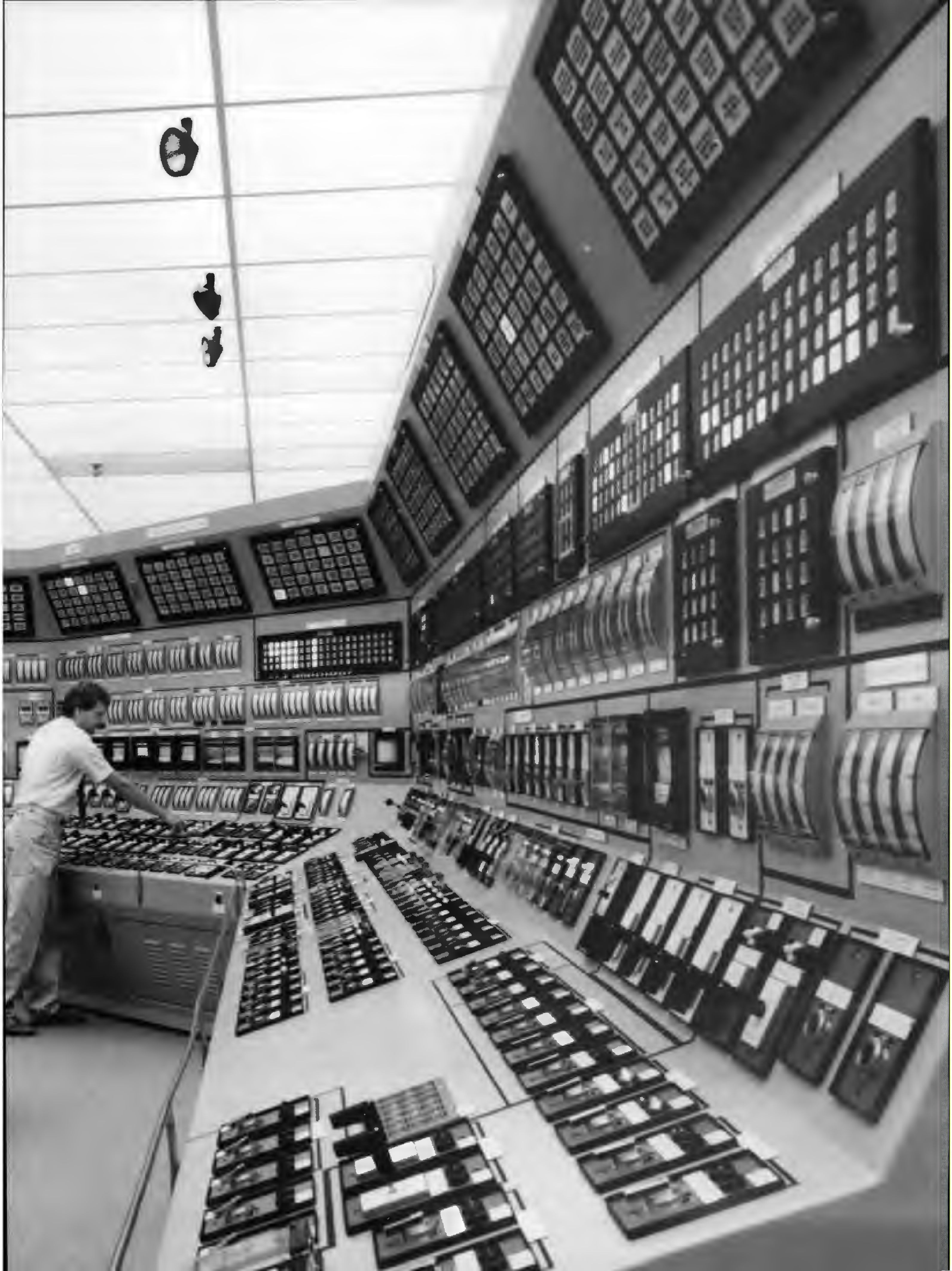
Even in plants using a form of computerized diagnostics to provide early warning of major changes in conditions, prompt operator attention and action are generally required to reestablish satisfactory operation. If the operator is unable to achieve or maintain operating conditions within the prescribed limits, the safety system will automatically shut down the reactor and most of the other power plant systems. Such shutdowns may cost utilities as much as $1 million/day and frequently last for several days while the operators try to determine what went wrong.

Advanced Control Systems Needed

The performance of U.S. nuclear power plants could be improved by using computer-based automation, artificial intelligence, and other advanced control technologies. The Advanced Controls Program at Oak Ridge National



The control room of the future depicted here will simplify reactor operation by having fewer alarms, sensors, and controls such as those in the modern control room of TVA's Watts Bar Nuclear Plant (shown in opposite photo by Frank Hoffman, DOE-ORO).



Laboratory (ORNL) is conducting exciting and important research and development on using advanced control technology to improve the safety, reliability, and economics of reactor operation. Since 1976, U.S. light-water reactor (LWR) power plants have, on the average, operated only ~60% of the time. Nuclear plants in some other countries have a much better record, partly because they use more advanced technology to control plant operations.

After the Three Mile Island incident, the Department of Energy (DOE) and the Electric Power Research Institute (EPRI) conducted extensive surveys of nuclear power plant owners and operators to pinpoint ways to improve the performance of our nuclear plants. Most of those polled indicated that simpler, easier-to-operate plant designs are necessary. Simpler operation should result in fewer operator errors, fewer unnecessary shutdowns, fewer challenges to the plant safety systems, and lower plant operation costs.

With recent advances such as computer-based data acquisition systems, process controllers, fiber-optic signal transmission, and artificial intelligence tools and methods, we now have many of the necessary ingredients for developing large, practical automated control systems. These systems can accomplish all the routine activities of an experienced human operator in an orderly, comprehensive—but much faster—way.

Automated controls can also manage systems that are more complex, simultaneously considering multiple aspects of the situation in a shorter time interval than is possible for a human operator without the aid of automation. Automation does not eliminate the role of the operator at nuclear power plants. Instead it elevates the operator from a "hands-on" role to the position of supervisor, planner, and strategist.

Many U.S. industries—steel, automotive, aviation, electronics, defense, and food processing—have already begun to improve their performance and competitive position in the world market through automation. To compete with other domestic power sources and foreign nuclear plant designs, the U.S. nuclear industry must also employ advanced automation technology in plant construction, maintenance, operation, and control systems.

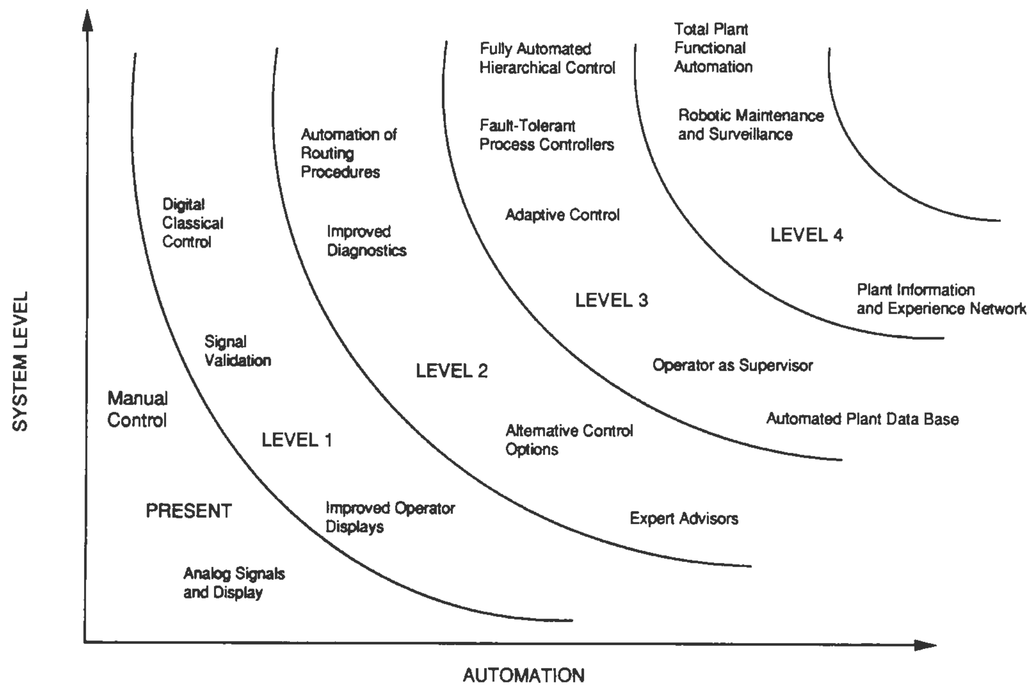
Advantages of Automated Systems

The advent of economical, reliable digital microprocessors has made it possible to design and build much more reliable and efficient operating and control systems. Because more computer memory is available, the control system is much better equipped to deal with sudden changes in conditions or to develop optimal operating strategies as a power plant ages. It also increases the potential for internal system diagnosis and early detection of component failures. EPRI has sponsored several demonstrations of advanced automated systems in operating plants such as the Monticello Boiling Water Reactor in Minnesota, owned by Northern States Power. Operational improvements from automating the feedwater control system at this plant are expected to save ~$500,000 each year. These projected savings are a result of the projected decrease in unnecessary shutdowns. The old feedwater control system had become unreliable because of aging components and non-fault-tolerant design.

A recent analysis by General Electric Company indicates that, by using advanced automation technology, the operating staff for a typical U.S. nuclear power plant could be reduced by about 100 people. This staff reduction would lower plant operating costs by about $4 million per plant year, for a total savings of about $400 million/year if this were eventually done for all 100 operating U.S. nuclear units.

In Canada, computerized control systems are used to provide direct digital control of major systems in 16 full-size commercial nuclear units. The performance record has been excellent, achieving over 84% operating time, partly because of automation. If all U.S. plants operated 84% instead of only 60% of the time, consumers would save more than $8 billion each year in electrical costs.

Planning studies indicate that using the distributed-control approach of these automated



Evolution of automation in nuclear power plants

Automated nuclear power control systems will likely be implemented in phases over several decades.

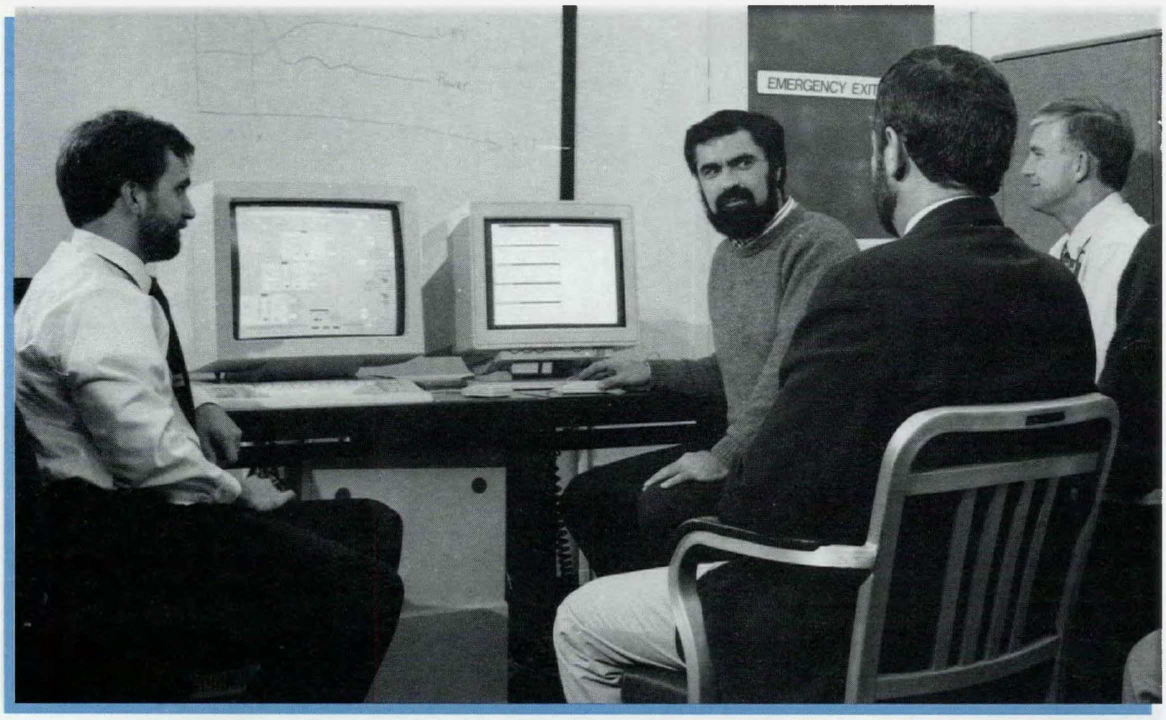
systems would also greatly decrease the amount of control signal wiring needed at a power plant construction site. The new designs could shorten the construction schedule for new plants by 6 to 10 months, again greatly reducing costs.

(Distributed control is a type of control strategy in which several small computers are distributed throughout the plant, and the control responsibilities are allocated to them. In an older strategy, one large computer is given all the responsibility and software; if that computer fails, the system crashes. In the distributed control strategy, if one computer fails, another computer can take over its responsibilities until repairs are made.)

The Japanese have gone even further in high-level control system technology by designing a plant-wide, fault-tolerant, computerized distributed-control system. The design, which has already been validated through simulation studies, will be implemented in ten new Japanese plants scheduled to become operational in the early 1990s. If we intend to remain competitive in the world market for advanced nuclear units, U.S. engineers must develop such advanced, automated systems as well.

Evolving Toward Automation

For the U.S. nuclear power industry, the transition from the current nuclear control systems to future automated designs will likely occur in phases over several decades, as represented in the diagram on this page. During the first phase, many of today's analog controllers will be replaced with more reliable digital controllers having similar capabilities. Automated data management at power plants will also be implemented; computerization of data gathering has already been done to a limited extent in some U.S. LWRs and is being planned for U.S. liquid-metal–cooled reactors (LMRs).



Ray Brittain (left), Pedro Otaduy (center with beard), and Luis Rovere (second row at right) have integrated several advanced control concepts into a supervisory control prototype.

The second stage of the transition will include automation of routine procedures such as plant startup, shutdown, refueling, load changes and certain emergency responses. The plant operators will be helped significantly by computer-based expert systems and control room displays showing the status of various plant systems. Several options of digital control strategies will be available.

A significant advance toward total automation will occur in the third stage, and the operator's role will be to interact with and monitor an intelligent, adaptive, automated supervisory control system. "Smart" sensors will validate their own signals. The process controllers will have the capability of reconfiguring the control logic to meet operational objectives selected by the supervisory control system. These objectives will change as plant operational mode varies from startup to power ascension to load following to shutdown or during operational upsets.

Plant systems will be completely computerized, and plant data bases will be instantly available to the control system and the operator. The operational history of all plant systems and components will be tracked in an automated data base, and the control system will recommend maintenance schedules and outages to the operator. Human performance modeling will be used to develop the optimal allocation of functional decisions so as to keep the operator alert, motivated, and informed about plant status. This is the level of automated control technology planned for the DOE-sponsored LMR concept.

The final stage, total automation of the plant, will include an intelligent control system, aware of the operational status of all systems and interactively communicating with the human operator concerning any degraded conditions, likely consequences of the degradations, and recommended strategies for minimizing the deleterious consequences. At this stage, most plant functions will be automated and robotized, including maintenance and security surveillance. The control system will be integrated in the national network of commercial power plant systems. Computers in the network will exchange relevant information concerning component operational experience and will alert the operator if such experiential data is relevant to the local plant. This level of advanced control technology, however, will not be reached in the United States for many years.

Advanced Controls Program Established

The September 1985 report of a 1985 DOE task team that studied this problem recommended establishing an Advanced Controls Test Operation (ACTO), a centralized, multiuser capability for designing, testing, and validating current and advanced nuclear power plant designs and designs for space-based nuclear power systems. According to the task team, this support capability is not currently available and not likely to be provided by industry because of the long-term high financial risks.

ORNL's unique strengths in control system design and analysis have led DOE to establish the Advanced Controls Program here. The program focuses on research to support advanced, automated control systems for a new LMR reactor design being proposed and sponsored by DOE. This new reactor concept includes a plant composed of nine small LMRs having a total power output of ~1100 megawatts (MW)—about the same as existing large water-cooled power plants. The lead designer, General Electric, has recognized the advantages of today's advanced technology and has specified that the plant will be almost totally automated.

ORNL's Advanced Controls Program plan will ensure a proper technological approach for achieving the automation in advanced reactors proposed by DOE. Providing national leadership in this development, the ORNL program will support four major kinds of activities: (1) establishing a control systems design environment and facilities, (2) demonstrating advanced control system designs, (3) testing and validating advanced control system designs by simulation, and (4) developing guidelines for control system computer codes and control hardware specifications. These activities will lead to the ACTO capability recommended by the previously mentioned DOE task team report.

Demonstrating Designs

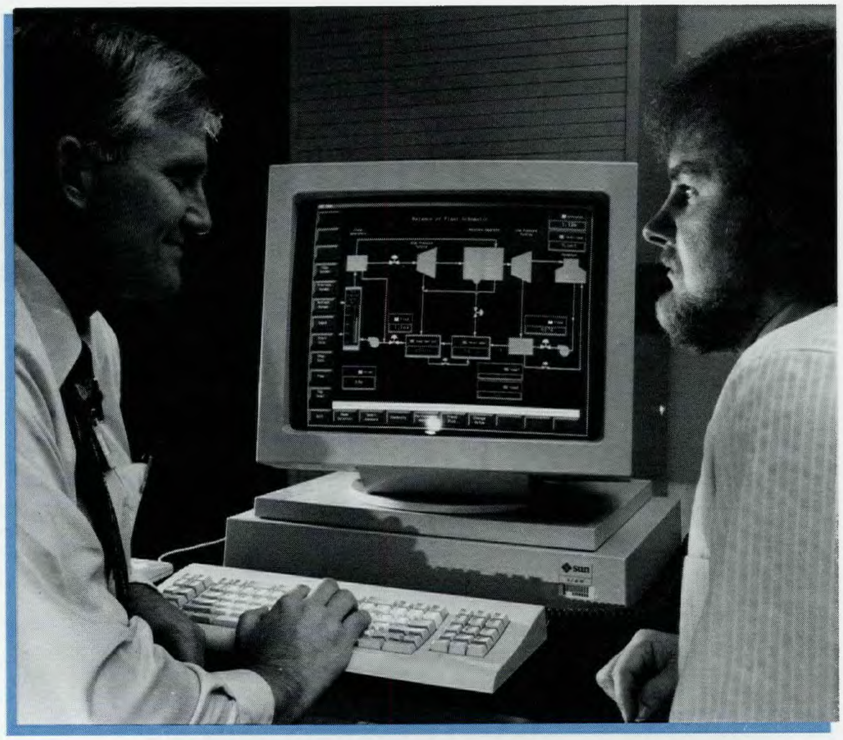
The Advanced Controls Program will first conduct demonstrations of prototypic advanced control system designs for selected aspects of the new LMR concept. Initial demonstrations will be done at ORNL using computer simulations. When possible, later demonstrations will be carried out on existing in-house research reactors at ORNL and at the LMR Experimental Breeder Reactor-II in Idaho Falls, Idaho. These demonstrated prototypes will be used by designers of DOE's new advanced LMR (ALMR).

"ORNL's unique strengths in control system design and analysis have led DOE to establish the Advanced Controls Program here."

The ALMR (and some other new designs of reactors) will incorporate multiple modules whose combined output will meet the projected electricity demand. This approach is used to increase the reliability of the plant. If one module is shut down for unexpected reasons, or for planned maintenance and for refueling, the other module can continue operation. One promising advanced control strategy for simplifying the job of the operator in this situation is the use of a hierarchical (layered) control structure, with each level of control supervising (and integrating) the controllers on the next lower layer of the hierarchy. Pedro Otaduy of ORNL's Engineering Physics and Mathematics Division, Ray Brittain of the Instrumentation and Controls Division (I&C), and Luis Rovere, a visiting engineer from Argentina, are developing such a hierarchical control strategy for the advanced LMR design.

Richard Wood of I&C is leading a demonstration of how advanced digital control and improved smart sensors can provide better control of the balance-of-plant group of systems—those involved in producing steam and, subsequently, electrical power from the heat generated in the reactors. Incidents originating in the balance-of-plant systems cause a significant reduction of the plant availability of conventional LWRs having the current analog control systems.

Syd Ball and Roger Kisner, both of I&C, are leading a project to develop and demonstrate software programs and control strategies for



Ed Ford (left) and Richard Wood are developing an advanced control system for the nonreactor part of the power plant.

automated control system strategies. In addition, man-machine interaction models and guidelines are being developed for use in designing control system interfaces with human operators.

Jim Robinson and Ed Ford of I&C are developing the controls analysis workstation, which includes a desktop computer and software providing the designer full capability from design of the control system through simulation to generation of computer codes.

As increased levels of automation are introduced into the design of complex systems, explicit attention must be given to the roles humans will play within the overall control system. Designers must integrate the characteristics of the hardware, software, personnel, and the environment in designing reactor control systems for maximum levels of safety, reliability, and economy.

Bill Knee and Jack Schryver, both of the Engineering Physics and Mathematics Division, are developing the needed human factors guidelines. During iterations of the system design, the impact of multiple human factors issues on overall system performance must be considered simultaneously. A state-of-the-art computer model of human cognitive behavior is being developed for use in this type of integrated analysis. Human factors issues being considered include: How much information is necessary for the operator to do the job and how much is too much to grasp? How much automation is helpful and how much is harmful because it makes the operator feel out of touch with the process? What are the roles of the operator and how do they change during operational upsets?

automated startup of the ALMR proposed by DOE. The startup of reactors, especially power plant reactors, is normally a complex process. Automated control systems should help speed and simplify this process. At ORNL, Amanda Renshaw and Ed Ford, both of I&C, and Raquel Corcuera, a visiting engineer from Brazil, are designing operator aids for the automated reactor startup project.

Advanced Design Environment

A centrally located, user-friendly, control systems design environment will be set up at ORNL as part of the Advanced Controls Program, with facilities provided initially for control system designers within the DOE community and, later, for industry users. Networked, intelligent, computer workstations are being designed that have advanced software tools and graphics capabilities. Plant and component models and data bases useful for control system design and plant simulation will be provided, as well as information resources concerning

Design Testing and Validation

The ability to simulate an entire plant in real time is critical to the design of a fully automated plant control system. Syd Ball and John Munro of I&C are integrating advances in computer architectures, software engineering, very-high-level computer languages, area networking, artificial intelligence, and data base management into a whole-plant, real-time nuclear power plant simulation capability.

The development of simulation modules and supporting data bases is another fundamental aspect of the Advanced Control Program, permitting control system designers to easily simulate the particular plant or part of the plant required to validate their design activity. The current modeling effort, led by Tom Wilson and Richard Wood of I&C, addresses the DOE-sponsored ALMR design.

ORNL has unique capabilities in the area of advanced control strategies. For many years, I&C personnel have conducted or sponsored graduate research in control system mathematics. Roger Kisner of I&C is currently collaborating with researchers at several universities to ensure that the best control techniques are available for testing and demonstration.

Program Interactions

The issues and research addressed by the Advanced Controls Program are also important to several other organizations. Exciting interactions with other researchers have resulted, and the research funding support is beginning to broaden. The joint DOE/EPRI ALWR project is only one example.

Another opportunity for interaction in this area comes in the request by a group of utility companies for assistance in upgrading their existing analog control systems with digital controls. Contract negotiations are complete on the project and are awaiting DOE-ORO approval.

We are also assisting in other DOE work, such as the New Production Reactor Program and the Advanced Neutron Source Program. Some NRC-sponsored, Modular High-Temperature Gas-Cooled Reactor work is also beginning to use some of our Advanced Controls Program facilities. We look forward to even greater expansion of our efforts in the future. ornl

Biographical Sketch

James D. White is manager of the Advanced Controls Program of the Instrumentation and Controls Division. Before assuming this position, he coauthored the *Nuclear Power Options Study*. 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 worked 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. From 1978 to 1980, White was group leader of ORNL's Thermal Hydraulics Program, which studied conditions associated with loss-of-coolant accidents in light-water reactors. White holds an M.S. degree in nuclear engineering from the University of Tennessee.

Global Warming and Nuclear Power

By John E. Jones and William Fulkerson

Average annual gaseous emissions from the tall stacks of the Kingston Steam Plant (facing page) include 79,000 tons of SO_2, 27,000 tons of NO_x, and almost 10 million tons of CO_2. More than 90% of this plant's SO_2 emissions are trapped by collectors in the stacks. One of TVA's 11 coal-fired power units, the Kingston plant burns about 10,500 tons of coal per day (coal pile in lower right represents ~40-day supply).

Inset: Global CO_2 emissions from fossil fuel combustion have more than tripled in the past 35 years.

Nuclear power currently makes an important contribution to the world's energy requirements, providing 17% of its electricity (21% of that used in the United States). But as global warming resulting from an intensified "greenhouse effect" becomes of greater concern, both the potential and the need exist for nuclear power to contribute even more. The question is whether nuclear power will achieve its potential.

Increases in the concentrations of carbon dioxide (CO_2) and other infrared-absorbing gases are believed to be causing a gradual warming of the planet. The ultimate climate changes that may result from this accelerated heating effect are still largely unknown. The increase of carbon dioxide emissions results primarily from burning of fossil fuels and burning of trees in the process of deforestation.

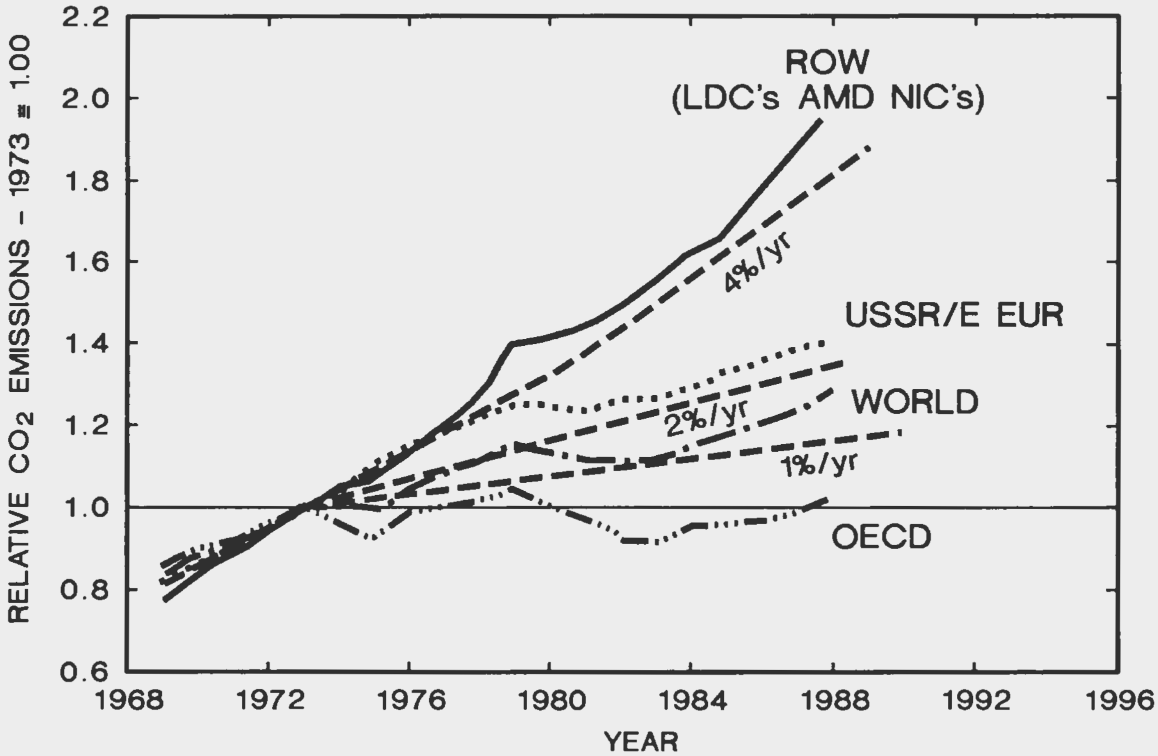
Atmospheric concentrations of other greenhouse gases, such as the chlorofluorocarbons (CFCs), methane, and nitrous oxide (N_2O), are also increasing. In 1987, an international agreement to control emissions of CFCs was signed in Montreal. It is likely that this effort will continue and that these gases will be controlled, not because of their contribution to global warming but because of the impact CFCs have on destroying the stratospheric ozone that protects life on Earth from excessive ultraviolet radiation in sunlight. The increases in N_2O and methane in the atmosphere that have been observed over the past two decades are likely attributable to anthropogenic causes, but their sources and sinks have not been characterized sufficiently to allow an obvious control strategy.

It appears probable, however, that we must make international efforts to control carbon dioxide emissions—which will be expensive and difficult to achieve. To accomplish control while ensuring an acceptable energy supply for both the industrialized and developing countries will require better energy technologies and an unprecedented level of international cooperation on energy system planning. For the immediate future, fossil fuels likely will remain the predominant energy source. In the longer term, nonfossil sources are essential for a sustainable world energy system, and nuclear power can play an important, if not dominant, role.

The challenge is to design and implement a safe and economic international nuclear power enterprise that will be socially acceptable and complementary to other nonfossil energy sources. The elements of such an enterprise should include: (1) safer reactors (preferably designs that are passively safe and deployable at various scales), (2) development of technologies to extend the resource base, (3) effective and permanent waste management strategies, and (4) strengthened safeguards against diversion of nuclear materials to weapons. Of course, all of this must be accomplished at competitive costs. These efforts can best be developed as cooperative international projects. In the process, institutional improvements are equally as important as technological improvements; the two must proceed hand-in-hand.

To fulfill its role in a balanced, resilient, international energy system, nuclear power must gain worldwide acceptance as a viable energy option at larger scale. New initiatives in the major nuclear technologies [light-water reactors (LWRs), high-temperature gas-cooled reactors (HTGRs), and liquid-metal–cooled reactors (LMRs)] are currently emerging from a fundamental re-examination of nuclear power in response to the challenges and opportunities in the 21st century. The use of modern technology and "passive" safety features in next-generation nuclear power plants offers the potential to simplify their design and operation, enhance their safety, and reduce the


CO2 PRODUCTION (billion tons of carbon)
6
5
4
3
2
1
0



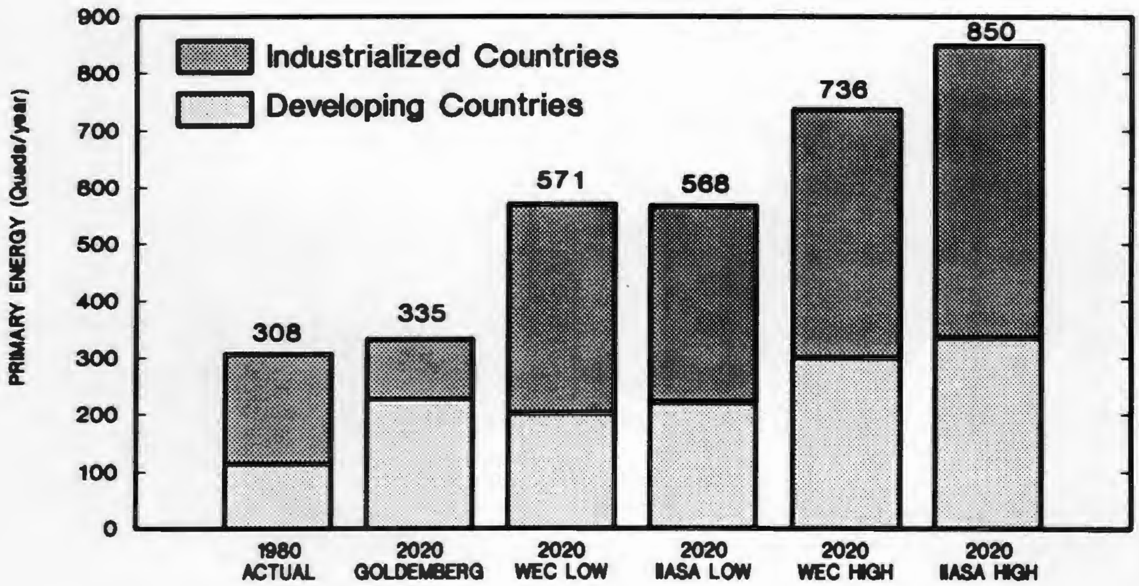
The Arab oil embargo slowed the growth rate of CO_2 emissions, shown as relative emissions by various nation groups: Organization for Economic Cooperation and Development (OECD) nations, Soviet Union and East Europe, and the rest of the world (ROW), which includes less developed countries (LDCs) and newly industrialized countries (NICs). Source: Computed from data in *BP Statistical Review of World Energy,* British Petroleum Company, June 1989.

cost of electricity. We believe these factors, together with improvements in the management and regulation of the nuclear enterprise, will enable nuclear power to regain public confidence and make a significant contribution to our energy future.

Toward A New Energy Strategy

Except for a remarkably brief flurry of activity after the Arab oil embargo in 1973, energy technology needs for the future have not been a high-priority issue in the United States. Haunted by uncertainties about demand growth and in the political, financial, and regulatory arenas during the last two decades, utility decisionmakers are increasingly wary of major expenditures for capital facilities. During the past few years, the availability of oil and gas at relatively low prices has lulled us into accepting the ever-accelerating use of fossil resources. Our nation is beginning to recognize, however, that we cannot continue to disregard the strategic and economic vulnerability associated with dependence on oil imports; nor can we ignore the increasingly ominous atmospheric changes resulting largely from an energy system based on fossil fuels. Fundamental global factors such as acid rain and the greenhouse effect with its potential for worldwide climate changes, the need to narrow the gap between developing and industrialized countries, and the new relationships between eastern and western nations taking place as a result of "glasnost" and "perestroika" have made it imperative that we approach the development of long-term energy strategy at this time from an international perspective.

Shortly after taking office, President Bush announced that a new national energy strategy will be developed. That process has been initiated by Secretary of Energy Admiral James Watkins and his staff. ORNL and other national laboratories are currently participating in the extensive analyses that will contribute to the development of this



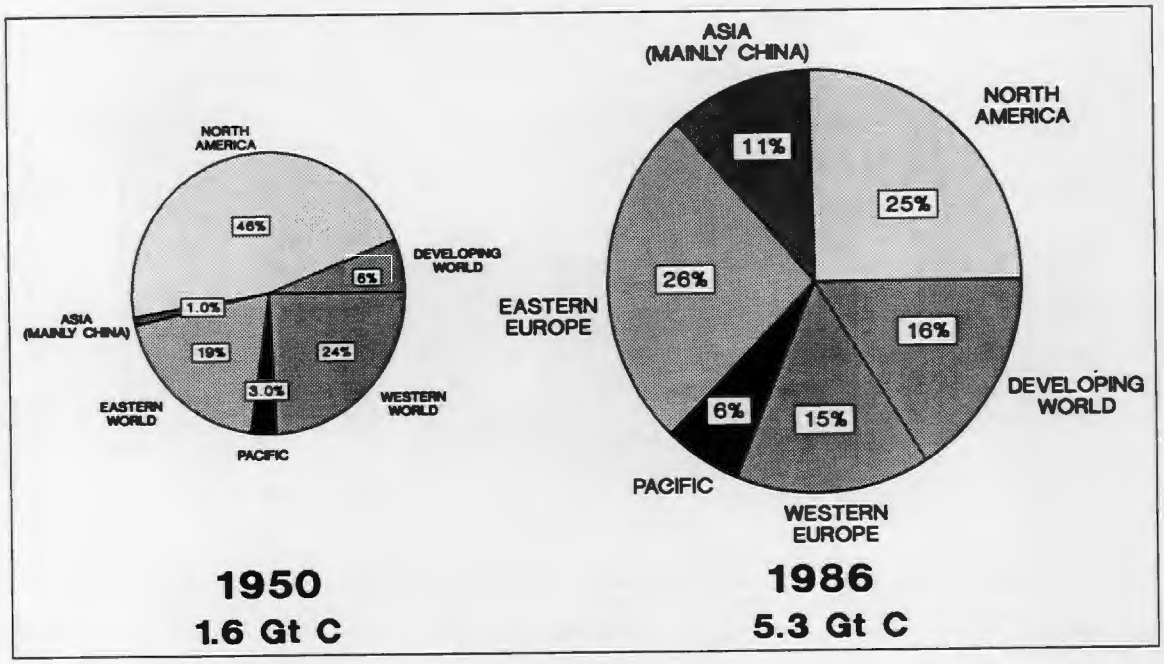
Alternative projections of global energy use by industrialized and developing nations include those by the World Energy Conference (WEC) and the International Institute of Applied Systems Analysis (IIASA). Source: Goldemberg et al., 1988.

strategy (see sidebar on p. 145). It is a particularly appropriate time for this "new look" at long-range energy planning, because of recent significant changes in the world political situation and because of our growing knowledge about the interrelationships between our world energy systems and the disturbing changes observed in the global atmosphere.

Energy research and development policy is confronted by two major uncertainties regarding future energy technology needs: (1) the rate at which energy demand will grow and (2) the urgency of controlling the greenhouse effect and other environmental, health, and safety problems. To allow for these uncertainties, it is important to have a balanced energy strategy that focuses on both improved energy sources and better end-use efficiency.

Whatever the future holds, developing more efficient energy technologies is an economically attractive approach to many problems facing both U.S. and world energy systems. Improved efficiency can reduce the costs of providing energy services, contribute to international competitiveness, help manage the environmental impacts from energy conversion and use, and improve energy security. However, despite the large and generally unanticipated efficiency improvement achieved by the United States and other industrialized nations over the past decade and a half, the rate of future progress is uncertain. For this reason, and to help correct existing and anticipated future environmental problems with the current energy system, it seems imperative that we significantly improve our energy supply technologies as well, especially in nonfossil sources. We need a new energy strategy with sufficient options to support world economic growth, respond to evolving environmental constraints, and recover quickly from disruptive and unanticipated political or natural events.

The current U.S. energy technology R&D efforts are, we believe, sufficiently broad. We are working, at some level of effort, on most of the promising options. Unfortunately, none of these technologies is currently developed to the point of being economically and safely substituted worldwide for the use of fossil fuels. In this article we focus on nuclear fission, which is the nonfossil energy source most nearly ready for large-scale deployment and the only one that currently offers the potential for significant energy production at economically viable prices.



Patterns of CO_2 emissions have changed considerably in recent years, as Third World countries have increased their industrial development.

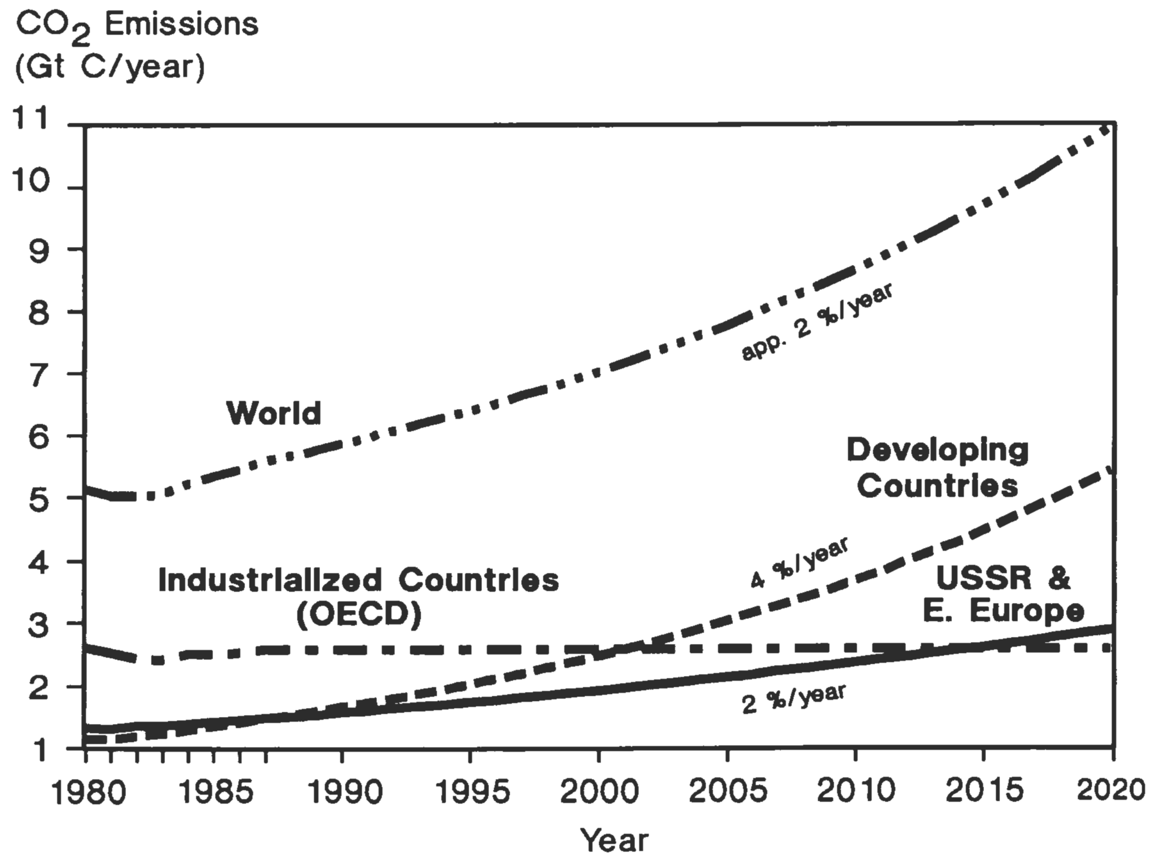
The Difficulty of Reducing CO_2 Emissions

First, however, we need to appreciate the magnitude of the problem of reducing global CO_2 emissions. The following facts may help give the proper perspective. Nearly 90% of the world's commercial energy needs are currently met by burning carbon-based fossil fuels. Since 1950, total global CO_2 emissions to the atmosphere from fossil fuel combustion have increased from 1.6 gigatons carbon/year (Gt C/year) to 5.3 Gt C/year, according to studies by the Electric Power Research Institute published in 1988.

To prevent a continuing increase in the atmospheric concentration of CO_2, the world's total emissions of the gas cannot exceed the estimated ability of natural sinks to absorb CO_2. *Cutting global CO_2 emissions sufficiently to accomplish this may require more than a 50% worldwide reduction in fossil fuel use and perhaps as much as an 85% worldwide reduction.* We are not currently optimistic about the prospects for capturing and sequestering any significant fraction of CO_2 from fossil fuel combustion. Gaining a better understanding of what the maximum allowable emission rate might be under various circumstances is an urgent research priority and will undoubtedly be one of the goals of the new Center for Global Environmental Studies recently established by the Department of Energy at ORNL.

During the same time period that fossil fuel use needs to be drastically reduced, the world's appetite for energy services is expected to grow to accommodate a global population of over 6 billion by the year 2000 and 8 billion by 2025 and to allow a continuing improvement in the quality of life for people of the world, especially in the developing countries. The associated increase in global GNP per capita is estimated to be 1.4% to 2.9% per year through 2025, according to a 1987 report by the World Resources Institute.

How might such a drastic reduction in CO_2 emissions be achieved? Since the Arab oil embargo, the world has at least begun to reduce the rate of increase of these emissions (see figure on p. 126). Although worldwide emission rates were rising about 4 to 5% per year before 1973, they have been rising at between 1 and 2% per year since that time—principally because the emission rates of the Organization for Economic Cooperation and Development (OECD) nations



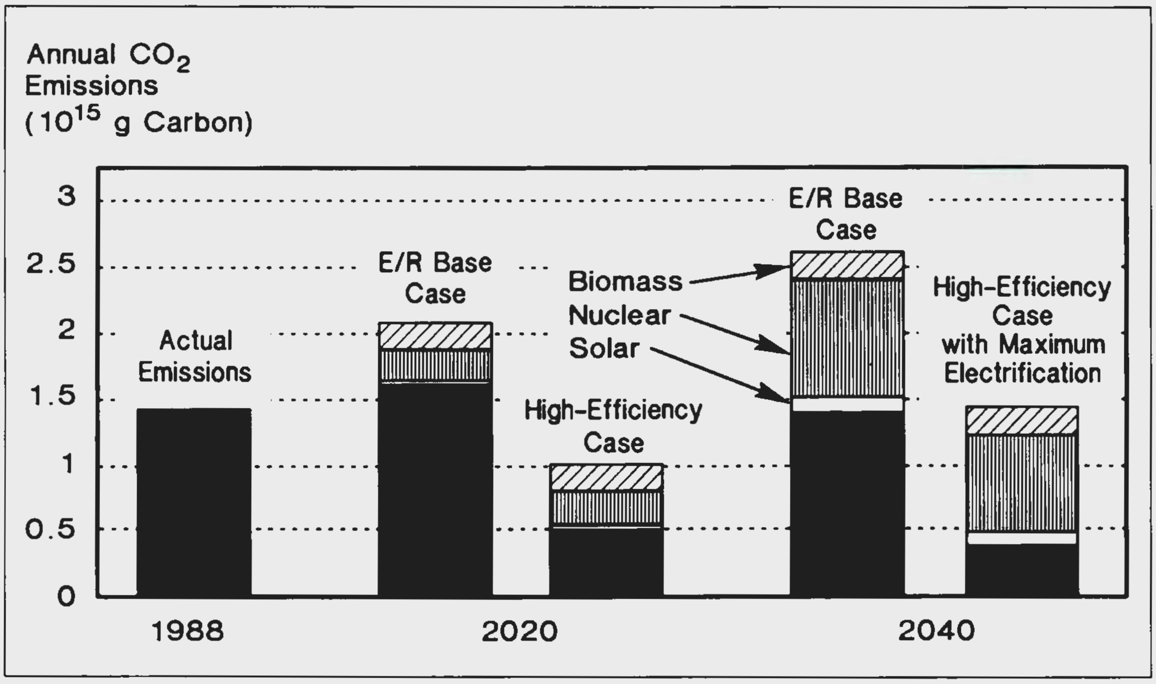
Extrapolating the average growth of CO_2 emissions for 1977 to 1987 shows the importance of developing countries. About two-thirds of the CO_2 emissions from ROW countries in 1987 were from the LDCs, including China and India.

have not increased. Also, emission rates of the Soviet Union and the eastern European bloc have moderated. On the other hand, emission rates of the rest of the world, the developing world, including China, have increased as if an Arab oil embargo had never occurred—currently at the rate of about 4% per year.

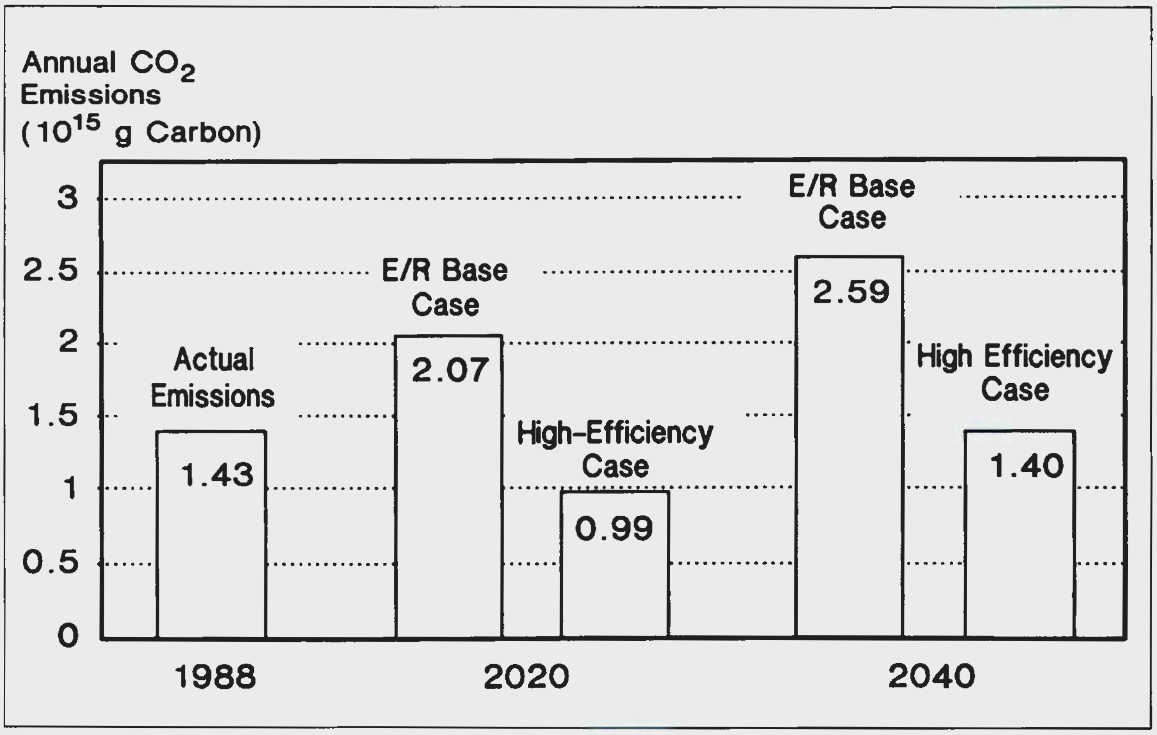
A simple extrapolation of the behavior of these developing nations during the past decade indicates that their emission rates will exceed those of the OECD nations by the turn of the century and thereafter will dominate (see figure above). Thus the energy choices made by developing countries will be exceedingly important in controlling future changes in the global environment. Also, if the increase in emissions of greenhouse gases and the related global climate changes are to be kept under control, the industrialized nations must take aggressive action to control their own emissions to offset the future increases from the developing world.

Can the industrialized world reduce CO_2 emissions? Of course, reductions are possible, if we are willing to pay a good deal more for energy than we do currently and if we will be satisfied with slower economic growth than we have enjoyed in the past few decades. But we are interested in a solution that does not require such sacrifices. Curtailing emissions by reducing fossil fuel use without paying higher energy costs and without drastically slowing economic growth will require much better energy technologies. Two technology improvement strategies are required: learning how to use and convert energy more efficiently and improving nonfossil energy systems, especially nuclear power, to a degree that they can be economic energy sources on a large scale and still be socially acceptable from the standpoint of safety and environmental impact.

The lower bar chart shown on p. 130, which compares CO_2 emission rates for two ORNL energy forecasts for 2020 and 2040, illustrates that a great deal can be accomplished by improving the efficiency of energy use. Both scenarios assume essentially the same growth in the economy and population. To show the effect



Curtailing U.S. emissions of CO_2 from fossil fuels will be difficult. Nuclear, solar, and biomass energy will all be needed for a sustainable reduction.



Improving energy efficiency in the United States can reduce CO_2 emissions from fossil fuel combustion. Base case forecasts are derived using the Edmonds-Reilly (E/R) model.

World Primary Energy Sources Needed In 2040 (TWyr/yr)

	Fossil Sources	Non-Fossil Sources				Total
		Hydro	Nuclear	Biomass	Solar and Other Renewables	
1988 Actual	9.4	0.71	0.6	~1.3	<0.1	12.0
2040 Scenarios						
ORNL-High Efficiency	3-5[a]	1-2	7-2[b]	3-4	1-2	15
ORNL-Base Case	18-10[b]	1-2	2-7	3-4	1-2	25
EPA-SCWP	8	2	1	2	1	14
EPA-RCWP	9	2	2	5	2	20

[a]Estimated fossil fuel ration
[b]Obtained by difference

Possible world energy supply scenarios for 2040 (in terawatt years per year) have been developed by ORNL and the Environmental Protection Agency [for a "slowly changing world with stabilizing policies" (SCWP) and a "rapidly changing world with stabilizing policies" (RCWP)].

of efficiency improvement alone, our calculation of emission rates assumes that nonfossil energy sources will not increase from their present levels over the next 50 years, except for some increase in hydropower. These emission rates (tops of the bars) are projected to be 2.07×10^{15}g C and 2.59×10^{15}g C for 2020 and 2040, respectively, unless evergy efficiency is greatly improved.

In the table shown here, we make some very crude estimates of how this primary energy might be supplied. To reduce the CO_2 emissions to about half their present level, we assume a fossil fuel ration for the world between 3 and 5 TWYR/year; currently it is about 10. Worldwide, we assume that hydropower can produce between 1 and 2 TWYR/year, biomass can produce 3 to 4 TWYR/year, and solar and other renewables, 1 to 2 TWYR/year. We then assume that nuclear power will make up the difference between total demand and the sum of these other energy sources. In the high-efficiency case, nuclear power must supply between 2 and 7 TWYR/year; in the base case (25 TWYR/year), it will need to supply a whopping 12 to 17 TWYR/year, which we believe is unrealistically large. Hence, the 3 to 5 TWYR/year fossil fuel ration assumed for the base case probably cannot be maintained.

In the high-efficiency case, which represents the very best we could reasonably expect to do, the emission rate could actually decrease by 2020 if society universally adopts the most efficient technology available that is economical. Reaching such a state would require aggressive government encouragement, as well as continuing improvements in the technologies available. Furthermore, efficiency improvements will have diminishing returns. To capture this expectation, we assumed, for the 2040 case, that technical efficiency is the same as for 2020, except that the

"For the United States, CO_2 emissions cannot be significantly reduced on a sustained basis without combining very high-efficiency energy use with very hefty growth of all the nonfossil energy power sources, including nuclear power."

trend toward less energy-intensive industry continues. A recent study headed by Roger Carlsmith, director of the Conservation and Renewable Energy Program at ORNL, indicates that our 2020 high-efficiency scenario may be too optimistic. Holding U.S. CO_2 emissions constant is probably the best we can expect to achieve with efficiency improvements alone, and even that will require aggressive government supportive action.

Sustaining an actual *decrease* in emission rates, rather than just keeping them constant, will take increased use of nonfossil sources, in addition to higher efficiency. As previously mentioned, none of these sources is currently ready to substitute economically for fossil fuels on a large scale. The best in the bunch is nuclear power, which is currently constrained by concern over a number of issues, including cost uncertainty, safety, waste disposal, and (in the United States, particularly) operational unreliability, as well as a stringent and changing regulatory environment. Should the nuclear establishment grow internationally to a much larger size, safeguards against terrorism and nuclear weapons proliferation will become a more pressing concern. However, the other nonfossil energy options, such as biomass and hydropower, are resourcelimited. Solar electric and wind technologies are intermittent and costly. Geothermal is geographically constrained and, in most cases, expensive to develop.

The figure at the top of p. 130 represents our estimates of the best we might expect in reducing CO_2 emissions by using nonfossil energy sources over the next 50 years, assuming that research and development is successful in making them more competitive. We estimate that in the United States by the year 2020, biomass could sustainably supply 10 quads of liquid fuels from about 20 quads of primary biomass fuel, and nuclear power could be increased by a factor of 3. This assumption is based on a new generation of reactors including light-water reactors (LWRs) incorporating passive safety features and passively safe reactor designs such as the Modular High-Temperature Gas-Cooled Reactor (MHTGR, see Homan's article on p. 102).

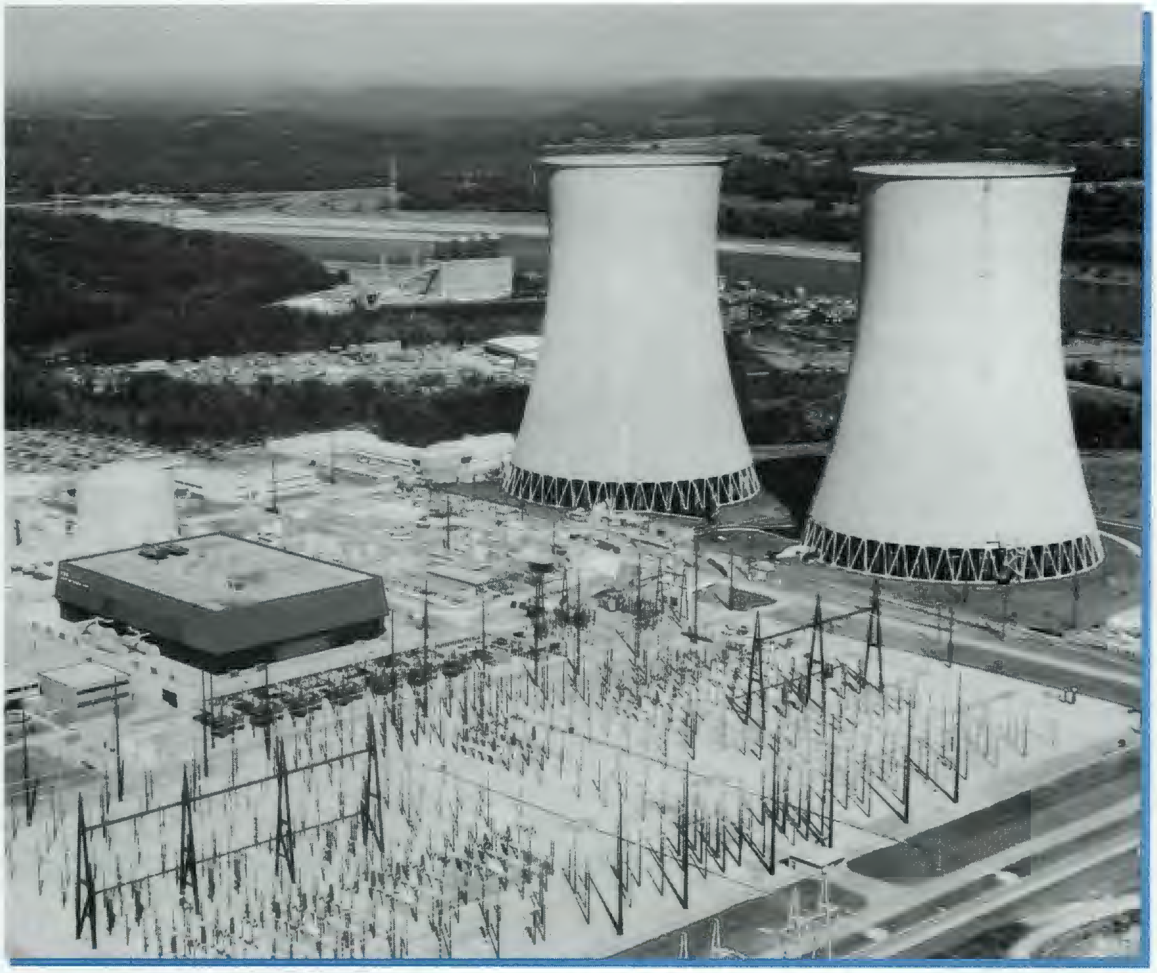
By the year 2040, we estimate that nuclear power generation in the United States could increase by a factor of 9 from present levels. That would require annual additions to capacity similar to the power plant building rates experienced in the late 1960s.

The situation for the world as a whole is qualitatively similar to that for the United States. Assuming that the economies of other nations, particularly developing nations, continue to grow and the world population also grows (but at a gradually declining rate), the demand for energy services 50 years from now will be much larger than it is today. Based on various forecasts, we might expect demand for primary energy to be in the range of 15 to 25 terawatt years per year (TWYR/year; 1 TWYR = 30 quads). Of course, demand could be much larger. It is hard to believe that it could be much less.

Nuclear Power's Important Role

Some environmental groups have taken the philosophical position that nuclear energy should have no role in responding to global warming. In view of the magnitude of the problem outlined above, this position poses a practical dilemma. Where will the nonfossil energy come from? A retreat from nuclear energy would likely lead to increases in both price and demand for fossil fuels. Further, it would result in an increase in atmospheric pollution. The hypothetical conversion of all current nuclear plants to coal-fired power plants would add over 8% to the annual global CO_2 emissions from fossil fuel combustion. (Assuming the same burning efficiency, conversion of these plants to gas, rather than coal, would add 5% to the annual global CO_2 emissions.) Compared with other energy sources, nuclear power has proven to be environmentally benign, with essentially no releases of toxic chemicals, carbon dioxide, sulfur oxides, or nitrous oxide. Although the problems of nuclear waste management are serious and must be resolved, nuclear wastes from power reactors are being safely stored currently with no environmental consequences.

To arbitrarily maintain an antinuclear stance while facing these realities is contrary to the common good. The United States must reduce



TVA's Watts Bar nuclear plant near Kingston, Tennessee, has been under construction since 1972. Eight other nuclear plants scheduled for completion by TVA have been canceled or deferred indefinitely since 1978.

The Sequoyah Nuclear Plant, operated by TVA near Chattanooga, Tennessee, supplies 1.2 million kilowatts of power per unit to the Tennessee Valley area.

"The point is clear: nuclear energy is an essential factor in an effective energy strategy for the future."

CO_2 emissions because we are a rich nation. Poor nations need more energy to survive and grow. Industrial nations should drastically reduce their demands for fossil fuel resources so that poor nations can afford them and have a chance to develop. Industrial nations can accept the risk of nuclear power—a very modest, reasonable risk.

This simple energy arithmetic shows a very clear worldwide need for nuclear power in the future. It demonstrates that, for the world as for the United States, CO_2 emissions cannot be significantly reduced on a sustained basis without combining very high-efficiency energy use with very hefty growth of all the nonfossil energy sources, including nuclear power. An analysis done for the Congress in 1989 by the Environmental Protection Agency indicates essentially the same thing—both types of technology development are needed. The EPA results are also presented in our table on p. 131.

From all these arguments, the point is clear: nuclear energy is an essential factor in an effective energy strategy for the future, although it is not the only ingredient, nor even the predominant one perhaps. The importance of nuclear power's role will depend on the effectiveness with which the industry solves the problems now facing nuclear enterprises, the progress of competing energy sources, and the future urgency of the CO_2 problem.

Preparing for the Future

Is the nuclear industry prepared to assume its future role? A short-term excess in electric generating capacity occurred as the growth in electric power demand declined following the oil shocks of the 1970s. As a result of this and other principally political and economic causes, no new nuclear power plants have been ordered in the United States since 1973 (except for a couple ordered in 1978 that were subsequently canceled). Even so, because of previous plant orders, 40% of all new electricity production in the United States during the interim period has come from nuclear plants.

With no new nuclear plants on order and few remaining under construction, this important nonfossil energy source will not contribute significantly to our energy growth requirements in the next decade. Acceptance of nuclear energy has been diminished by the accidents at TMI and Chernobyl and, in the United States, by other problems, including major delays and cost overruns and relatively poor operating performance compared with Western Europe and Japan. In the United States, the investment risk for utilities has become intolerable because of the complex regulatory system and the potential for political intervention without investor recourse. The dilemma we face is that, on the one hand, nuclear power appears to be an important element in a balanced, resilient energy system needed to address global warming and support economic growth; and on the other hand, nuclear power is opposed by many, even including some of those who are most outspoken about the threat of global warming.

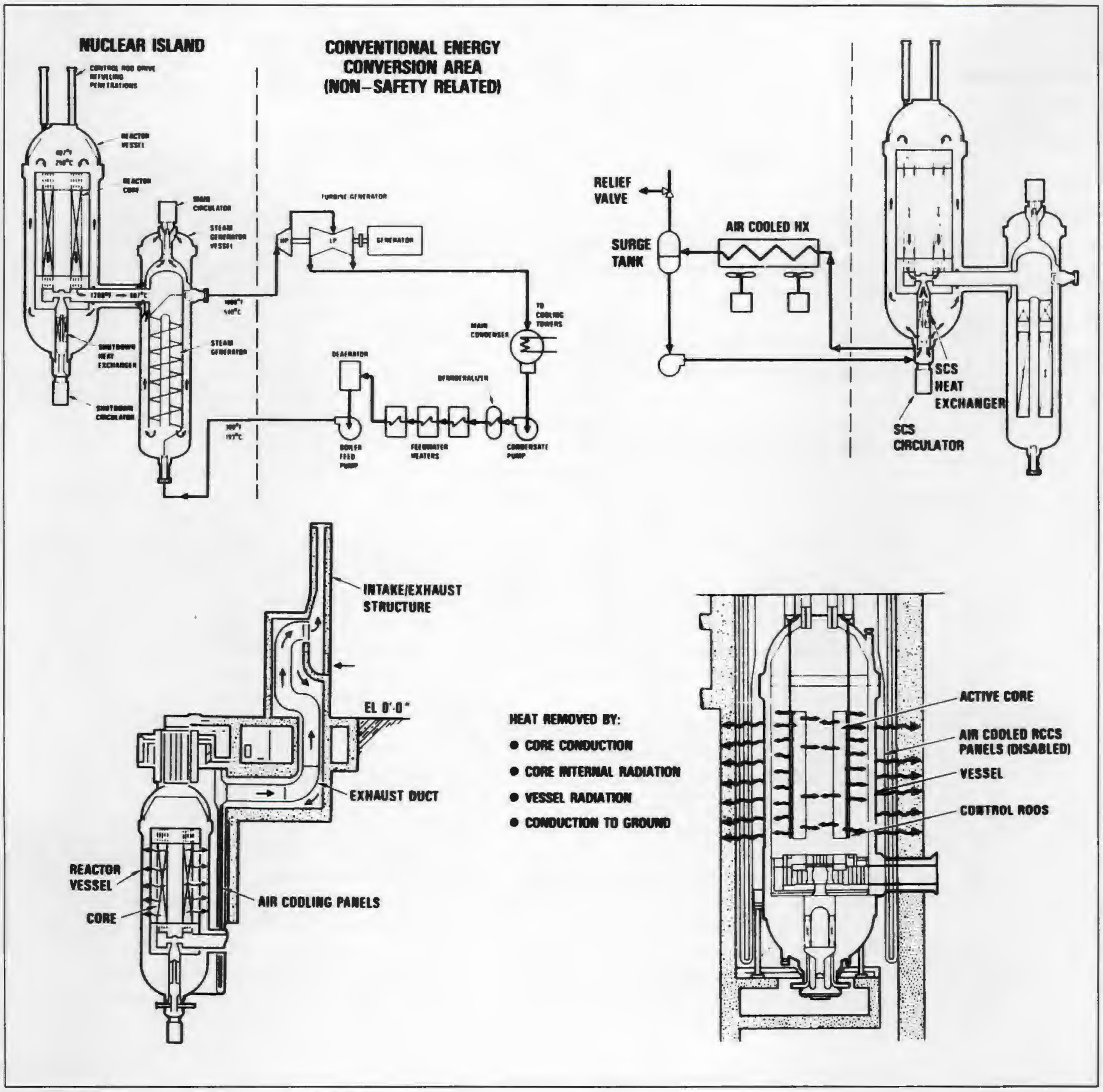
A new direction has recently emerged in the U.S. Civilian Reactor Program, and to a limited extent in Europe, that offers some hope for dealing with this dilemma. We refer to the emerging consensus on increased use of modern technology such as automated fail-safe control systems (see White's article on p. 116) and "passive" safety features (see Forsberg's article on p. 110). These improvements offer the potential to simplify the design and operation of next-generation reactors, enhance their safety, and perhaps reduce their cost.

To the greatest practicable degree, the passive safety goal provides plants that, when challenged by maloperation or unforeseen events, have incorporated in their structures inherent design features that will maintain the plant in safe, stable, undamaged conditions without operator intervention or external power sources. This general philosophy is being applied in all advanced reactor designs, although the degree to which passive safety systems are implemented varies.

A Safer Generation of Reactors

Uncertainties abound regarding the future of nuclear power. However, the need for nuclear

"The key features of the MHTGR design are helium coolant, a high-temperature core design, a passive heat removal system, small unit size, and below-grade siting."



The MHTGR concept offers the potential for greater safety and much higher thermal efficiency in reactor power production. Shown here are the various means for removing heat from the MHTGR, beginning with the conventional power cycle, shutdown cooling system, passive heat removal by natural circulation of air, and ultimate heat removal to the surrounding earth. Each alternative will cool the core adequately to avoid fission product release.

"The HTGR concept has always been attractive from the standpoint of safety because of its low power density and high thermal heat capacity."

energy is clear, and promising advanced concepts are emerging. In the United States, licensing reform is being addressed by the Congress, and the Bush Administration has taken an aggressive stance that "nuclear power is an essential link in the overall strategy for dealing with projected electricity shortages in the 1990s." Assuming that global warming is an important issue, we would like to look beyond today's uncertainty and explore the role of nuclear power and the new, safer generation of nuclear reactors.

LWRs. The overwhelming majority of existing reactors around the world are LWRs based on U.S. technology. There is great incentive to pursue evolutionary LWR designs that incorporate modern technology and some additional passive safety features, because of the very large experience base with this technology that provides: (1) high confidence that such reactors are well-understood (no surprises); (2) a strong, existing industrial base to support future reactors; and (3) the minimization of costs for the development of new technologies. A number of development efforts are under way for advanced LWR designs with improvements ranging from evolutionary changes to revolutionary new concepts. These programs are supported by U.S. vendors, the utilities (through EPRI), and by DOE (see sidebar discussion in *ORNL Review*, Vol. 19, No.1, 1986)

Even more advanced developmental features for LWRs are being explored in a modest ORNL development program to further enhance the passive safety features (see Forsberg's article on p. 110). In Europe, Sweden is pursuing development of the Process Inherent Ultimate Safety (PIUS) reactor concept, which is a revolutionary design that also offers extensive passive safety features.

HTGRs. The High-Temperature Gas-Cooled Reactor (HTGR) concept and its supporting base technology originated in the late 1950s. Efforts to commercialize the HTGR in the late 1960s and early 1970s resulted in the sale of about a half dozen plants that were subsequently cancelled as a result of the decline in electric load growth. The HTGR concept has always been attractive from the standpoint of safety because of its low power density and high thermal heat capacity.

Following a detailed assessment completed in September 1985, the Modular High-Temperature Gas-Cooled Reactor (MHTGR) became the principal focus of the U.S. HTGR program. It is also a major focus of the German HTR program. The key features of the MHTGR design are helium coolant, a high-temperature core design, a passive heat removal system, small unit size, and below-grade siting. With this design approach, fission product retention in the reactor system is ensured even in the event of human error or major component or system failure.

Although the present MHTGR concept is designed for steam-cycle electricity generation, future evolution of the technology will combine the concept with high-efficiency gas turbines (helium-driven) for electricity generation, which could yield much higher thermal efficiencies—perhaps on the order of 50%. It has long been recognized that the HTGR offers a unique potential for high-temperature process heat for clean coal conversion and many other industrial applications.

LMRs. The Liquid Metal Reactor (LMR) program has undergone similar evolution from a large plant design, based on the Fast Flux Test Reactor and Clinch River Breeder Reactor projects, to the current focus on a small modular reactor featuring passive safety.

The focus of this effort is the Power Reactor Inherently Safe Module (PRISM) concept, which features modular construction of small units, passive heat removal based on a natural-circulation air system, siting in an underground silo, pool-type construction with all primary system components in the reactor vessel, seismic isolation, and metal fuel. The designers indicate oxide fuel might also be used in PRISM without design changes. Passive safety features of PRISM, based on behavior of the metal fuel, ensure a passively safe response to events such as loss-of-coolant flow and power transients.

The metal fuel is part of an Integral Fast Reactor (IFR) concept, developed by Argonne National Laboratory, for reprocessing and fabricating the LMR fuel. Recent investigations are exploring the potential for separating and recycling the very long-lived actinides to the reactor, along with the fuel. Actinides can be burned in the LMR fuel, providing the potential to minimize the disposal of extremely long-lived actinides in the high-level nuclear waste repository. By doing so, concerns about monitoring these hazardous wastes for thousands of years could be minimized, but at the expense of handling additional radioactive materials in the LMR fuel cycle.

For the most part, international LMR programs continue to focus on the more traditional large-plant designs. However, Japan appears to have an interest in collaborating with the United States in advanced LMR activities.

ORNL's Perspective

Improved LWRs with enhanced "passive" safety features in the 500 to 800 MW(e) size range will likely become the workhorse nuclear technology in the United States and throughout most of the industrialized nations. The reasons for this conclusion are that LWR technology is established and that improved designs featuring enhanced "passive" safety features are emerging.

For smaller increments of power or for special circumstances in industrial countries, and especially for developing countries, the advanced MHTGR seems ideally suited. This technology will likely be commercialized in the early 2000s by the United States, the Federal Republic of Germany, and Japan because it offers the highest degree of passive safety, modular design and modest unit size, proliferation resistance, well-developed technology, and an ability to close the HTGR fuel cycle.

The LMR concept relates principally to the long-term need for the breeder, although the option to recycle actinides in LMRs to reduce long-lived actinides in the high-level nuclear waste repository may stimulate earlier interest. In any event, the timing for commercialization of this technology will likely be somewhat farther into the future than the development of alternative technologies.

Depending on the worldwide growth rate of nuclear power, this might occur in the 2020 to 2050 time period. Of course, R&D and a prototype or demonstration plant must precede commercial implementation.

Nuclear's Long-Term Viability

Perhaps it is appropriate at this point to address the long-term viability of nuclear power as a world energy source and the issue of whether the use of nuclear power can be sustained at the rates projected. Recent projections of uranium supply by the Organization for Economic Cooperation and Development and the International Atomic Energy Agency show that the world's economically recoverable uranium resources (at $130/kg) may be far greater than previously thought. They indicate an ensured supply of ~6 million metric tons and an additional 14 to 18 million metric tons in speculative resources at this recovery cost. Projections of world nuclear power growth rates (without consideration of global warming) are about 2% per year. If that were to continue indefinitely, the present ensured and projected uranium resource would last well over 100 years. However, if a high growth rate is necessary to respond to global warming, additional uranium resources will be necessary within the next 40 to 50 years.

Several options will be available then for extending the uranium resource base. First, experience in ore recovery has demonstrated that the introduction of advanced technology generally results in economic recovery from much lower-grade ore. For example, in the copper industry, ores of an order of magnitude lower grade than was previously considered practical are now being processed economically. Second, if the allowable price of uranium is raised from $130/kg to $300/kg, which would add only about 5 mills/kWh to the cost of electricity from nuclear power, the uranium resource base would expand by a significant margin—perhaps by a factor of 5 to 10. Third, improvements in uranium utilization efficiency in the once-through fuel cycle would further slow the depletion of high-grade uranium.

"Improved LWRs with enhanced 'passive' safety features in the 500 to 800 MW(e) size range will likely reemerge as the workhorse technology in the United States and throughout most of the industrialized nations."

Technology Can Improve Public Acceptance of Nuclear Power By:

- Improving the Performance of Existing Nuclear Plants
- Developing Advanced Designs with Passive Safety Features
- Resolving the Problems of Nuclear Waste Management
- Developing Ways to Extend Nuclear Resources
- Improving Safeguards of Nuclear Materials

Fourth, introduction of the breeder reactor would extend the uranium resource by more than a factor of 50 from whatever base resource is available, by breeding fissionable fuel from uranium-238 or thorium-232.

With all of the available options for economically extending the uranium resources, it seems reasonable to assume an adequate resource base to support the most aggressive deployment of nuclear power projected in view of global warming for a minimum of 1000 years.

Enhancing Public Acceptance

In order to expand nuclear power significantly, a number of institutional issues will also need to be resolved to the satisfaction of the public and the utilities. The job is made more difficult, of course, because we have no accurate means to measure what constitutes the condition of public or utility acceptance. Clearly, scale may be a factor. For example, it may be acceptable if the probability of a core meltdown is one in 100 years, but not at all acceptable if the number is one in 10 years. If the probability of such meltdown were 10^{-4} per reactor year, the nuclear enterprise would have to be limited to about 100 reactors. A thousand reactors would be too many, because that would increase the probability to one meltdown per 10 years.

Furthermore, the conditions of acceptance may be fickle and change with circumstance. As global warming becomes of greater concern, the public's acceptance of a greater commitment to nuclear power may increase. But the public doesn't necessarily think in terms of probabilistic risk assessment. In the case of nuclear power, Steve Rayner and Robin Cantor of ORNL's Energy Division have suggested that TLC is more important to the public than any probabilistic study. "T" represents *trust* in the institutions running the nuclear enterprise, "L" stands for *liability* (who will pay the cost of any accident), and "C" indicates *consent*, emphasizing that the potentially affected public must have some voice in agreeing to the arrangements of the technology's application.

Elizabeth Peelle of the Energy Division has argued that in certain circumstances community involvement and public participation in decision making is the best way of obtaining consent. It may have a good deal to do with arranging for institutional fixes that provide the necessary public trust as well. As poorly as we understand the conditions of public acceptance, we have a sort of faith that improvements in the technology can help, and we know that the technology can be made considerably better.

In five important areas, improved technology can make a difference in public acceptance of nuclear power. The first is in improving the performance of existing operating power plants. Various state-of-the-art technological improvements are available for making the current power plants more reliable, with fewer unscheduled outages. A major objective, of course, is to increase the capacity factor of the existing plants and to ensure that they are operated so as to prevent any major incident, such as occurred at Three Mile Island. In fact, the best way nuclear power could become acceptable is for it to become invisible to the public—simply to be always chugging away, producing power in a very reliable way.

The second area relating to acceptability is, of course, the safety of power plants. This can be improved by the adoption of LWR designs incorporating more passive safety features. Alternatively, new reactor concepts such as the MHTGR or LMR reactor designs may be necessary to achieve acceptance for a very large-scale nuclear enterprise—not only in this country, but worldwide.

To become completely acceptable, the nuclear enterprise must manage its wastes to public satisfaction. Substantial, but very slow, progress is being made in this area. There are improved technologies for handling both low-level and high-level radioactive waste, and many institutional innovations have developed between and among states as a result of the Nuclear Waste Policy Act. It is still uncertain how we will actually arrive at a solution to the problem of high-level radioactive waste.

A fourth area affecting acceptability is the necessity of extending fissile material resources. A very large-scale nuclear enterprise that would contribute substantially to preventing global climate change will require the adoption of resource-extension technologies (e.g., breeder reactors), perhaps by the middle of the next century.

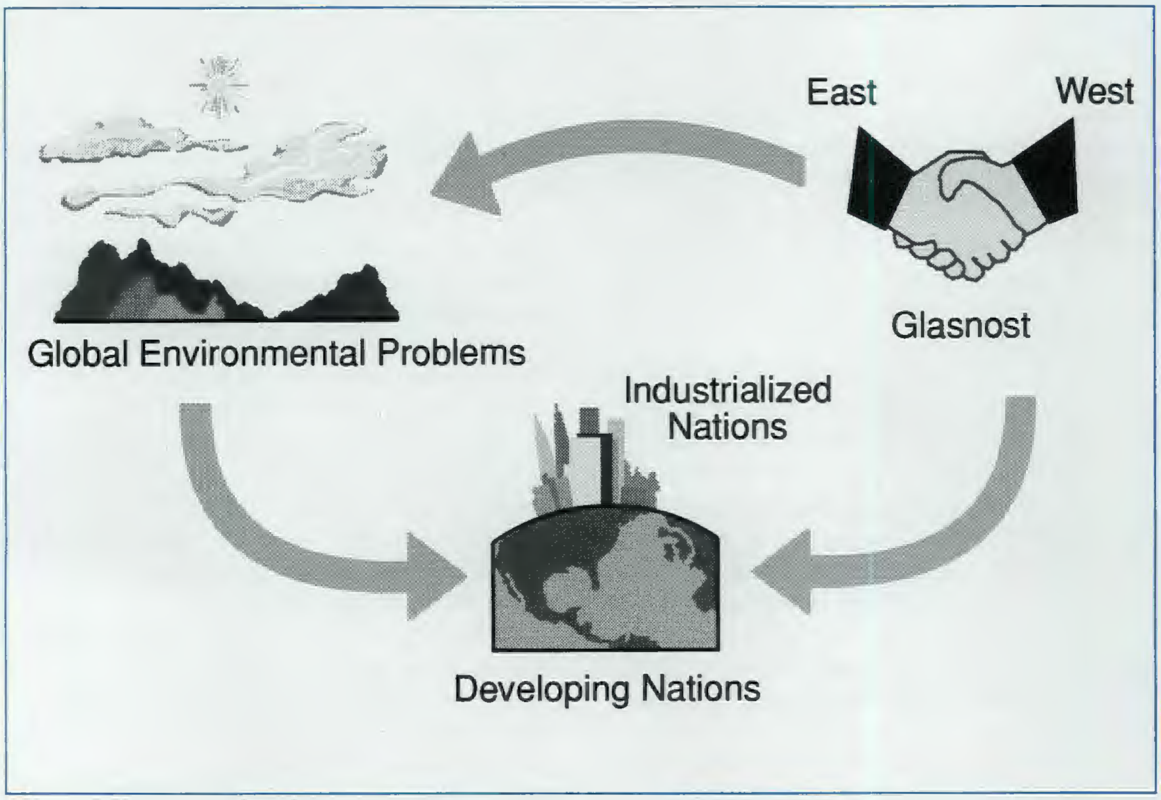
The final area of concern is safeguards. As the scale of the nuclear enterprise increases, more attention must be given to safeguards against clandestine diversion of nuclear fuel to weapons (e. g., by terrorists) or against countries using their nuclear facilities for the proliferation of nuclear weapons. Solutions here are not primarily technical, except for technologies to detect diversion activities or changes in the power system to eliminate the possibility of weapons production. Increasing safeguards will, instead, require better institutions and more cooperation between nations.

An equally important factor in improving the nuclear industry and enhancing its public acceptance is the establishment of institutional and regulatory reforms to better manage the nuclear enterprise. The regulatory process is slow, cumbersome, and bureaucratic. Licensing reform is critical to the future of nuclear energy. Prelicensing of standardized plants may be an appropriate basis for the licensing process. Without suggesting any prescriptive form for the solution, it is apparent that the nation needs institutional reforms, which will require the participation and cooperative effort of representatives of government, industry, regulators, and the public at large.

A Global View

In the final analysis, we must think about nuclear power as a world system. We are all in it together. Whatever goes wrong with the system in any part of the world affects the system everywhere, as Chernobyl so clearly demonstrated. We must think in terms of institutions that can manage a global enterprise. We must include the developing nations in this global enterprise, and we must think and plan very carefully so that the technologies developed over the next two decades will be designed specifically to meet the needs of both the industrialized world and the developing countries.

"In the final analysis, we must think about nuclear power as a world system."



Fundamental global changes are shaping the future's international technology needs.

The three developing nations that are currently the largest contributors to the greenhouse effect are China, India, and Brazil. They are not signatories to the Treaty on the Nonproliferation of Nuclear Weapons, but all three countries already have a burgeoning nuclear enterprise—and two of the three already possess nuclear weapons. Promoting the expansion of nuclear power in these countries hardly constitutes much additional risk with regard to nuclear war or the use of nuclear weapons. We must realize that nuclear power is likely to grow in developing countries regardless of what we do in the United States. We can influence nuclear power development in these countries if we work closely with them to develop institutions and technologies that best serve their needs.

To fulfill its role, nuclear power must gain worldwide acceptance as a viable energy option. The use of modern technology and "passive" safety features in next-generation nuclear power plants offers the potential to simplify their design and operation, enhance their safety, and reduce the cost of electricity. Such improvements, we believe, are necessary in order for nuclear power to regain public confidence and make a significant contribution to our global energy future. Achieving this public confidence and revitalizing the nuclear enterprise may also be our best hope for a viable nonfossil source for controlling global warming. ornl

John Jones

Bill Fulkerson

Biographical Sketches

John E. Jones, Jr., became director of ORNL's Engineering Technology Division (ETD) in 1989, after serving for the past four years as director of Reactor Programs. He has also served as head of the ETD fossil energy programs, head of the division's Fossil Energy Technology Section, and later head of its Engineering Analysis Section.

Jones, who came to ORNL in 1958, participated in many of ORNL's early experimental and research reactor programs, including the Homogeneous Reactor Test, the Molten Salt Reactor Experiment, the Oak Ridge Research Reactor, and the High Flux Isotope Reactor. He has a B.S. degree in mechanical engineering from the University of Kentucky and has done extensive graduate work in engineering and mathematics at the University of Tennessee.

Bill Fulkerson, ORNL's Associate Director for Advanced Energy Systems, joined the Laboratory's Metals and Ceramics (M&C) Division in 1962, shortly after receiving his Ph.D. in chemical engineering from Rice University. In 1967 he became a group leader in the M&C Division, doing research on the fundamental properties of ceramics. From 1970 to 1975, Fulkerson headed a National Science Foundation project at ORNL on ecology and analysis of trace contaminants. In 1974, he became head of the Environmental Impact Section of the newly formed Energy Division; a year later Fulkerson became director of the Energy Division and served in this position until May 1989.

Getting More fr

Electric utilities are providing financial incentives for customers to install energy-efficient appliances.

Many Americans are concerned about global warming and other environmental problems caused partly by electricity production, about possible shortages of electricity and increases in energy prices during the 1990s, and about declining U.S. competitiveness in the world marketplace. Some remedies for these problems, says Eric Hirst of ORNL's Energy Division, are to (1) improve electric-utility planning and provide utilities with information on ways to minimize the cost of electricity services and (2) encourage utilities to take advantage of the potential for greater energy efficiency. Below is a summary of two reports, coedited or authored by Hirst, that outline possible solutions to national problems.

Least-cost utility planning. In one region, new factories are being constructed and new homes, stores, schools, and hospitals are being built to meet the needs of employees the factories will hire. The local electric utility decides that the expected growth in demand for electricity services can be met only by building a new power plant.

In another region, a similar growth in demand for electricity services is anticipated. However, the utility has no plans to build a power plant, rejecting this option as too expensive and unnecessary. Instead, it is improving the efficiency of its existing power plants and transmission system. It is also providing information and incentives to encourage building owners to purchase more energy-efficient appliances, tighten their structures to prevent heat losses, and consume electricity chiefly during the hours when demand is low.

This utility will minimize its cost of services by improving the efficiency of existing systems that provide and consume electricity. As a result, customers will face fewer rate increases and the utility avoids the environmental effects, regulatory problems, and capital costs posed by building a new power plant.

The second utility has used "least-cost planning," the subject of a new report released jointly by Lawrence Berkeley Laboratory and ORNL. The report, *Least-Cost Planning in the Utility Sector: Progress and*

om Electricity

Challenges, presents "a new way for utilities and state regulatory commissions to consistently assess a variety of demand and supply resources to cost-effectively meet customer energy-service needs."

This new planning paradigm differs from traditional utility planning in at least four ways: (1) it explicitly includes conservation and load management programs as energy and capacity resources, (2) it considers environmental and social factors as well as direct economic costs, (3) it involves public participation, and (4) it carefully considers the uncertainties posed by various resources and external factors.

Hirst was an editor of the report, which notes that nationwide use of least-cost planning could significantly increase U.S. economic productivity and reduce national energy costs, environmental impacts, and controversies over construction and siting of new energy facilities. It also suggests several ways that the U.S. Department of Energy could help overcome barriers to least-cost utility planning.

DOE could identify regulatory alternatives that reward utilities for successfully implementing least-cost plans (e.g., competitive bidding to provide lower-cost electricity services). It could encourage utilities and regulatory commissions to develop and share information about planning successes, analytical tools, innovative regulatory strategies, and the benefits and costs of conservation and load-management technologies and programs. Finally, DOE could promote the incorporation of environmental and other social factors into electric-utility planning.

Energy-efficiency and load-management programs. More and more electric utilities throughout the United States are providing financial incentives for customers to install more energy-efficient air conditioners, heat pumps, water heaters, and refrigerators. Through special rates, they are encouraging electricity use during low-demand hours and winning permission to interrupt the electric power supply to specific equipment when electricity is critically needed elsewhere in the system. All of these approaches can slow the increase in consumer electric bills and help utilities avoid the need to build new power plants, with their attendant financial and environmental impacts.

Utilities are adopting energy-efficiency and load-management programs to meet the needs of customers for low-cost energy services, to improve environmental quality, and to enhance their economic competitiveness. An ORNL report by Hirst, *Electric-Utility Energy-Efficiency and Load-Management Programs: Resources for the 1990s*, suggests that efficiency of electricity use could be further improved by utilities through a number of strategic and aggressive actions. Hirst advises utilities to support efficiency standards for buildings and appliances; develop innovative pricing mechanisms to control electricity demand; and work with public utility commissions to update rate regulations so that utilities are economically rewarded, not penalized, for improving efficiency of electricity use. (For more information, consult the ORNL/CON-284 and ORNL/CON-285 reports.)

ORNL Calculates Global CO_2 Emissions

Worldwide emissions of carbon dioxide (CO_2) from fossil fuel burning and cement production rose for the fourth consecutive year, according to calculations done at ORNL. This trend is of concern because of the potential for global warming from increasing atmospheric concentrations of CO_2 and other "greenhouse" gases.

Using fossil emission data compiled by the United Nations Statistical Office and cement production data from the U.S. Bureau of Mines, Gregg Marland and Tom Boden of ORNL calculated that global CO_2 emissions from fossil and cement sources in 1987 were 1.59% higher than in 1986. The researchers work for ORNL's Carbon Dioxide Information Analysis and Research Program, funded by the Department of Energy's Office of Health and Environmental Research.

"We calculated the amount of carbon injected into the atmosphere, mainly from fossil fuel combustion, to be 5.60 billion metric tons in 1987, compared with 5.51 billion metric tons in 1986," states Marland. "The 1987 value is slightly over 1.1 metric tons of carbon for every person in the world."

The U.S. contribution to this total is 1.22 billion metric tons of carbon, or about 5 metric tons of carbon per person. U.S. emissions, which are now about 22% of the world total, rose 1.87% from 1986 to 1987, in contrast to a 0.42% increase in Western Europe and a 6.35% increase in South Asia and Southeast Asia.

Global emissions of CO_2 from fossil fuel burning climbed steadily until the energy crisis of 1973 and the oil price jumps of 1978–1979 stalled world growth in energy use and CO_2 emissions. The emission rate remained about the same in 1974 and 1975 and actually dropped from 1980 to 1983. From 1984 through 1987, the CO_2 emission rate steadily increased.

The largest rate of growth over the past four years has been in CO_2 emissions from burning natural gas—the fuel that actually discharges the least CO_2 per unit of useful energy. Emissions from natural gas have risen 47% since 1973; in contrast, emissions from solid fuels have grown by 43% and emissions from liquid fuels have remained virtually constant (2% total growth) over the 15-year period.

Although emissions from the United States have nearly doubled (1.8 times) since 1950, the U.S. share of total global emissions has declined from 42% in 1950 to 22% in 1987 because other areas of the world have been experiencing high growth rates.

Based on 1987 data, Marland says, "It is still true that collectively three countries—the United States, the Soviet Union, and China—account for over 50% of global emissions."

Fossil fuel combustion and cement manufacture are not the only sources of CO_2 to the atmosphere. "Carbon dioxide," says Marland, "is also discharged when forests are cleared to provide croplands or pastureland—a process that is now occurring primarily in the tropics. Although it is difficult to estimate the rate of CO_2 release from tropical forest clearing, the best current estimates suggest around 1.8 billion metric tons of carbon per year."

The National Energy Strategy: ORNL's Contributions

In July 1989, Energy Secretary James D. Watkins announced DOE's plans to solicit views and begin a consensus-building process to develop a new national energy strategy (NES). ORNL has played a role in the formulation of this plan by focusing on ways to improve energy efficiency, use of renewable energy, understanding of energy and global climate change, energy technology for developing countries, electrical transmission and distribution systems, and technology transfer.

The multifaceted process of arriving at a strategy is coordinated by the DOE Office of Policy, Planning and Analysis. A series of public hearings (including five already held) will provide public comment. DOE program offices will develop policy options that are identified in the public hearings. A working group of the Economic Policy Council and a National Laboratory Advisory Committee will provide reviews. The DOE national laboratories have been asked to prepare white papers on five topics central to the planning process. An interim NES report is scheduled for publication in April 1990, and the final report should be completed by the end of 1990.

ORNL staff members mostly from the Energy and Environmental Sciences divisions are contributing to strategy development. Bill Fulkerson, associate director for Advanced Energy Systems, represents ORNL on the National Laboratory Advisory Committee. Roger Carlsmith leads the interlaboratory team preparing the white paper on energy efficiency; he is assisted by Eric Hirst, Marilyn Brown, A. M. (Bud) Perry, Kathi Vaughan, and Kay Zimmerman. Fulkerson, Jack Ranney, Tom Rizy, and Bob Van Hook have collaborated on a white paper on renewable energy, led by DOE's Solar Energy Research Institute. Mike Farrell, Bob Cushman, Ed Hillsman, Carolyn Hunsaker, Tony King, Billy Manuel, Gregg Marland, and Steve Rayner worked on the white paper on energy and global climate change, led by DOE's Lawrence Livermore National Laboratory.

Fulkerson and Tom Wilbanks contributed to a white paper on energy technology for developing countries, led by DOE's Lawrence Berkeley Laboratory. Brown, David Feldman, and Dennis White contributed to a white paper on the technology transfer process, led by DOE's Pacific Northwest Laboratory. John Stovall currently is assisting the DOE Office of Energy Storage and Distribution in characterizing research and development needs in electrical transmission and distribution systems.

In addition, Randy Hudson of the Engineering Technology Division has been assisting DOE's Office of Nuclear Energy in its NES activities. This support includes developing nuclear plant electricity generation projections out to the year 2030, estimating future plant costs, and reviewing the NES energy modeling efforts.

Drafts of the five white papers were completed in September. Final versions will be made available at the upcoming series of public hearings. ORNL staff members will doubtless be called upon to participate in additional areas during the development of the national energy strategy.

Oil Crises and Military Fuel Supplies

By Dick Davis, Jerry Hadder, Sujit Das, Russ Lee, and Paul Leiby

The *U.S.S. Dwight D. Eisenhower* can carry 2.7 million gallons of Navy jet fuel, to support the operation of 85 aircraft. DOE and ORNL have been helping the Navy better forecast the availability of Navy jet fuel and diesel fuel during military and political crises.

Petroleum shortages can result from a variety of causes—political turmoil, war, or a natural disaster (e.g., earthquake). The severity of these "oil crises" depends on the extent of the supply disruption, the demand for fuel, the amount of crude oil or product reserves on hand, and the availability of alternative supplies.

The Department of Energy (DOE) and the Department of Defense (DOD) have a keen interest in the causes and effects of potential oil crises. Both are also seeking ways to reduce U.S. vulnerability to oil shortages.

DOE and ORNL have been helping DOD analyze the military's vulnerability to oil crises. Over the last three years, ORNL has modified several complex computer models originally developed by DOE's Energy Information Administration to evaluate the behavior of world energy markets during military and political crises and the potential impact of these events on the availability of civilian and military fuels.

The Oak Ridge work is directed at forecasting free-world production and shipping patterns for crude oil and refined products for the next 10 to 20 years. One prediction is that the free world will continue to be heavily dependent on the Middle East for crude oil (see figure on p. 100), but we also need to be able to predict the potential impacts of various possible military or political events on world oil marketing.

Navy Fuel Study

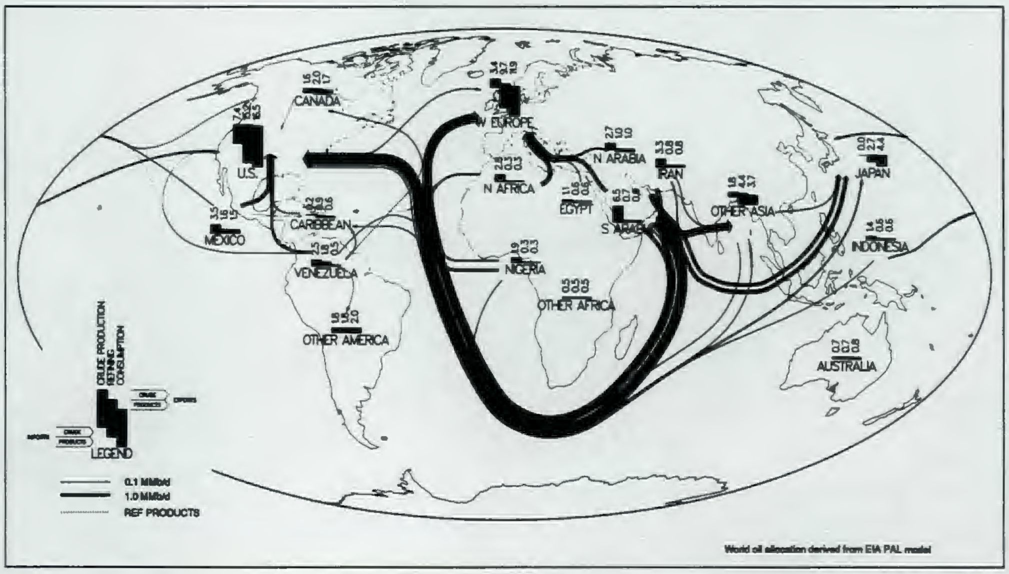
The Department of the Navy in DOD has been particularly interested in our program and has been working closely with DOE in defining world oil market disruption scenarios and analyzing the effects of potential shifts in the supply or quality of Navy jet fuel and diesel fuel. For example, the Navy depends heavily on JP-5 jet fuel for flying its high performance aircraft such as the A-6, F-14, and F-18 jets. The Navy uses JP-5 because, compared with commercial jet fuels, it is less likely to ignite and thus is safer to carry on ships (see facing photo). However, because of the limited demand—primarily by the Navy, relatively few refiners supply JP-5.

During peacetime, refiners can meet the demand for military fuels. However, under the emergency conditions of a military or political conflict or perhaps a severe natural disaster, it may be extremely difficult to meet the demands. Under these conditions, supply lines must be protected, and stockpiles must be available to meet the needs. Depending on the type of conflict, the military demand for fuel might increase to 2 or 3 times the normal consumption just at a time when crude oil supplies in world markets might be reduced. ORNL's program is involved in analyzing such situations and providing DOE and DOD with alternatives to better handle them.

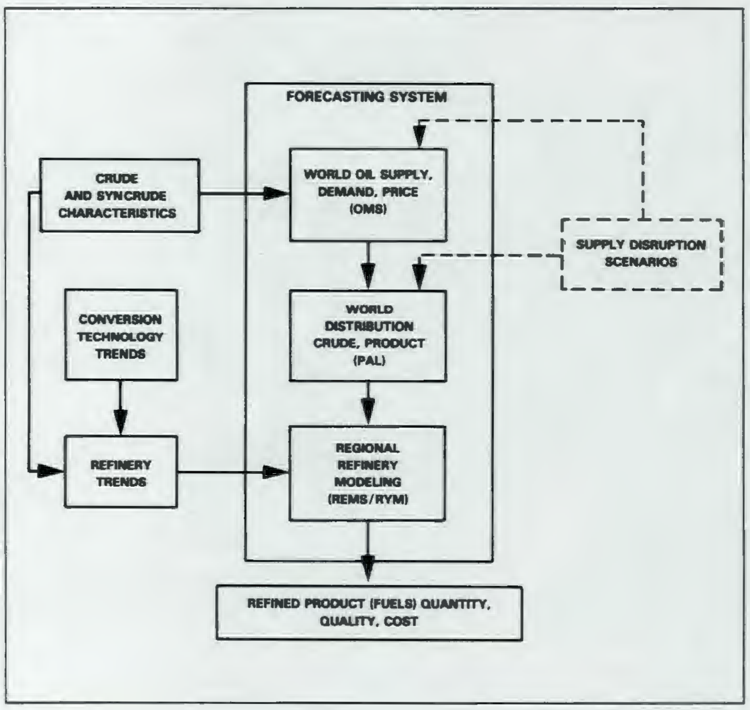
Key Projections

Forecasting fuel availability and prices and the balance of supply and demand are some of the issues we have studied this past year while helping the Navy develop an improved Mobility Fuels Forecasting System. Project team members Jerry Hadder, Sujit Das, Paul Leiby, Russ Lee, and Dick Davis at ORNL released a report in October 1988 that analyzed the availability of Navy fuels under normal (business-as-usual) conditions and as a result of two hypothetical crude oil supply disruptions.

In a "political disruption" scenario assumed to last 90 days, petroleum exports from the Persian Gulf, Algeria, and Libya are reduced by 50%.



Projected free-world petroleum distribution (crude oil and refined product) in 1995 is an essential component of the business-as-usual scenario for oil supply and demand.



The Navy Mobility Fuels Forecasting System and supporting activities (acronyms refer to analytical models).

The "military mobilization " scenario assumes total loss of petroleum exports from these areas for 90 days, a 40% reduction of crude oil output from the North Sea, and triple the normal military demand for petroleum because of "military mobilization" to meet the crisis.

The models provided these key findings:

• Navy jet fuel production would virtually end, assuming that petroleum product price differentials follow past trends

• Petroleum refiners could satisfy demand for military fuels during the disruptions, but the cost of Navy jet fuel could double during the "political disruption" and possibly quadruple during the "military mobilization"

• The availability of a fuel for military use could be increased during disruptions by, for example, relaxing requirements on fuel quality; however, such an action could result in decreased production of other fuels.

Our forecasting system is being evaluated for use in analyzing the effects of Environmental Protection Agency proposals to improve the quality of gasoline and diesel fuel. These studies are being performed against a background of growing concern about environmental quality as well as national security (U.S. gross oil imports rose to over 7 million barrels per day in 1988, the highest level in 7 years). We have also begun to analyze the potential effects of various jet fuel characteristics on engine performance and maintenance. Both DOE and the Navy have a common interest in better predicting fuel availability and U.S. vulnerability to oil shortages—key concerns for our energy future. ornl

Paul Leiby (left), Jerry Hadder, Dick Davis, Sujit Das, and Russ Lee discuss various fuel supply disruption scenarios.

Biographical Sketches

Dick Davis is associate director for Space and Defense Technology Programs for Martin Marietta Energy Systems, Inc. He is the former head of the Regional and Urban Studies Section of ORNL's Energy Division. He has a Ph.D. degree in geography from Ohio State University. He came to ORNL from Battelle-Columbus in 1976.

Jerry Hadder is manager of the Navy Mobility Fuels Forecasting Project. After carrying out process engineering assignments at Dow Chemical Company and Exxon Company, U.S.A., he joined the Energy Division in 1980. An Oak Ridge native, he holds an M.S. degree in quantitative methods from Louisiana State University.

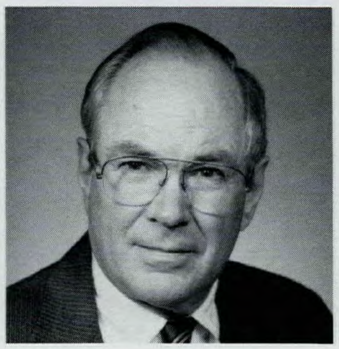
Sujit Das, research staff member of the Energy and Economic Analysis Section of the Energy Division, joined ORNL in 1984. He earned an M.S. degree in engineering and an M.B.A. degree from the University of Tennessee.

Russ Lee is leader of the Resource Modeling and Technology Economics Group in the Energy Division. A former faculty member of the University of Iowa and Boston University, he has a doctorate in geography from McMaster University. He joined ORNL in 1981.

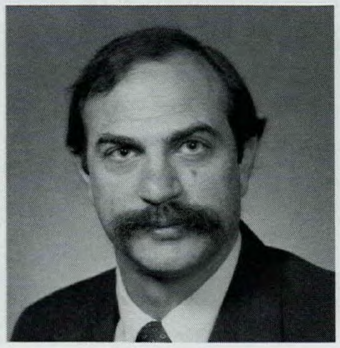
Paul Leiby has been a research associate in the Energy Division since 1987. He has a master's degree in public policy from the John F. Kennedy School of Government at Harvard University.

RE: Awards & Appointments

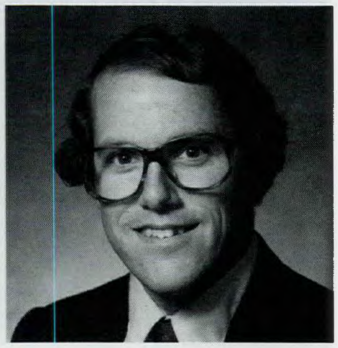
John Jones



Hal Glovier



John Miller



James Roberto

The Office of the Laboratory Director has been restructured at the associate director level. The six associate directorates are **Bill Appleton,** Physical Sciences and Advanced Materials; **Bill Fulkerson,** Advanced Energy Systems; **Bill Morgan,** Operations; **Tom Row,** Chemical, Environmental, and Health-Protection Technologies; **Chet Richmond,** Biomedical and Environmental Sciences; and **Alex Zucker,** Nuclear Technologies.

Carl Edward Oliver, formerly chief scientist at the Air Force Weapons Laboratory in Albuquerque, New Mexico, has been named ORNL's director of the Office of Laboratory Computing.

Joe Herndon has been appointed director of the Robotics and Intelligent Systems Program.

Robert C. Ward has been named associate director of ORNL's Engineering Physics and Mathematics Division, and **Reinhold Mann** has been appointed head of the Intelligent Systems Section and director of the Center for Engineering Systems Advanced Research in ORNL's Engineering Physics and Mathematics Division.

John E. Jones, Jr., has been appointed director of ORNL's Engineering Technology Division. **Franklin J. Homan** has been named director of Reactor Programs, replacing Jones.

H. A. (Hal) Glovier has been named director of ORNL's Research Reactors Division, replacing **A. L. (Pete) Lotts,** who has retired. **W. K. (Walt) Brown** has been appointed associate director of this division.

Ray S. Booth has been appointed technical director of ORNL's Liquid Metal Reactor and Light Water Reactor programs.

C. R. (Randy) Hudson has been appointed the United States delegate to the Organization for Economic Cooperation and Development Expert Group on Capital Cost Reduction of Nuclear Power Stations.

John S. Cook has been appointed head of the Molecular and Cellular Sciences Section in ORNL's Biology Division. He also is chairman of the Publications Committee of the American Physiological Society.

John C. Miller has been appointed head of the Chemical Physics Section of ORNL's Health and Safety Research Division.

James B. Roberto has been named associate director of ORNL's Solid State Division and head of its Thin Films and Microstructures Section. The recently named head of the division's Particle–Solid Interactions Section is **David M. Zehner**.

William Martin has been appointed associate director of ORNL's Engineering Technology Division, and **Richard Cheverton** has been named head of the division's Pressure Vessel Technology Section.

Tuan Vo-Dinh has received a French award—the Medal of the Languedoc-Roussillon Region—for his scientific achievements and collaboration with scientists at the University of Perpignan in France. He also has been appointed a topical editor of the new international journal, *Polycyclic Aromatic Compounds*.

Donald B. Trauger and **William Pechin** have been appointed assistant editors of the journal *Nuclear Safety*, edited by Ernest G. Silver of ORNL.

Herman Postma, former ORNL director and senior vice-president of Martin Marietta Energy Systems, Inc., has been elected vice chairman for East Tennessee of the Tennessee Higher Education Commission.

William L. Russell has received the 1989 "EMS Award" from the Environmental Mutagen Society for his "long and distinguished career of research and scholarly achievement in the fields of mammalian genetics and mutation research" and specifically for his pioneering role in studies of mutagenesis in mammalian reproductive cells.

Three members of ORNL's Solid State Division have been elected "scientific members" of the Böhmische Physical Society. They are **Tony E. Haynes,** "for studies of epitaxial film formation by low-energy ion beam deposition"; **Stephen Pennycook,** "for development of Z-contrast, high-resolution imaging in electron microscopy"; and **Terrence Sjoreen,** "for studies of high-energy ion implantation in germanium."

George P. Smith has been named the winner of the Electrochemical Society's

William Russell

Tony Malinauskas

Elizabeth Peelle

Virginia Tolbert

second biannual Max Bredig Award in Molten Salt Chemistry.

The publication "Tables for Determining Statistical Significance of Mutation Frequencies," which was coauthored by **Kimiko Bowman**, has been chosen as a "Citation Classic" by the Institute for Scientific Information.

Stephen Stow has been appointed chairman of the newly created Education Committee for the Southeastern Section of the Geological Society of America.

James R. Weir has received a 1989 Special Award for Excellence in Technology Transfer from the Federal Laboratory Consortium. He was cited for work leading to five nickel aluminide licenses and market-place interest in other technologies.

Vic Vaughen has been named head of the Office of Operational Readiness and Safety in ORNL's Chemical Technology Division.

Barry Peyton is a co-recipient of the 1988 Gordon Bell Prize, which recognizes outstanding achievement in the application of supercomputers to scientific and engineering problems. The team on which he served excelled in raw performance—solving a problem in the fastest possible way.

James R. Palmer has been named manager of industrial partnerships in the Energy Systems Office of Technology Applications.

Steven M. Bartell has been appointed to the Editorial Advisory Board for *The Handbook of Environmental Chemistry* and to the Participating Board of Editors for the ecotoxicology section of the technical journal *Chemosphere*.

S. Marshall Adams has been elected a fellow of the American Institute of Fishery Research Biologists.

Michael T. Naney has been named a fellow of the Mineralogical Society of America.

Anthony P. Malinauskas has been appointed director of ORNL's Waste R&D Program.

Claud E. Pugh has been named director of the Laboratory's Nuclear Regulatory Commission Programs, and **Luci Bell**, former associate editor of the ORNL *Review*, has been appointed his technical assistant.

Thomas F. Scanlan has been appointed head of the Waste Management Operations Section in ORNL's Environmental and Health Protection Division.

For her research on the social impacts of large energy facilities, **Elizabeth B. Peelle** was the 1988 recipient of the Award for Applying Sociology from the Society for Applied Sociology.

Robin Cantor has been appointed technical assistant to associate director **William Fulkerson.**

Michael P. Farrell has been appointed deputy director of the Center for Global Environmental Studies, whose director is **Robert I. Van Hook**. **William R. Emanuel** will coordinate Global Systems Analysis, the center's main focus. **Paul Kanciruk** will coordinate Data and Model Systems; **Billy G. Eads,** Measurement Science and Instrumentation; **Steve Rayner**, Policy, Energy, and Human Systems Analysis; and **Monica G. Turner**, Large-Scale Environmental Studies.

Lynn Boatner received the Distinguished Alumnus Award in Physics for 1989 from Texas Tech University.

William R. Hamel has been appointed to the U.S. Army Science Board.

Paul D. Ewing and **Richard A. Hess** have been certified as electromagnetic compatibility engineers by the National Association of Radio and Telecommunications Engineers, Inc.

Virginia R. Tolbert has been named treasurer of the North American Benthological Society.

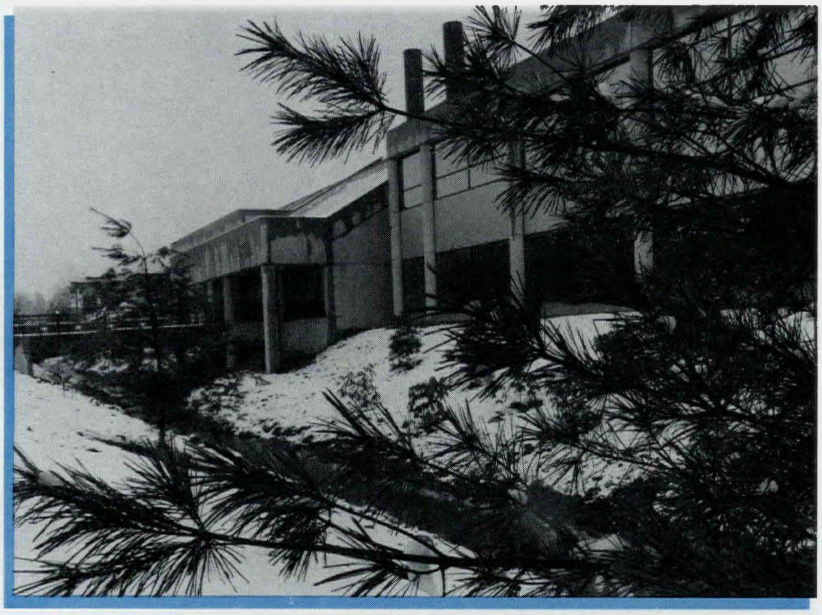
The new Biomedical and Environmental Information Analysis (formerly Information Research and Analysis) Section of the Health and Safety Research Division is headed by **Po-Yung Lu** and has three new group leaders: **John S. Wassom,** Human Genome and Toxicology Group; **Robert H. Ross,** Chemical Hazard Evaluation and Communication Group, and **Park T. Owen,** Hazardous Materials and Environmental Information Group.

Dave Moses has been appointed manager of ORNL's New Production Reactor Program.

Deok K. Lee received a Technical Achievement Award from Energy Systems for his contibution to the ORNL fusion energy program. ornl

A Tour of the HTML

By Felicia Foust



The HTML is attracting an increasing number of academic and industrial users and guest researchers.

Most people are familiar with the "front" of the Oak Ridge National Laboratory through pictures taken of the Holifield accelerator tower, the Swan Pond, and other locations near the main entry to the Laboratory. Since July 1987, however, a growing number of guests have learned about an outstanding new facility located near the "back" of ORNL. These are the people from industries and academic institutions who have visited or become "users" of the High Temperature Materials Laboratory (HTML) located behind Buildings 4508 and 4500-South.

Even though it is not located near the front of ORNL, this new laboratory is certainly in the forefront of DOE-designated user facility programs, having in place more than 60 signed user agreements with industries and universities (32 of these are with industries, 28 with universities, and 3 with other government facilities). Through these agreements, qualified users have access to the HTML's modern state-of-the-art materials characterization instruments and the expert research staff responsible for facility operation.

There are two types of user agreements—proprietary and nonproprietary. If research results will be published in the open literature, a nonproprietary agreement is signed, and there is no charge to the HTML user for equipment and staff assistance. If the user wishes to retain data rights to his project, a proprietary user agreement is signed and the user is charged a fee, determined by DOE, for use of the facility and aid from the staff. Under terms of the standard user agreement between the user organization and Martin Marietta Energy Systems, Inc., that organization has access to all DOE-designated user facilities operated by Energy Systems, once the agreement is in place.

To initiate a user agreement, the industry or university representative generally contacts the user center coordinator for the particular facility of interest, since requirements may differ. The new Office of Guest and User Interactions, headed by Barry Burks (see *ORNL Review*, Vol. 22, No. 1, 1989, p. 46), will help to simplify the paperwork and serve as a central coordination center for all of the DOE user facilities located at ORNL. Visitors and guest researchers will now be able to contact this one office, rather than many, to complete the necessary application forms and clearance arrangements.

Researchers wishing to use the HTML must first submit a research proposal. The proposal is then reviewed by the HTML User Advisory Committee, which includes representatives from industry, academia, ORNL, and DOE's Oak Ridge Office. When a proposal is accepted, the HTML staff and the guest researcher work out a suitable schedule for completing the research project.

Visitors are always welcome at the HTML, and a phone call to the user center coordinator is all that is required to set up a tour. Energy Secretary James Herrington, U.S. Representative Marilyn Lloyd, Senator James Sasser, former senator

Howard Baker (when he was President Reagan's Chief of Staff), Assistant Secretary of Conservation and Renewable Energy Donna Fitzpatrick, and Joseph Coors, president of Coors Ceramics, Inc., have been among the facility's most distinguished visitors. In a typical month, about 15 tour groups of up to 100 people visit the facility, with interests ranging from casual curiosity to serious inquiries about research capabilities and requirements for becoming a user. Many of our current user research activities are a result of such visits.

DOE's Assistant Secretary of Conservation and Renewable Energy, Donna Fitzpatrick, was the featured speaker at the dedication of the HTML on May 6, 1987. Shown (from left) with HTML director, Vic Tennery; acting ORNL director, Alex Zucker; and Martin Marietta Energy Systems senior vice president, Herman Postma.

A typical tour of the facility starts in the lobby at a photographic display of the major instruments in each user laboratory and samples of the research results produced by each instrument. A floor plan of the building shows visitors the locations of the three Metals and Ceramics Division research groups housed in the building, as well as the four HTML user centers.

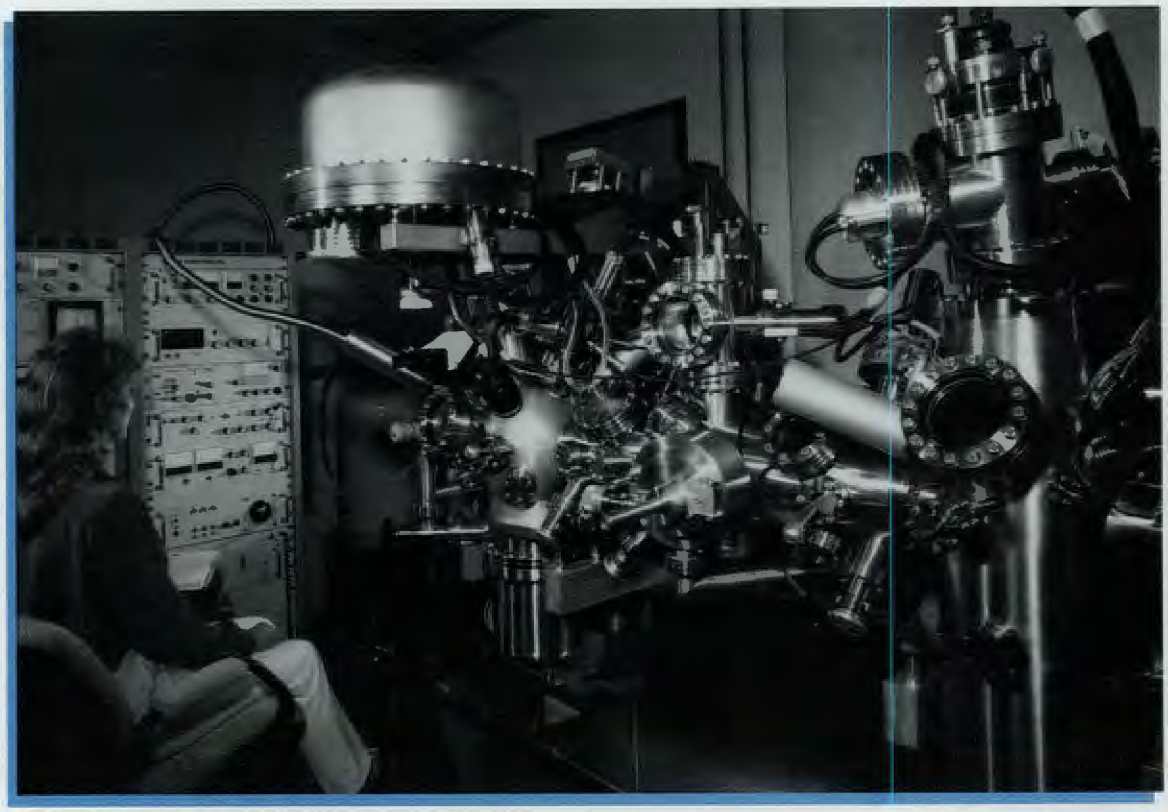
As we leave the lobby, we point out to visitors the wall plaque commemorating the HTML's dedication, in April 1987, and listing our Department of Energy sponsor in Washington, Albert A. Chesnes, director of DOE's Heat Engine Propulsion Division. We hope they also notice the other plaque, representing a "High Honor" Award to the HTML from *Research & Development* magazine in their 1988 national Laboratory of the Year competition.

Turning to the left, we enter the Materials Analysis User Center (Group Leader, Ted Nolan) which occupies the entire east end of the ground floor. This center includes six major analytical instruments in separate laboratories, as well as two specimen preparation laboratories. The specialized instruments are used to determine microstructure and microchemistry of materials. Fascinating micrographs from the electron microscopes in this center decorate the HTML hallways.

In the first lab, we show visitors the ESCA/ SIMSLAB2, a $1 million-dollar instrument used to study the isotopic composition and binding energy of surface atoms. Ashok Choudhury and Larry Harris, the principal operators, use the instrument for projects investigating corrosion of metals, failures of metals and ceramics, and interface bond chemistries.

At the end of the corridor, we enter a lab containing the Auger spectrometer, a very sophisticated instrument for determining the chemical composition of the first layer of atoms on solid surfaces. Ray Padgett, the instrument's principal operator, has spent much of his career using this spectroscopic technique for detailed analysis of specimen surfaces.

In the next lab, visitors view the impressive 4000EX Ultrahigh Resolution Transmission Electron Microscope. Because of its sensitivity to noise and vibration, the surrounding walls have been covered with noise-absorbing material. The 4000EX is used to study microstructural features of materials at the atomic level. Structural variations on a micro-scale, even those undetectable by X-ray diffraction, are readily



This $1 million-ESCA-SIMS dual-unit system is used to investigate the chemical state of surface constituents (ESCA function) and for depth-resolved isotope identification (SIMS function). The inter-connecting preparation chamber allows several different sequential analyses of the same sample under continuous ultrahigh-vacuum conditions.

characterized through the imaging done by Larry Allard, principal operator of this instrument.

Next door to the 4000EX is the 2000FX Analytical Electron Microscope. Karren More is the principal operator of this microscope, which is the primary transmission electron microscope used to characterize both the microstructure and crystallography of a specimen, and the chemistry of specimen micro-regions that are several orders of magnitude smaller than are typically characterized using the scanning electron microscope (SEM) or electron microprobe. The lighter elements, including boron, can be measured with this instrument.

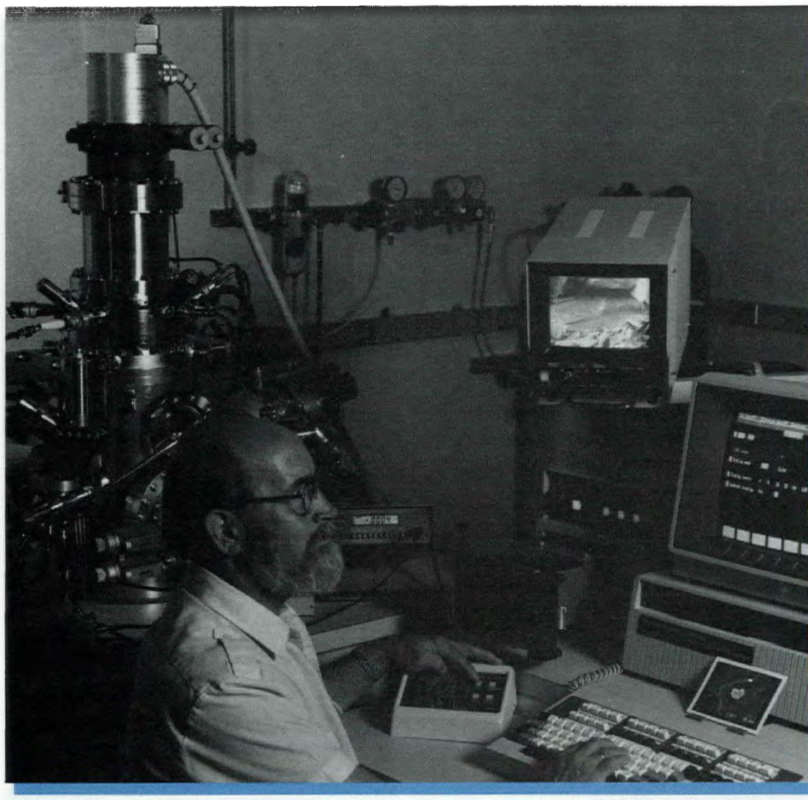
The next area we show visitors is the Hitachi S-800 Field Emission SEM. The most heavily used instrument in the HTML to date, the S-800 is operated principally by Dorothy Coffey to identify critical flaws and failure modes in ceramic and metal specimens. Using these analyses, researchers can relate the specimen's surface features to processing variables and/or failure behavior. Other applications of these results include characterization of starting materials, such as ceramic whiskers, and the effects of high-temperature and corrosive environments on a wide range of materials. Using the S-800, users can perform elemental analyses for boron and all heavier elements.

The sixth instrument in this user center complex is the JEOL 733 Electron Microprobe. Operated by Tommy Henson, this is one of the principal analytical tools for instrument elemental analysis of specimen micro-areas. The composition of a broad range of materials can be determined using the microprobe with micrometer-sized samples. This information often helps identify contaminant sources and the causes of component failures in engineering structures.

Our tour of the HTML then proceeds to the western end of the building's back corridor, to the lab area occupied by the X-Ray Diffraction User

Center and two of the HTML's three Physical Properties User Center (PPUC) labs. Camden Hubbard has responsibility for both of these centers.

The high-temperature X-ray unit, operated by Burl Cavin, is unique in having a self-contained furnace that provides the capability to identify crystal phases and measure phase-change kinetics at up to 2750°C in vacuum and to 1600°C in air. Because crystallographic changes at elevated temperatures significantly affect the performance of high-temperature structural ceramics and alloys, this instrument plays a vital role in user research. A second X-ray unit is used for making very accurate measurements at room temperature. The entire X-ray system is computer-controlled and includes a computerized data base for crystalline phase identification that lists characteristics of thousands of elements and compounds. This sophisticated combination allows users to identify unknown phases in material specimens in a fraction of the time required for manual searches—and with much higher certainty.



The Scanning Auger Microprobe, operated by Ray Padgett, probes the chemistry of the first few atomic layers of a sample surface, using a finely focused 200-Å electron beam.

Proceeding on our tour of the PPUC facilities, the first lab next door to the X-ray center houses the dual-push-rod-dilatometer, an instrument that measures the thermal coefficient of expansion for materials as a function of temperature. It is one of the few computer-controlled dilatometers currently available. In the adjoining lab, we find the Differential Scanning Calorimeter, used to measure specific heat, latent heat, and transition temperatures on samples as small as 100 mg, and the Differential Thermal Analysis/Thermogravimetric Analyzer (DTA/TGA), which is used to detect chemical reactions and phase changes in solids as a function of temperature. The third PPUC lab, located in the front hallway immediately behind the dilatometer lab, contains a Laser-Flash Thermal Diffusivity instrument that measures the diffusivity of materials at temperatures up to 2000°C on dime-sized samples. Ralph Dinwiddie assumed responsibility for this instrument's operation in September 1989.

Next on the tour is the downstairs section of the Mechanical Properties User Center (MPUC). This center, headed by Matt Ferber, also occupies some of the second-floor area. In the downstairs front hallway, visitors view a new instrument that is very popular with our users—the Mechanical Properties Nanoindenter. It is capable of making and measuring specimen surface indents less than 1 nm deep and is commonly used to characterize the mechanical behavior of various solid material surfaces.

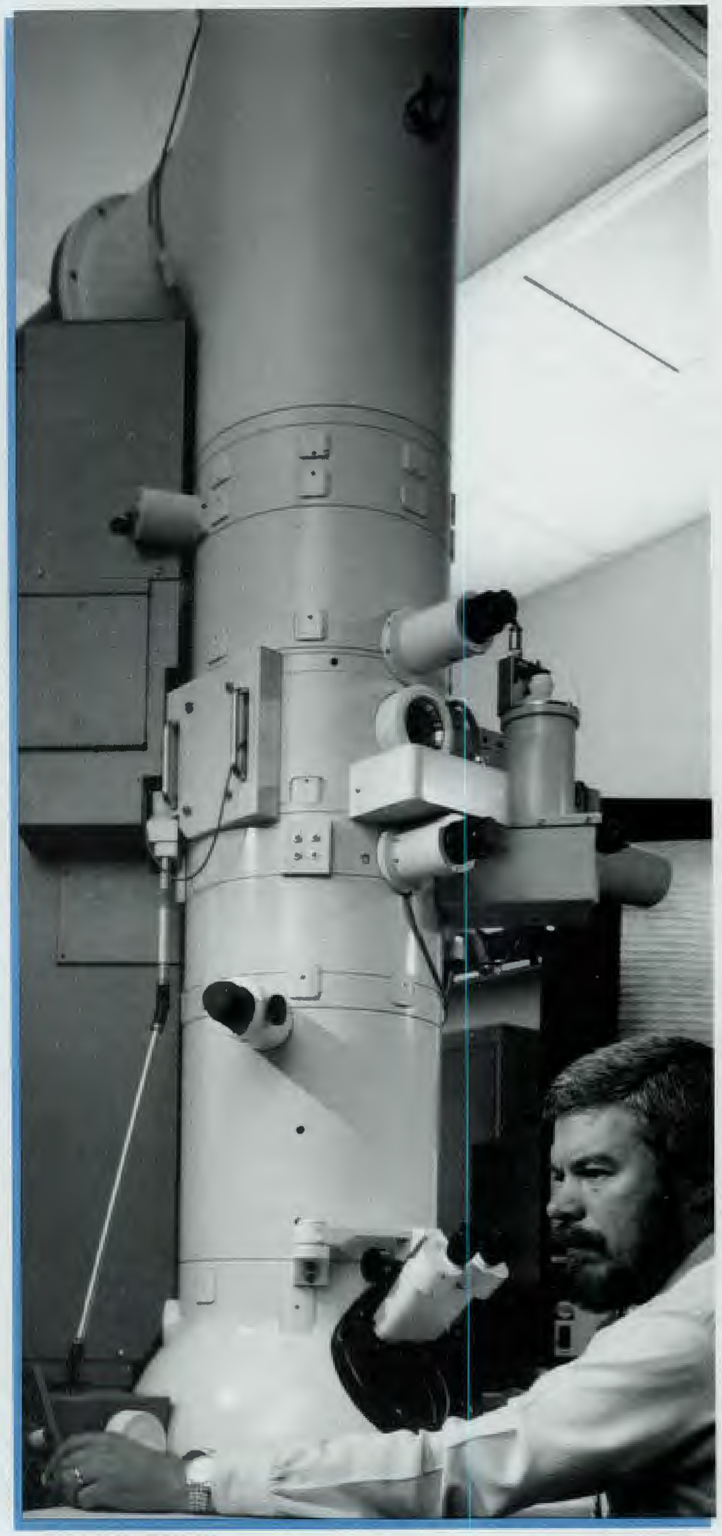
Using the JEOL 4000EX Ultrahigh Resolution Transmission Electron Microscope, operator Larry Allard produces images of crystal structures at atomic-level resolution.

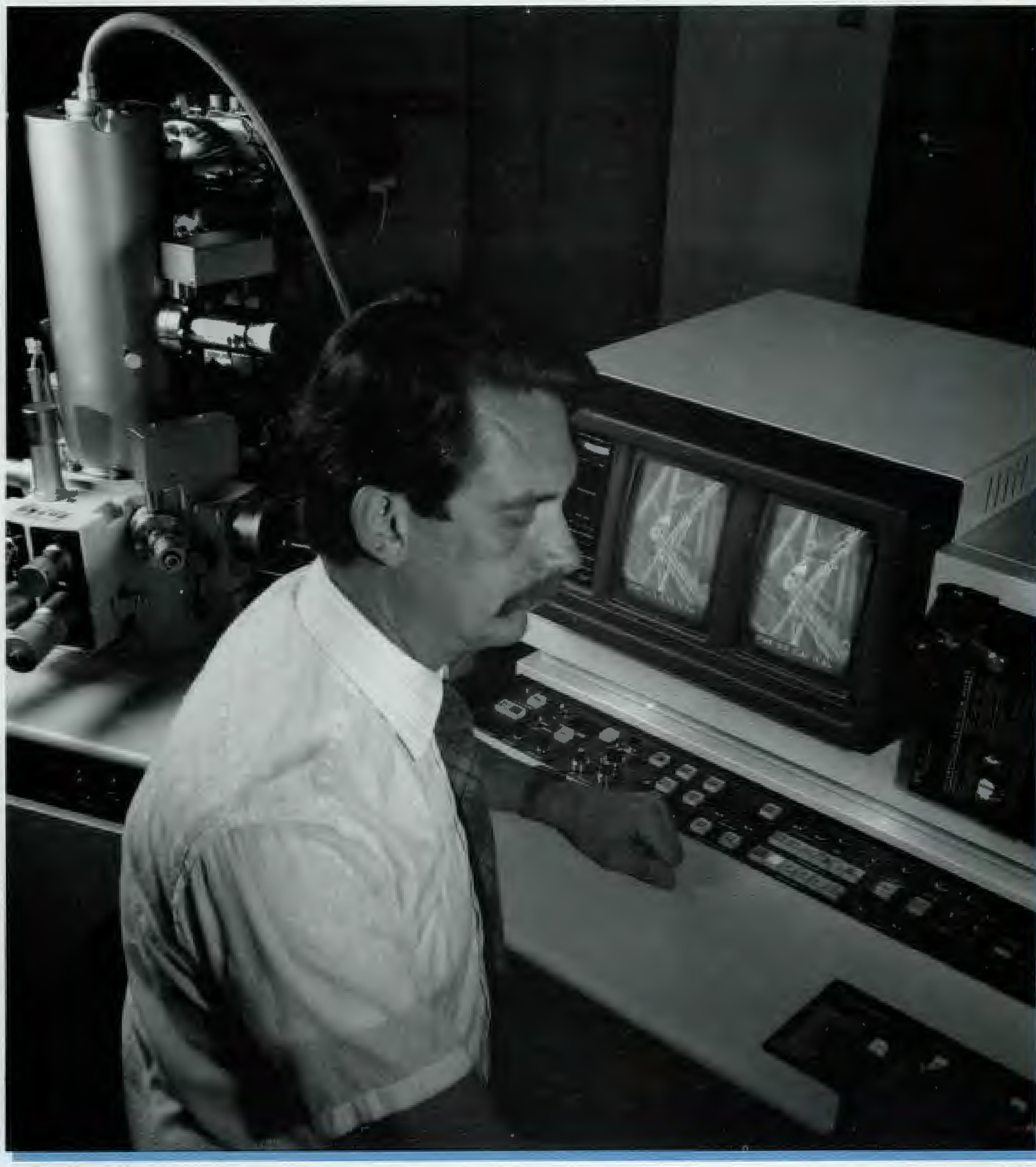
The Universal Test Machines, located on the western ground floor of the HTML, are operated principally by Ralph Martin. These state-of-the-art servohydraulic and electromechanical machines make detailed measurements of mechanical properties of materials, such as tension, compression, flexure, and fatigue under a wide range of temperature and stress conditions. A microprocessor controls the test machines, offering all the facilities normally needed in dynamic loading experiments. More complicated user-designed programs can also be facilitated through a computer interface with the microprocessor.

In the second-floor MPUC labs, visitors see specialized banks of tensile-test machines that have been modified for determining tensile properties of ceramic materials. Michael Jenkins operates the tensile facility and six flexure test systems housed in another second-floor laboratory. The total of 12 tensile machines and their related instrumentation make up the most comprehensive tensile testing facility for brittle materials in the United States.

We conclude our tour by taking visitors back to the HTML lobby, where we hand out brochures describing each major piece of equipment in the user centers and explaining how to initiate a user agreement.

The HTML has frequently been described as a "national resource," and we believe it is proving to be extremely valuable in our nation's efforts to compete internationally in the field of advanced materials. We look forward to sharing this resource with a growing number of visitors and users in the 1990s.





Ted Nolan is operating the most used of HTML's specialized instruments, the Hitachi S-800 Field Emission SEM. It provides both three-dimensional images of a specimen's surface and a "map" identifying the location of various chemical elements on that surface.

Felicia Foust, a veteran of the U.S. Air Force, attended the University of Florida. She holds an Associate Degree in Business Administration from the Knoxville Business College. She joined the staff of ORNL in 1962 as a secretary in the Neutron Physics Division, working with Everett P. Blizard in his capacity as editor of the American Nuclear Society's *Journal of Nuclear Science and Engineering*. When Blizard retired, Foust moved to the Y-12 Plant as secretary to Dixon Callihan, director of the Critical Experiments Facility there. In 1975 Foust returned to ORNL, joining the Metals and Ceramics Division. She worked as secretary to V. J. Tennery, director of the HTML, until January 1989, when she became coordinator for the HTML User Center. In this position, Foust is responsible for promoting the user program and assisting researchers in becoming facility users.

First HTML Users' Group Meeting

On August 18, 1989, the HTML User Center staff hosted the first Users' Group meeting at ORNL. All of the principal investigators listed on the 106 HTML research proposals submitted to date were invited to participate, and the 30 attendees represented 5 universities and 13 industrial companies. V. J. Tennery, director of the HTML, welcomed users to the one-day meeting, which featured stimulating and informative technical presentations and informal discussion periods, as well as a formal general meeting of all participants to end the day.

Martha Rohr, DOE-ORO's Acting Branch Chief for Energy Technology, acted as moderator and introduced speakers for the technical sessions. These featured a variety of HTML research results, such as (1) the microstructure of alumina matrix composites, presented by M. H. Rawlins of American Matrix, Inc.; (2) electrical transport properties of $YBa_x Cu_x O_x$ (F) superconducting films on sapphire, presented by R. T. Young of Energy Conversion Devices, Inc.; (3) ion-beam and plasma technology for hydroxyapatite deposition and analysis, presented by J. R. Stevenson, Ionic Atlanta, Inc.; and (4) gas-metal reactions at elevated temperatures and microstructure and phase transformation in the SiC–AIN ceramic alloys, presented by R. Lee of Ceramic Process Systems Corporation.

Tennery gave a summary report on the status of HTML research proposals, indicating that 106 user research proposals have been submitted to the facility; of these, 18 have been completed and 73 are currently active. Through the facility's eighth quarter of operation, records indicated ~950 user-days of HTML research, and two-thirds of this time represented use by industrial researchers.

Al Chesnes, director of the DOE's Heat Engine Propulsions Division, and the HTML's sponsor with DOE in Washington, addressed a general meeting of the group. Chesnes expressed his support for the work going on at the HTML and his confidence that it will prove to be of great value in revitalizing America's competitive position in advanced materials research. He informed the group of users that, in spite of the rapid growth in utilization of the HTML and its potential for expanded usefulness to a broad range of industrial, academic, and government researchers, there has been no increase in the HTML's budgetary allocation since its inception four years ago. He invited users to offer their support for maintaining the HTML's funding resources at the level necessary for upkeep to the expensive instrumentation and for expansion of the facilities to meet the growing needs in specific, nationally important, research areas.

Al Chesnes, the HTML's DOE sponsor (left), Joe Coors, president of Coors Industries, Inc., and Clyde Hopkins, president of Martin Marietta Energy Systems, Inc., discuss benefits of the HTML user facilities, following a press conference at which Coors announced licensing of a new ORNL "gel-casting" process and plans to build a ceramics facility at Oak Ridge.

Following Chesnes, Barry Burks, director of the new Office of Guest and User Interactions at ORNL, also addressed the Users' Group. He explained how the staff of the new ORNL office will be able to help streamline paperwork and facilitate future access to the HTML and other ORNL user centers.

The HTML staff is sensitive to the needs and suggestions of its users. This was made clear in the meeting's final session, which was an open discussion soliciting user and staff recommendations for improved operational performance and suggestions for setting new instrumentation priorities.

RE: Educational Activities

Molding Tomorrow's Scientists

By Helen S. Payne

Miguel Rodriguez-Velez (right), a student from the University of Puerto Rico, worked with advisor Anthony Palumbo of the Environmental Sciences Division investigating the ecological resilience of epilithic bacteria in artificial streams.

Yes, it's possible—that student spending the summer, several months, or a couple of years assisting in one of ORNL's research laboratories may be tomorrow's Nobel Prize winner in physics or chemistry! Then again, maybe not—but it *is* highly likely that some of these students will pursue graduate science degrees and someday work as members of important research teams or as teachers of future U. S. scientists. It is certain that these young people are a vital part of our nation's base for technological development and economic survival in tomorrow's world. We are proud to know we have helped many choose and succeed in scientific careers through ORNL's cooperative programs that offer exciting research opportunities for college students and faculty members.

It has become obvious that, if we want our country to maintain its high standard of living and competitive position in the world market, we must find ways to attract, motivate, and train young people for the scientific disciplines. DOE's Office of Energy Research strongly supports efforts to prevent the predicted shortfalls in America's technological workforce. One major effort enlists the participation of the national laboratories, including ORNL, in supplementing college and university resources for science and engineering education. These state-of-the-art laboratories, with their costly specialized facilities and prestigious and enthusiastic scientific staffs, offer opportunities for student and faculty research experiences that most campuses cannot provide. At ORNL and the other national laboratories, educational programs are being developed to provide greater academic interaction on various levels.

As a project administrator in ORNL's Office of University and Educational Programs, I coordinate college and university-level activities designed to encourage and support students who have shown interest and ability in scientific areas. Research appointments for terms of 2 to 12 months are made to undergraduate and graduate students and for up to 2 years in postdoctoral fellowships. Faculty appointments for 2 months to a year are also made at ORNL. These not only assist in the rapid transfer of ORNL-developed technology but also update the experimental techniques and scientific information of university staff members, who then share this knowledge with both students and faculty colleagues in a beneficial "ripple" effect. Stipends to cover expenses or maintain salary are provided for the faculty appointments by the DOE University/Laboratory Cooperative Program (ULCP) and/or ORNL divisional funding. Oak Ridge Associated Universities (ORAU), a consortium of academic institutions, often serves as administrator for these programs (see Dave Rupert's article in the *Review*, Vol. 22, No. 1, 1989).

In 1988, ORNL was host to more than 1000 undergraduate and graduate students, faculty, and postgraduate appointees as guest researchers, and the number is increasing each year. Most academic guests come for short-term research projects, but nearly one-third are given full-time assignments to ORNL divisions, performing research that may last as long as two years.

ORNL also interacts with universities by awarding research and development (R&D) subcontracts, encouraging short-term research in our DOE User Facilities and other resources, supervising students, collaborating with faculty on research participation appointments, lending personnel and equipment to academic institutions, and establishing research collaborations with universities and academic consortia.

New national programs, such as the Science and Engineering Research Semester, enable us to recruit and appoint upperclass and graduate students, faculty, and faculty-student teams from throughout the country to carry out research projects in the national laboratories, including

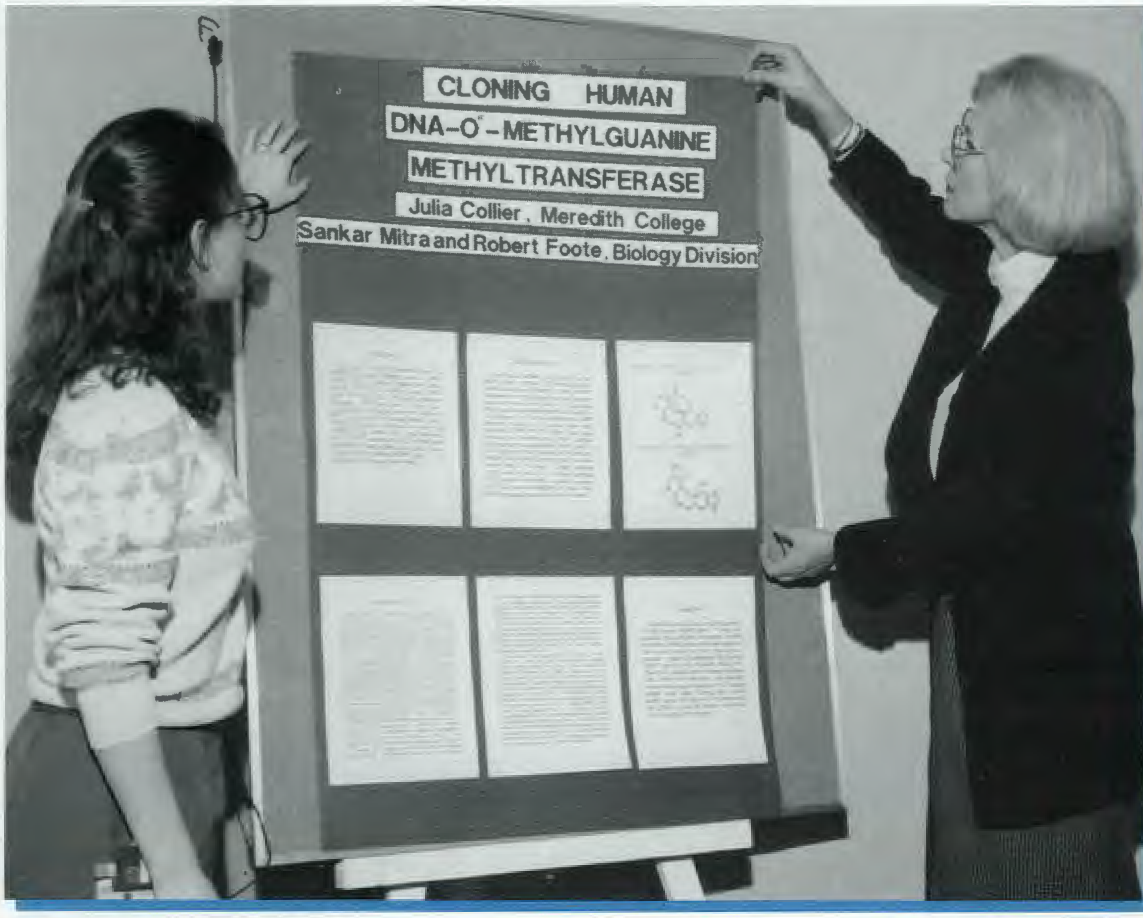
ORNL. During the fall semester of 1989, ORNL participants included students from Yale; the state universities of Virginia, Pennsylvania, Florida, and Wisconsin; liberal arts schools such as Transylvania (Kentucky) and Slippery Rock (Pennsylvania); and minority schools such as Texas A&M University, Selma University (Alabama), and the University of Puerto Rico, as well as others.

Student fields of study and research embrace the life sciences, physical sciences, mathematics, computer science, and many branches of engineering. Yet the students develop friendships and a mutual rapport during their ORNL research experience that will form the basis for interdisciplinary understanding, appreciation, and collaboration in the future. The ORNL staff mentors during these appointments often have a strong influence on the students' scientific careers in the years that follow. Staff scientists are almost universally eager to teach and counsel newcomers their field, giving the students a sample of how challenging and exciting scientific research can The ORNL programs have helped boost many nt and capable young people toward their of a scientific career.

he end of their term at ORNL, both ts and advisors complete evaluation form hese clearly indicate that th

research experience has a positive impact on career choices and the pursuit of a graduate science degree. For example, Elicia Kleinpeter, an ORNL research participant in the spring of 1989 from Cedarville College in Ohio, will return here after graduation to continue her studies and to begin related graduate work at the University of Tennessee in Knoxville. Penny Shaw, another spring semester student, has returned to the Georgia Institute of Technology to complete her graduate degree in nuclear engineering. Devon Stair, a student from Washington State University, found it easy to combine his enthusiasm for automobiles and engines with an ORNL research project developing new materials that may improve engine designs of the future.

Research participants often use their experiences at ORNL to fulfill college curriculum requirements. Papers and seminars prepared at ORNL earn college credit for some of our student visitors, and some of the reports are published in national journals or presented at important scientific conferences. Students take their ORNL research experiences seriously, as illustrated b Julia Collier, a senior from M North Carolina, wh sum



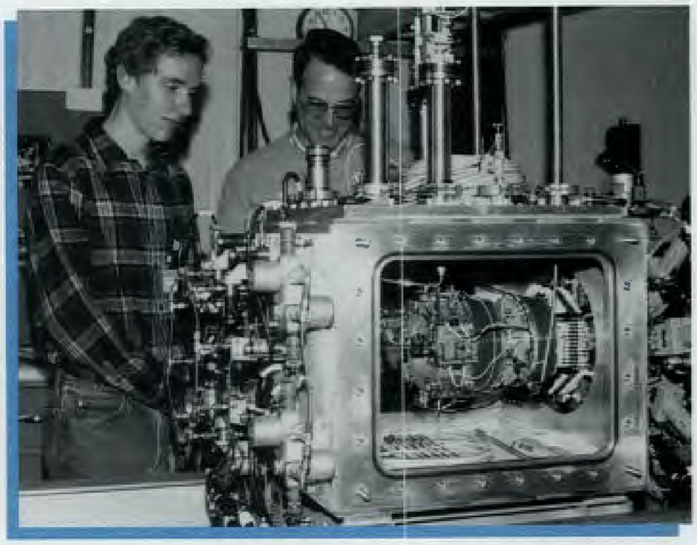
Research papers and seminars prepared by student researchers at ORNL are often used to justify college credit. Helen Payne (right) helps student Julia Collier display her results effectively.

Transylvania University in Lexington, Kentucky, is now busy organizing a group of peers and faculty members for an ORNL visit to learn about the facilities and areas of research here—strong proof that his stay at the Laboratory was a valuable and meaningful experience.

ORNL also benefits from the student researchers. In addition to infusing the Laboratory with their youthful enthusiasm, students usually work very hard and contribute to research progress. Sometimes they may become involved in a significant new development. For example Robin Reddick, a University of Tennessee graduate student, helped his ORNL staff mentors, Bruce Warmack and Tom Ferrell of the Health and Safety Research Division, develop the new photon scanning tunneling microscope—one of three ORNL developments that earned a 1989 R&D 100 Award!

Time, patience, and considerable effort are given by the staff scientists and research group members who work with our student guest researchers to ensure that their experiences here are positive and worthwhile. However, almost all of the staff involved in these programs agree that the time and effort are well spent. Although the value in terms of future contributions to our nation's science infrastructure cannot be fully measured, we are confident that many of these students become better, more dedicated science professionals because of their participation in the ORNL programs.

Students selected for a research term at ORNL gain knowledge, experience, poise, confidence—and sometimes even a little humility—from their interactions with "real" scientists in the Laboratory environment. The genuinely warm



The rapport that develops among ORNL's college research participants from various science areas is the basis for interdisciplinary understanding, appreciation, and collaboration for the future.

acceptance and encouragement they receive here have lasting positive effects on both the scientific and personal aspects of their lives. When they begin a research experience at ORNL, most students are both excited and apprehensive; when they leave, these are the confident young scientists of tomorrow. ornl

Biographical Sketch

Helen S. Payne is project administrator for college and university-level activities in the ORNL Office of University and Educational Programs. She received her B.S. degree in biology from Tennessee Technological University and has done graduate work at the University of Tennessee in biology and educational administration. Payne came to ORNL's Biology Division in 1960, left in 1964 to work as biology teacher and acting head of the Science Department at the Webb School of Knoxville, then rejoined ORNL in 1969 as a research associate in the Biology Division. She assumed her current position in 1988.

Science Honors Workshop Challenges Students

By Luci Bell

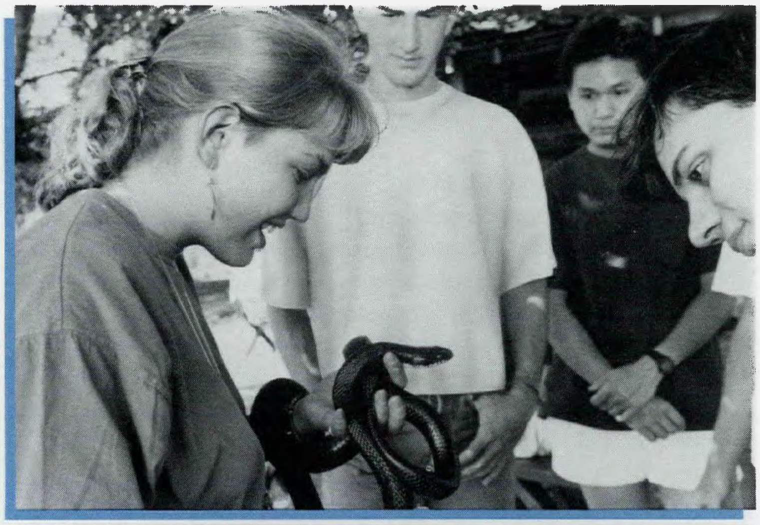
At the July 1989 dedication of ORNL's new multidisciplinary Center for Global Environmental Studies, Director Alvin W. Trivelpiece spoke about "Education, Environment, and Global Concerns." The subject was an especially appropriate one for some very special guests at the ceremonies—the student participants in the 1989 DOE High School Science Honors Program workshop at ORNL. This select group of high school students came to ORNL from all 50 states, Puerto Rico, Canada, Italy, Japan, the United Kingdom, and West Germany. They were chosen by the governors of their states and by the U.S. ambassadors to the foreign countries to come to ORNL's Environmental Sciences Division (ESD) for two weeks of research and study on environmental problems, with an emphasis on global issues.

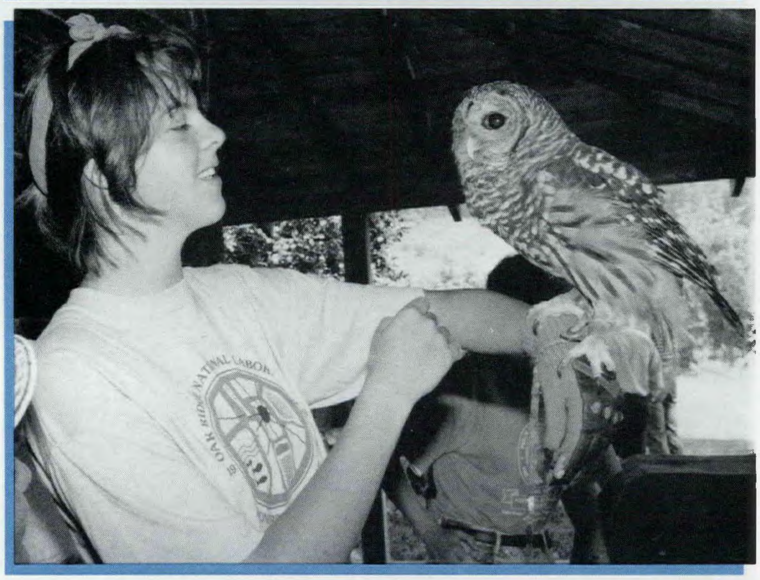
Trivelpiece welcomed the students and encouraged them to consider careers in science and engineering, pointing out that recent studies show projected U.S. shortfalls of 400,000 scientists and 275,000 engineers shortly after the turn of the century. He challenged the students to use science as a tool for solving our planet's environmental problems, quoting words by Ernest Hemingway—"The world is a fine place. It is worth our fighting for it."

The Science Honors Program is one of several DOE initiatives aimed at preventing the predicted shortfalls in U.S. technological expertise. By bringing outstanding high school students into the stimulating and encouraging research environment of our national laboratories, DOE hopes that many of these students will be influenced to pursue scientific careers. As a diversified center of research and development, ORNL is an appropriate research classroom for this program.

Fifty-seven high school students and 10 teachers came to ORNL to participate in environmental science studies. It would be hard to find a more diverse group. Besides their differences in geographical location, the students had hobbies ranging from soccer and juggling to modeling and flyfishing. Their college destinations ranged from Harvard and other Ivy League schools to Rhodes College, the University of Toronto, state universities, and—of course—"undecided." What the participants have in

ORNL Director Alvin Trivelpiece (right) visited honors students doing research at the ESD Aquatic Ecology Center: Loyde Hazada (left foreground), a freshman at the University of Puerto Rico, Hans Eckman (University of Georgia) and Graham Cummons (University of Wisconsin).





During a study unit at Freels Bend cabin on the Oak Ridge Reservation, students got acquainted with some East Tennessee wildlife.

common is a love of science, which led them to apply for the honors program.

Two of the students had also been honors program participants at other locations, and it was interesting to have their perspectives on how the ORNL program compares. Leila Tabibian, from Lake Oswego, Oregon, took part in the DOE program in 1988 at another national laboratory. She said, "The program last year also had an environmental focus, but I've enjoyed the one here much more. Everything was so well planned, and the projects were really interesting." Steve Chan, from Poughkeepsie, New York, said, "The program I attended last year in California was on supercomputers. It was nice to go to the beach in my spare time, but here at ORNL I've been really impressed with how friendly everyone is and how helpful the teachers are." The "teachers" that Chan mentions are the dedicated ESD staff members who give freely of their time and effort to ensure that the students have a productive and enjoyable research and learning experience at ORNL.

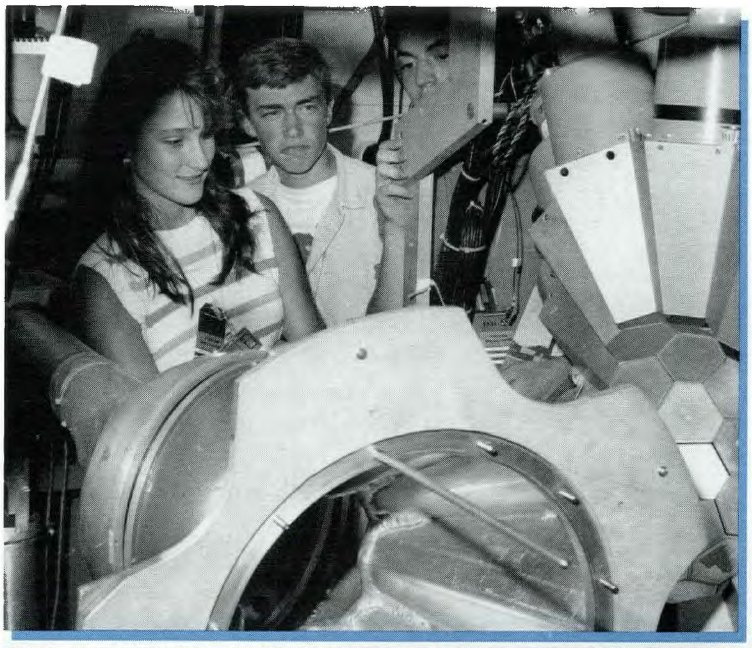
Linda Cain, who coordinates precollege activities for ORNL's Office of University and Educational Programs, feels that the real credit for the success of the honors program should go to the helpful ORNL staff members who convey to students their love of research and their belief that science can make our world a better place. To quote student Jen Klug (whose father is also a scientist) of Richland, Michigan, "Being surrounded by science all my life, I had already developed a love for it. Now I also have a deep respect for scientists, after seeing the time and work they put into their research."

Most of the honors program students really enjoyed the "hands-on" laboratory experiences, both indoors and outdoors. They especially appreciated the opportunity to go beyond the classroom and gain experience doing field research on the environment. Excursions into ORNL's National Environmental Research Park were a part of the experience. Renee Iha from

Honolulu, Hawaii, was particularly enthusiastic about her experience here. "My project was really fun to work on," she said. "We were assessing the natural plant communities in the area, so we got to hike and be outdoors a lot."

Students also learn about the more strenuous and serious aspects of research, such as record keeping and data analysis. To quote student Steve Chan again, "In research, it's not enough just to gather information; you also have to be able to draw conclusions from it."

Recreation was not neglected, of course, since honor students also love to have fun! The students were special guests at a luncheon following the July 13 dedication of the ORNL Center for Global Environmental Studies, and they also visited Dollywood and took an evening cruise on the Knoxville Queen riverboat during their stay here. Friendships quickly developed as the students lived and worked together; Jeremy Davis of Fort Smith, Arkansas, said that "After the first couple of days, we were treating each other like old friends." Steve Chan probably summed up the feelings of the student group best when he said, "Our research projects were really challenging, but the camaraderie we shared and the friendships we built were incredible!" Our hope is that, on this foundation of challenging research and shared camaraderie, these young scientists will build a strong technological future for our nation.



High school honor students (left to right) Wally Martin of Washington State, Roderich Roettger of West Germany, and Kenneth Liu of Virginia are impressed with ORNL's high-tech laboratory equipment.

Fun and friendship are important elements of the Science Honors Workshop at ORNL.

The *Review* staff would like to give special credit and thanks to Jane Anderton, an undergraduate student from the University of Tennessee, who worked at ORNL as an intern in the Public Relations Office of Martin Marietta Energy Systems during the summer of 1989. She interviewed the honors program students and provided some of the information on which this article is based.

The Real Thing

"This is the real thing!" says Susan Kelleher, an enthusiastic college student who extended her 1989 spring semester of research at ORNL to include the summer as well. "I just got involved—got my compounds synthesized—and it was time to pack up and go," Susan explained. "I wanted to stay and see how they turned out and what their properties are."

Susan has been interested in veterinary medicine since the third grade and has spent summers working with veterinarians and at the zoo in Buffalo, New York, near her home. She loves animals and, most of all, she says, "I really like the science of it." She began her college career as a biology major at Alfred University in Alfred, New York, a small school with about 2000 undergraduate students.

After taking a class at Alfred taught by Dr. Wesley Bentz, whom Susan describes as "this fantastic chemistry professor," she decided to major in chemistry as well. "Chemistry just helps me understand so many things in the world," Susan says. "I understand acid rain now, and the need for nuclear power—and how the solutions work when I give my mom a perm! I decided this was something I could do and do well, so I wanted to learn more about it."

To do that Susan applied, at the end of her sophomore year, for a research opportunity at the Argonne National Laboratory. Because these appointments usually are awarded to final-semester juniors and seniors, Argonne did not make her an offer at that time but later offered to circulate her application through the other national laboratories to see if some of their research opportunities might match her interests. Bruce Moyer, a group leader in ORNL's Chemistry Division, saw her application and contacted Susan. He sent her some research papers and information about the group's work, and a match was made.

Susan joined the group in January 1988 to begin working with Richard Sachleben on synthesizing and characterizing crown ethers—organic compounds that are used, for example, in hydrometallurgical processes for the selective extraction of metal cations. Her specific research project assignment was to synthesize and characterize alkylated derivatives of ionizable dibenzo-14-crown-4-lariat ethers. By substituting various reactive groups during the synthesis of these ethers, the researchers hope to determine what affects their extractant properties and to optimize the compounds for selectively removing particular metal cations. This might prove useful in industrial processes such as those for purifying effluent waste streams.

During her semester here, Susan was asked to synthesize these ethers

“Here they treat you like a person, give you responsibilities, and ask your opinion on things.”

with the aim of improving their ability to extract the alkali and alkaline earth metals in two-phase separations. “I was given this project,” Susan says, “and told to design the equipment, build it, and make the compounds. I was made responsible for my own work—that's the most important thing. At school they lay out the experiments for you and tell you exactly what to do, but you never really understand why you're doing it, or what's going on. You don't have to think. Here they treat you like a person, give you responsibilities, and ask your opinion on things.”

As a result, Susan extended her stay at ORNL through the summer so she would have time to help determine the binding properties and equilibrium constants for the compounds she had synthesized. “It's been great,” Susan explains, “because the people here do care about what they're doing, and I could sort of ‘come out of the closet’ and talk about chemistry with other people who are really interested in it too.”

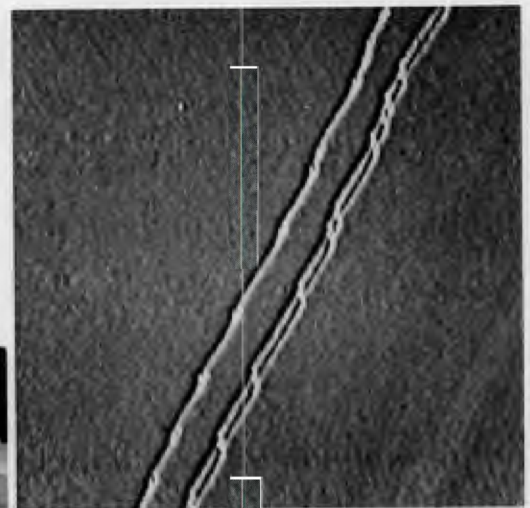
Susan believes this research experience has helped her integrate what she has already learned and has provided a focus for the future as well. “I know now that I really love research,” she says, “and I definitely plan to apply for graduate school. I'll

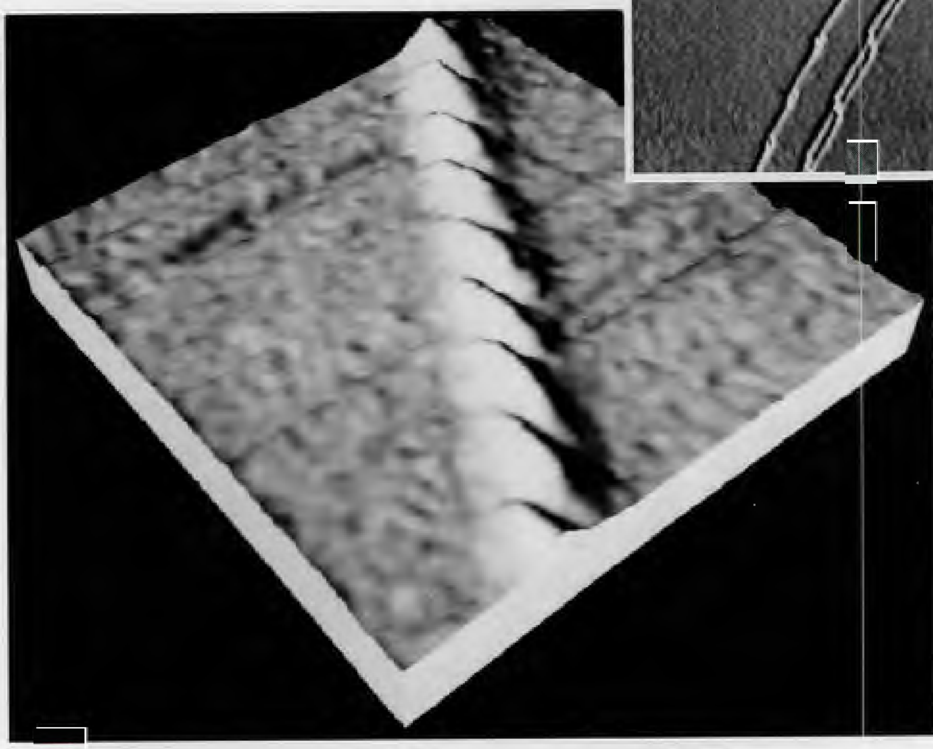
probably get a master's degree in chemistry and then work toward a doctorate in veterinary medicine, possibly at the University of Tennessee. This should give me a good background for a research career in that area.”

When asked how well our ORNL research program works from a student's point of view, Susan was very positive. “It's well organized, and everybody's willing to help,” she said. “There's a lot of paperwork involved in this program, but Helen Payne understands the needs of the students so well and is helpful in getting everything done. And I'm so grateful for the way Rick (Sachleben) and the group I'm working with has encouraged and supported me during my research project.” Susan enjoyed the social events planned for ORNL's student researchers, and she also joined enthusiastically in some activities with her own research group, such as softball and hiking in the Smoky Mountains.

Were there any negative aspects of her stay here? “Not really,” Susan says, “except that I wish the seminars were not presented at four o'clock on Wednesdays. That's when I'm really in the middle of my work for the week. As for the total research experience at ORNL—it's been great. What you learn here is so much more than just information from books. I wish everyone could do this!” *–Luci Bell*

ORNL Obtains STM Images of DNA





ORNL-produced STM images of DNA plasmid from *E. coli* bacteria.

ORNL has obtained vivid images of DNA using a scanning tunneling electron microscope (STM).

The ORNL STM is routinely producing a variety of clear images of DNA taken from bacteria commonly found in the human digestive tract. The very first DNA image was obtained earlier in 1989 by researchers from DOE's Lawrence Berkeley Laboratory and Lawrence Livermore National Laboratory.

ORNL plans to explore the possibility of using the STM to determine the locations of genes on chromosomes in cells (mapping) and the arrangement of DNA constituents in individual genes (sequencing) in the human genome, the complete set of instructions for human development.

The sharpness of the ORNL images of DNA indicates that the STM can detect changes in DNA structure as well as the binding to DNA of certain proteins and other foreign substances.

Images were obtained of the plasmid DNA isolated from *E. coli* bacteria; this DNA ring contains two complete genes. Before imaging, the DNA was exposed to ultraviolet light and enzymes to relax the supercoiled molecule, which was then mounted on a graphite surface. ORNL researchers found that its structure does not conform to the standard right-handed DNA double helix and that it has unexpected, unexplained nodes.

STM technology is about seven years old; its developers received a Nobel Prize in Physics in 1986. Only recently has the STM been used for biological imaging; its primary applications have been in research on metal and semiconductor surfaces.

The DNA images were obtained by the electron STM operated by Dave Allison and Bruce Warmack, both of the Submicron Physics Group in ORNL's Health and Safety Research Division. Another recent achievement of the group was the development of the award-winning photon STM (see "Technical Highlights" on p. 176).

ORNL Studies Clean Air Issues

On June 12, 1989, President George Bush submitted to Congress the proposed Clean Air Act Amendments of 1989. The bill reauthorizing the Clean Air Act of 1970 would guarantee (by the year 2000) a permanent 10-million-ton reduction of sulfur dioxide from 1980 levels and set a schedule for regulating toxic air emissions. In addition, the bill would sharply reduce pollutants that contribute to photochemical smog, principally urban ozone, and would establish programs for the use of vehicles operated on alternative fuels, such as methanol (the fuel traditionally used by race cars in the Indianapolis 500).

Two ORNL projects have focused on ozone and methanol. Milton Russell, an ORNL and University of Tennessee Collaborating Scientist, has studied and written about the problems of ground-level ozone reduction. His article, "Ozone Pollution: The Hard Choices," was published in the September 9, 1988, issue of *Science*, and his editorial, "Clean Air Isn't Free," appeared on the op-ed page of *The Washington Post* on June 13, 1989, the day after the President announced his clean-air proposals. These essays were drawn from Russell's ORNL technical memoranda, *Tropospheric Ozone and Vehicular Emissions* and *Ozone Pollution: The Hard Choices*.

Another ORNL project involves the evaluation of methanol as an automobile fuel under ordinary driving conditions. This project, which should receive increased emphasis and attention if the President's proposals become law, is headed by Ralph McGill, manager of the Department of Energy's Federal Methanol Fleet Demonstration Project and staff member of ORNL's Engineering Technology Division.

Methanol-fueled cars are believed less likely than gasoline-fueled cars to promote the formation of ozone, the chief ingredient of photochemical smog, because they emit potentially lower levels of hydrocarbons and nitrogen oxides, but what is even more important, they may emit lower levels of reactive hydrocarbons. Ground-level ozone is formed when reactive hydrocarbons are mixed with nitrogen oxides in the presence of sunlight.

"ORNL has provided industry with valuable information on lubricants for methanol engines."

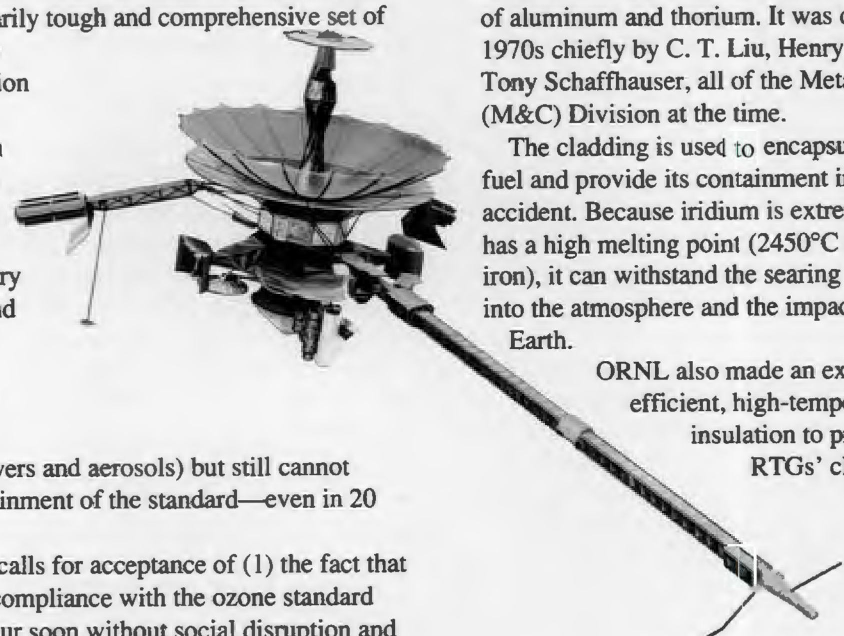
As part of the national evaluation, ORNL has leased ten turbocharged 1987 Buick Regals, five specially equipped to operate on a mixture of methanol and gasoline (at a cost of $17,000 each), and five that use only gasoline. Since 1987, more than 400 ORNL staff members have driven the vehicles more than 140,000 miles for work purposes. The methanol-fueled Regals at ORNL use fuel derived from high-sulfur Appalachian coal and get 11 mpg, about half that of the gasoline-fueled cars because methanol has only half the energy density of gasoline.

As a result of the study, ORNL has provided industry with valuable information on lubricants for methanol engines, cold-weather starting, vehicle maintenance, and in-use emissions of methanol vehicles. McGill believes that methanol-fueled cars will be competitive with their gasoline counterparts if the specially equipped cars are manufactured on a large scale and if the price of methanol drops in response to increased transportation needs for the fuel. These conditions are possible if the nation adopts the President's proposal that one million "clean fuel" cars be manufactured by 1997 to help eliminate smog in the nation's large cities.

In his writings, Russell argues that ozone pollution presents the nation with difficult choices. Ozone, he points out, is not life-threatening but does irritate the lungs and impair lung function; it also damages vegetation. The hydrocarbon sources that promote ozone formation are everywhere; they include industrial processes, solvents, paints, dry cleaning fluids, inks, household cleaners, aerosol propellants, and, of course, motor vehicles.

More than 100 U.S. areas have failed to comply with ozone limits set by the Clean Air Act of 1970; because of their basin topography, which concentrates the pollutant, Los Angeles and other parts of Southern California are frequent violators. However, Russell states that attempts to provide Southern California citizens the same level of protection against ozone given other U.S. citizens could require disruptive social changes that cannot guarantee attainment of the air quality standard.

"For example," Russell writes in the *Post* editorial, "Southern California is proposing an extraordinarily tough and comprehensive set of controls on transportation (virtual elimination of gasoline and diesel vehicles), industry (dry cleaners and bakeries), and consumer products (lawn mowers and aerosols) but still cannot ensure attainment of the standard—even in 20 years."



The *Galileo* satellite, which will send a probe to Jupiter and explore its moons, was launched on October 17, 1989.

Russell calls for acceptance of (1) the fact that universal compliance with the ozone standard cannot occur soon without social disruption and (2) the possibility that research may lead to more protective, more efficient, and possibly cheaper control systems.

"Based on present evidence," he writes in the *Post*, "much should be done to lower ozone. But the sacrifices of other social goals appear too high to justify some of the measures needed to attain the standard everywhere, at least soon. Open debate is needed on how much control makes sense and how soon."

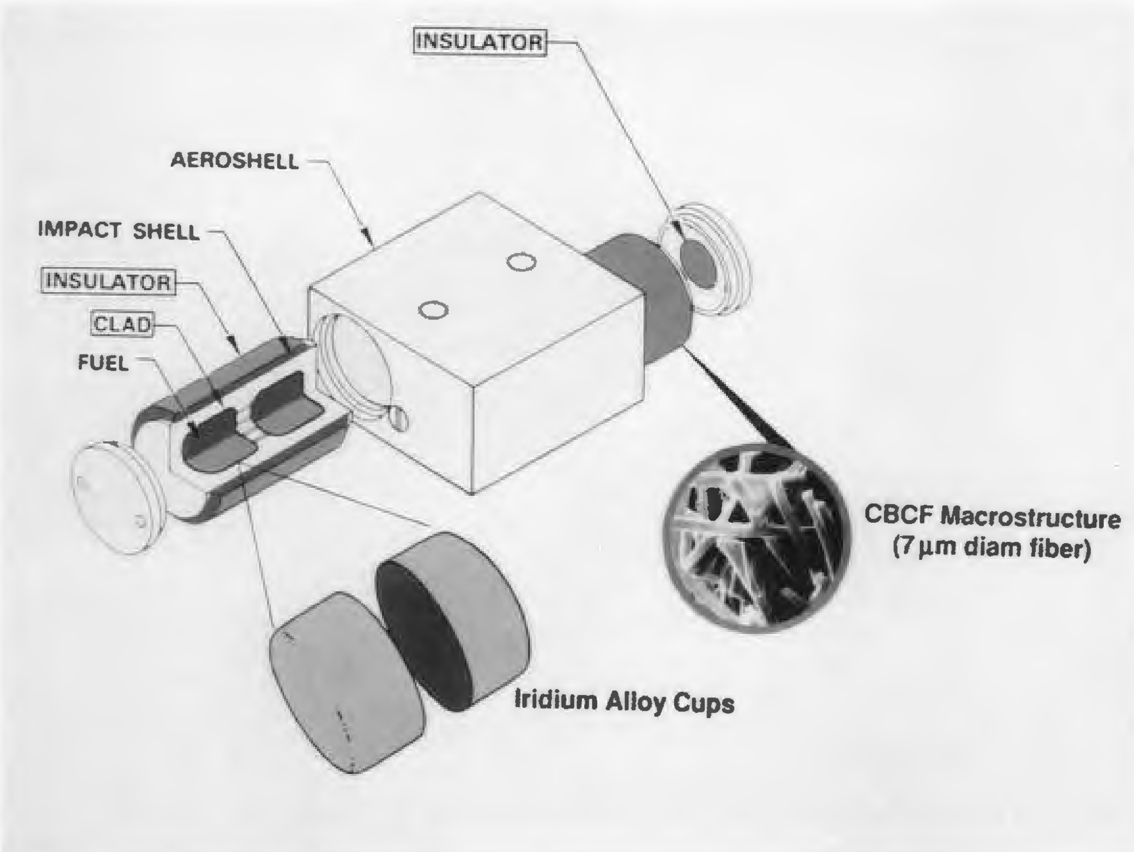
ORNL Alloy and Insulation Aboard *Galileo* Satellite

Materials made in Oak Ridge are aboard *Galileo,* the satellite launched October 18, 1989, that is headed for a rendezvous with Jupiter and its moons. The satellite's radioisotope-powered thermoelectric generators (RTGs), which supply electricity for the instruments that explore, navigate, and communicate, contain cladding and insulating materials produced by an ORNL program.

Like the *Voyager II* spacecraft, which completed its tour of the planets when it flew by Neptune on August 24, 1989, the *Galileo* has ORNL-made cladding for its plutonium-238 heat source that generates electricity. The cladding is an iridium alloy containing 0.3% tungsten and minor additions of aluminum and thorium. It was developed in the 1970s chiefly by C. T. Liu, Henry Inouye, and Tony Schaffhauser, all of the Metals and Ceramics (M&C) Division at the time.

The cladding is used to encapsulate the isotopic fuel and provide its containment in case of an accident. Because iridium is extremely tough and has a high melting point (2450°C vs 1500°C for iron), it can withstand the searing heat of reentry into the atmosphere and the impact of falling on the Earth.

ORNL also made an extremely light and efficient, high-temperature thermal insulation to protect the *Galileo* RTGs' cladding from the heat pulse of accidental re-entry into Earth's atmosphere. The insulation is composed of bonded mats of carbon fiber employed within the heat source. The carbon-bonded, carbon-fiber (CVCF) insulation maintain cladding temperature within a preferred range during normal operations. Chief developers of the CBCF insulation were Walt Eatherly and J. M. Robbins of the M&C Division.



This schematic of a radioisotope thermoelectric generator for the *Galileo* satellite shows cladding and insulation prepared by ORNL and the Y-12 Plant.

ORNL's M&C Division staff have also completed iridium alloy cladding materials and CBCF insulation for the 1990 Ulysses mission of the European Space Agency, which will harness the gravitational pull of Jupiter to loft a satellite into an orbit around the poles of the sun. These materials have been assembled into RTGs at the DOE–EG&G Mound Applied Technologies Laboratory in Miamisburg, Ohio.

Using a more cost-efficient manufacturing process and working with the Oak Ridge Y-12 Plant facilities, ORNL and Y-12 staffs are now preparing improved iridium alloy components for cladding of two new National Aeronautics and Space Administration missions. They are the comet rendezvous asteroid flyby (CRAF) and the Cassini satellite, which will orbit Saturn and send probes to its moon Titan.

Collaborating with Carl Sagan

Determining the origin of the pink and blue blotches on the surface of Neptune's moon Triton is a goal of an Oak Ridge National Laboratory study being done in collaboration with noted astronomer Carl Sagan. The coloration was observed in images sent back to Earth from the spacecraft *Voyager II* on August 24, 1989, when it flew by Neptune before leaving the solar system.

Ed Arakawa and Tom Callcott of ORNL's Health and Safety Research Division are studying methane ice along with Bishun Khare, a visiting scientist from Sagan's Laboratory for Planetary Studies at Cornell University, and graduate

ORNL optical physicist Ed Arakawa and French graduate student Christine Bruel examine a refrigerated sample holder for methane ice. They are trying to determine if radiation-induced changes in methane ice are responsible for the observed pink-and-blue blotches on Neptune's moon Triton.

student interns from the Ecole Superieure d'Optique in Orsay, France. Since 1982, the ORNL physicists have been providing Sagan with information on the absorption, reflectivity, refractivity, and scattering of light from samples simulating planetary materials and atmospheres.

Pure methane ice is clear, but methane ice crystals that have been irradiated—as they are irradiated by the trapped charged particles in Neptune's magnetosphere—are converted into colored organic molecules.

At ORNL the spectrum of pure methane ice has been obtained for most wavelengths of visible and invisible light. The next step will be to inflict radiation damage on frozen methane samples by exposing them to charged particles. Then optical analyses of the transformed methane ice will be done to determine the spectrum changes caused by radiation.

The French graduate students who worked this past summer at ORNL with Arakawa and Khare are Caroline Meisse, who measured the optical constants of simulated comet dust from Sagan's lab and from pieces of the Murchison meteorite from Australia, and Christine Bruel, who measured the optical properties of methane ice.

In 1984 Sagan, Khare, Arakawa, Callcott, and others published a paper on "The Organic Aerosols of Titan" in the journal *Advances in Space Research*. They concluded that the haze particles in the atmosphere of Titan, a moon of Saturn, may contain over 100 organic chemicals.

The paper was published after Cornell (and later ORNL) reproduced Titan's atmosphere by passing sparks through a flask containing 90% nitrogen and 10% methane. Eventually they created the reddish brown haze seen in images sent back by the *Voyager I* and *II* spacecraft, which flew past Saturn and Titan in 1980 and 1981. These dark reddish organic solids are called tholins by Sagan and Khare.

Tholins are aerosol particles containing complex organic molecules that appear as dark matter in photos. Tholins result when charged particles trapped by Saturn's magnetic field hit Titan's nitrogen-and-methane atmosphere—a process similar to one that may have given rise to life on Earth billions of years ago.

Tholins can be synthesized from simulated Titanian atmospheres by irradiation with high-energy electrons in a plasma discharge. Calculations of the optical properties of Titan tholins closely reproduce the observed spectrum of Titan, the Cornell University researchers found. ORNL's measurement of the complex refractive index of thin films of Titan tholin prepared by an electrical discharge through a gas mixture was the key initial step.

When the Cornell scientists added water to the organics created in the irradiated nitrogen-methane atmosphere, they obtained a mixture of amino acids—the building blocks of proteins, which are fundamental to life on Earth. According to the paper, "Many of these molecules are implicated in the origin of life on Earth, suggesting Titan as a contemporary laboratory environment for prebiological organic chemistry on a planetary scale."

Sagan, who considers the ORNL optical physics laboratory one of the best in the world for measuring the optical constants of planetary materials, believes information on changes in the optical spectra of materials and atmospheres during simulation experiments will help determine the composition of actual planetary materials and atmospheres.

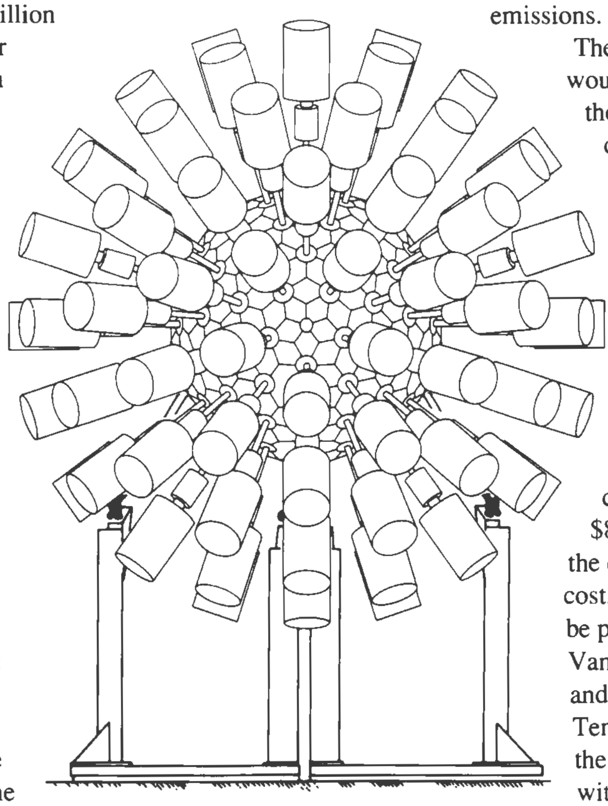
ORNL Chosen as Site for Gammasphere

A DOE panel has recommended siting the "Gammasphere" at ORNL, giving another boost to the Laboratory's flourishing basic physics program. This proposed $16-million experimental device for nuclear physics would be a 3.5-m-diam spherical array of 110 state-of-the-art gamma-ray detectors.

The DOE panel, which also considered Argonne National Laboratory and Lawrence Berkeley Laboratory as possible sites for the Gammasphere, made its recommendation to the Office of High Energy and Nuclear Physics in DOE's Office of Energy Research. That office, which sponsors nuclear physics research at ORNL, will decide whether to seek funding for the project in DOE's fiscal year 1991 budget request, to be presented to Congress in January 1990.

If funded, the Gammasphere would improve the ability of the Holifield Heavy Ion Research Facility (HHIRF) to study gamma rays produced in energetic collisions between heavy ions—the electrically charged nuclei of atoms—and target nuclei. Precise measurements of the number, energies, and directions of gamma-ray emissions from colliding ion beams and target atoms provide the most direct evidence of fundamental changes in the structure and behavior of the atomic nucleus—including size, shape, and spin—in response to the stress of high-energy collisions.

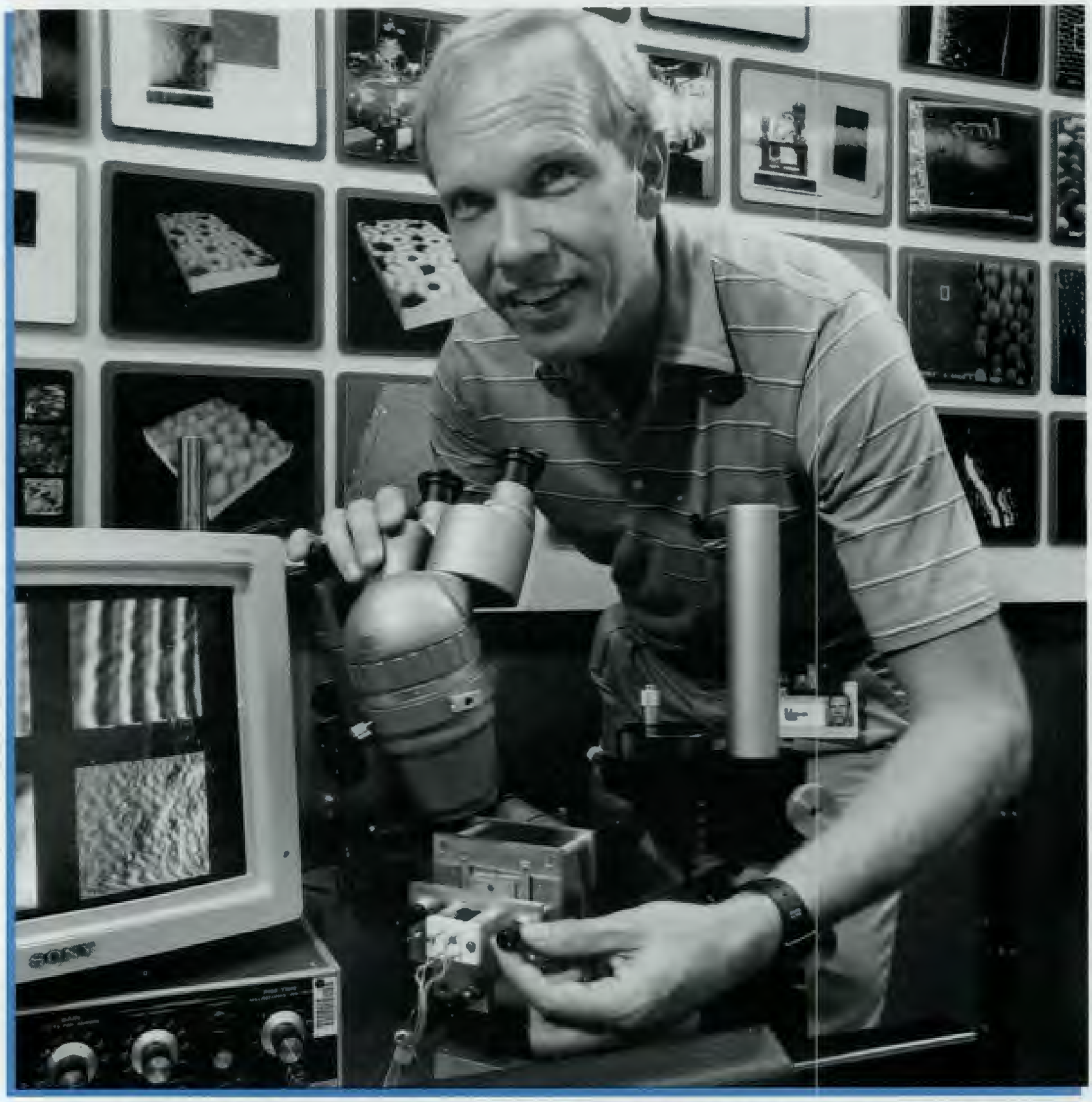
Some 300 researchers from more than 100 universities and laboratories throughout the United States and abroad are using HHIRF's two smaller gamma detector systems—the Spin Spectrometer (72 sodium iodide gamma detectors on a spherical structure) and Close-Packed Array (21 Compton-suppressed germanium crystals around a central core). Each of the Gammasphere's 110 germanium crystals would offer three times the volume of the individual detectors of the Close-Packed Array for capturing and counting gamma emissions.



Schematic of the proposed Gammasphere.

The Gammasphere would be operated at the HHIRF in conjunction with the Recoil Mass Spectrometer, which DOE approved in early 1989. To help attract the Gammasphere to ORNL, the state of Tennessee has committed $800,000 toward the estimated project cost, with $100,000 to be provided by Vanderbilt University and the University of Tennessee through the Science Alliance with ORNL.

Four Oak Ridge Innovations Win R&D 100 Awards



Bruce Warmack adjusts the photon scanning tunneling microscope he helped to develop. The instrument can visualize details of living samples as small as 10 nm—about 1000 times smaller than a human hair.

Three ORNL developments and one from the Oak Ridge Y-12 Plant were selected among the top 100 new technology advances in 1989 by the editors of *Research & Development* magazine. The ORNL developments that received R&D 100 awards were the photon scanning tunneling microscope for imaging biological specimens, a gasless metal atomization and spray-forming nozzle for making finished products, and a transmission polarizer for neutron beams from research reactors. The Y-12 Plant development extends the analytical capabilities of infrared spectroscopy to the manufacturing and research environment.

The total number of these awards received by Energy Systems (and its predecessor) in the past ten years is now 44. These award winners were selected from among thousands of U.S. scientific achievements on the basis of their importance, uniqueness, and usefulness.

Photon STM. Two ORNL researchers and a University of Tennessee graduate student were honored for their invention of a new microscope for imaging the fine structural details of bacteria, viruses, and other biological samples. This new instrument, a photon scanning tunneling microscope, has potentially important advantages over other types of research microscopes.

Unlike the electron microscope, the new device can image samples that are not electrically conductive or coated with conducting materials. Thus, researchers can study living and other biological samples at high magnification. Already, the new microscope has imaged *E. coli*, a common bacterium found in the human digestive tract.

In addition, unlike the scanning electron microscope, the new instrument can be operated outside a vacuum environment. Thus, the samples can be examined in air—an important advantage if they are alive.

The novel instrument is similar to optical microscopes because it uses light (photons) to image samples. However, it can image details as small as 100 nanometers—about one-thousandth the diameter of a human hair, making it more powerful than conventional optical microscopes.

In the new system, photons from a laser "tunnel" between the sample and the sharp tip of an optical fiber probe, which transmits them to a detector. The varying elevations in the sample surface vary the intensity of the tunneling photons. The changes in photon intensity are translated into electrical signals by the detector. This information is stored by a computer, which uses it to construct a three-dimensional image of the surface structure. (Most microscopes yield only two-dimensional images.)

The new microscope can also provide spectroscopic information that permits researchers to "map" the chemical composition of the surface they are studying, which might enable researchers to characterize the human genome. Another possible application of this mapping capability is in the production of integrated electronic circuits.

Although the microscope is currently not as powerful as electron microscopes (which use electrons rather than light to image samples), its developers are working on modifications to increase its resolution by a power of 10. This improvement would make its resolution comparable to that of a typical scanning electron microscope, which can image details as small as 10 nanometers.

Bruce Warmack and Tom Ferrell of the Laboratory's Health and Safety Research Division conceived and designed the photon scanning tunneling microscope. The device was built by Robin Reddick, a student at the University of Tennessee who is conducting graduate research at ORNL.

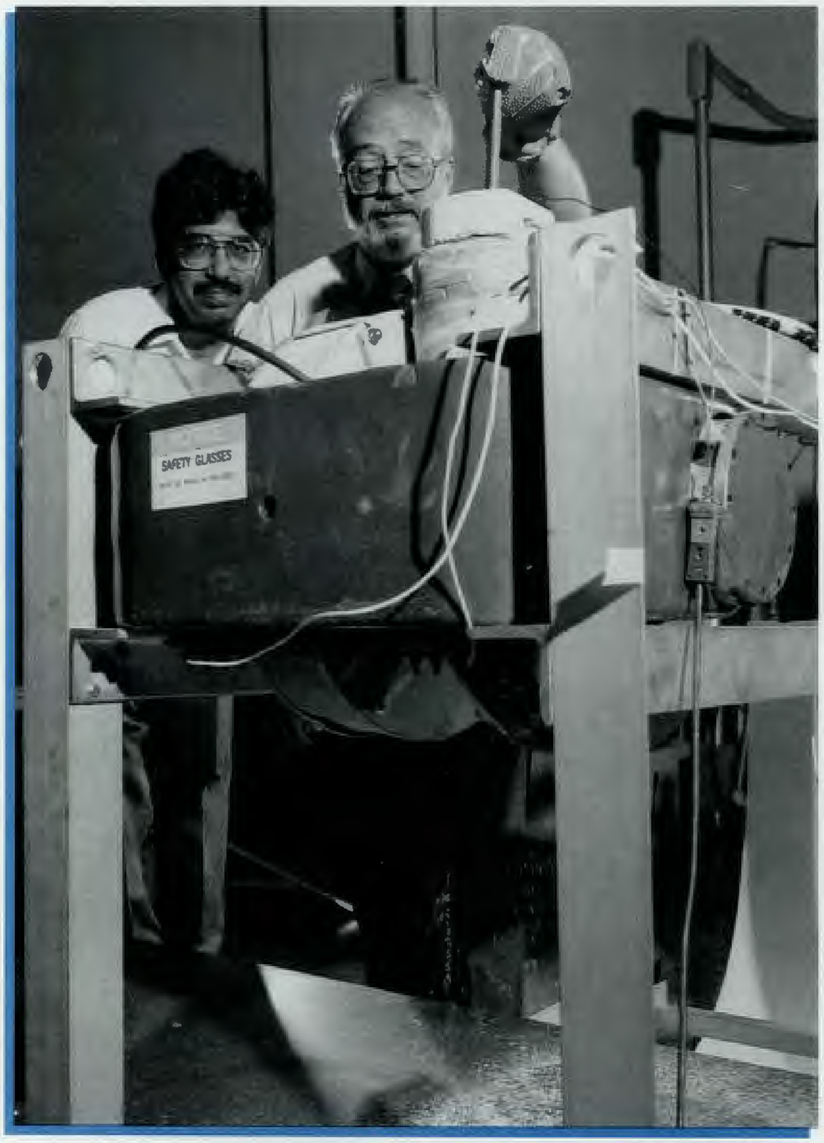
Gasless nozzle. The gasless atomization nozzle developed at ORNL offers an economical, clean, and simple method for producing high-quality powders from molten metals or alloys. Compaction of fine metal powders is considered the best, least costly method for manufacturing a wide range of automotive, aerospace, and household products. The ORNL device is also useful for the spray deposition of sheet and plate material, which can be easily fabricated into finished products.

The gasless atomization nozzle uses magnetohydrodynamic (MHD) forces to accelerate a flowing molten stream of metal and then atomize it into minute individual droplets. The MHD process produces irregular particles of a narrow size distribution that are more easily consolidated than commercially produced spherical particles into compact products having a uniform grain size and improved fatigue strength.

Because the atomization process can be carried out in a vacuum, it can also do what commercial processes cannot—atomize reactive metals such as titanium and refractory metals such as niobium, molybdenum, tungsten, tantalum, and their alloys.

Unlike other atomizers, this device uses no compressed gases, giving it several other advantages over commercial methods. It can cool the liquid droplets at a controlled rate to produce a range of metallic microstructures possessing distinct mechanical properties. Unlike commercial processes, it traps no inert gas. The dissolved inert gas in commercial powders expands during consolidation, leaving pores that

"The gasless atomization nozzle . . . offers an economical, clean, and simple method for producing high-quality powders from molten metals or alloys."



Vinod Sikka (left) and David Hobson show that the gasless atomizing nozzle they developed can produce fine droplets of molten tin that impinge and solidify on a substrate.

could be highly damaging to the fatigue strength of rotating machine parts. Finally, because the ORNL device requires no equipment for storing or recycling compressed gas, its capital and operating costs should be lower than those of devices used for commercial powder production.

Developers of the MHD nozzle are David O. Hobson and Vinod Sikka of ORNL's Metals and Ceramics Division and Igor Alexeff, professor in the Department of Electrical Engineering at the University of Tennessee.

Transmission polarizer for neutron beams. Two ORNL researchers have developed a new device for polarized neutron research. The device produces polarized beams for small-angle neutron scattering research yet minimizes the loss of neutron intensity in the polarization process. The device will greatly improve the ability of neutron scattering researchers to study the magnetic properties of materials such as the high-temperature superconductors and to determine the structure of hydrogen-containing polymers and biological materials.

The polarizer, which deflects neutrons of one spin state in a nuclear-reactor-generated neutron beam without affecting neutrons of the other spin state, allows the efficient use of neutrons at a wavelength that is abundantly available from the normal reactor spectrum (2.5 Å). The new neutron polarizer will work with about 65% efficiency at 2.5 Å, whereas the best previous devices, constructed at the Institut Laue Langevin research reactor in Grenoble, France, will not perform in this short-wavelength range.

The ORNL polarizer uses a stack of about 80 "magnetic supermirrors," multilayered structures analogous to broad-band optical filters. They are deposited on a neutron-transparent substrate to polarize a neutron beam from a research reactor.

The novel idea is the use of a single-crystal silicon mirror substrate that is nearly transparent to neutrons for neutron-beam transmission. This allows the device to polarize a beam of sufficient width to be usable in neutron experiments.

These supermirrors are a series of layers of two materials having the correct refractive index to permit neutron reflection at angles well beyond the normal reflection angle. Standard commercial sputtering techniques were used to produce the layered stack by using a new design method; the result is a polarization device far better than any commercially available.

To optimize the layer thicknesses needed for high reflectivity, a new algorithm was developed. The mathematical techniques used in the design are expected to have far-reaching implications for other types of optical devices.

Inventors of the transmission polarizer are Herbert Mook and John Hayter of ORNL's Solid State Division.

Beam "plumbing" accessory for infrared spectroscopy. The R&D 100-winning development by Louis Powell and Peggy Horton of the Y-12 Plant's Development Division (and two collaborators from Harrick Scientific Corporation) is an MHP-1 barrel ellipsoid infrared inspection accessory for extending the powerful analytical capabilities of diffuse reflectance and emission infrared spectroscopy to the manufacturing and research environment.

Possible applications of the accessory are to monitor (1) the curing and aging of adhesives and plastics and to determine the moisture content of plastics and ceramics; (2) the levels of specific impurities in ceramic materials; (3) the amount of contamination of solid surfaces by oils, silicones, and dust; and (4) the composition of thin films of organic materials, ceramics, and glasses.

With this accessory, the collimated infrared spectrometer beam is transferred several meters down a 5-cm-diam Pyrex glass tube and focused by a parabolic mirror mounted within the barrel ellipsoid onto one focal point of the ellipsoid below the barrel. Located above the barrel at the second focal point is a detector with an integrating lens. This arrangement increases the collection efficiency to more than four times that of conventional diffuse reflectance accessories.

Because the barrel ellipsoid does not extend as far as the sample location focal point, the sample can be any size as long as it is flat or convex. Infrared windows isolate the optical transfer tube from the spectrometer and barrel ellipsoid, and

John Hayter (left) and Herb Mook examine a neutron supermirror of the type used in the transmission polarizer.

these three components are separately purged to eliminate water vapor and carbon dioxide from spectra.

The optical transfer tube system makes the accessory highly flexible, greatly increasing the productivity of individual spectrometers by "plumbing" the spectrometer beam to where it is needed; this feature provides for a dual reflection/emission role and opens the door for development of new accessories for specific applications unconstrained by sample compartment dimensions.

An image of G. Louis Powell of the Y-12 Plant at the focus of a parabolic metal mirror—part of an optical "beam plumbing" system that he helped develop. The system efficiently links an infrared spectrometer and a remote sample to be analyzed.

ORNL Receives Grant for Transgenic Mouse Program

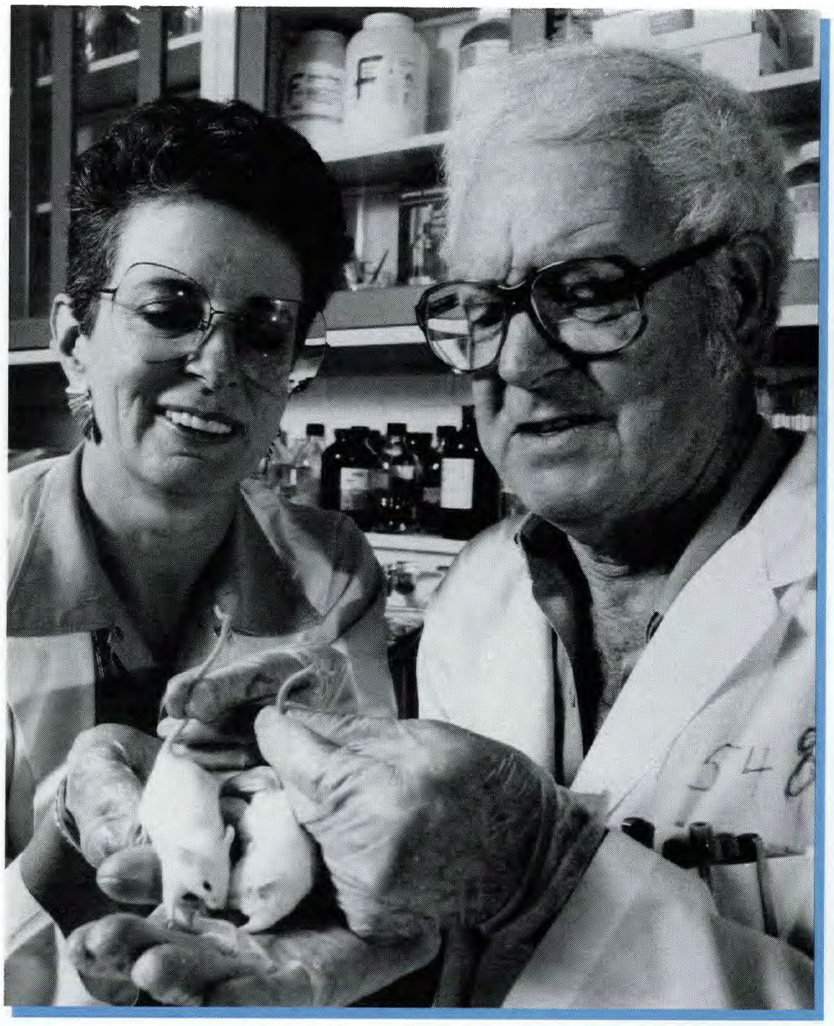
The National Institute of Child Health and Human Development has awarded a 5-year, $1.2 million grant to ORNL for a new "transgenic-mouse" program that could lead to a better understanding of how genes function.

Because mice and humans have a similar genetic makeup, the information obtained through this program could be useful to a National Institutes of Health–DOE project to "map" the locations of human genes on chromosomes and to determine the molecular makeup of these units of heredity.

Under the program, researchers led by Richard Woychik of the Biology Division are demonstrating a new molecular technology with mice. They are producing mutations in mice by inserting foreign genetic material (DNA) in mouse cells, making the resulting mice "transgenic." The foreign DNA can disrupt natural mouse genes responsible for body functions, giving rise to altered traits and new disease conditions in the animal.

"The novel feature of this approach," says Woychik, "is that the inserted foreign DNA can be used as a molecular 'tag' to locate the gene and to determine its role in inducing the observed abnormality or disease. This technique is most promising for sensitively detecting mouse genes that are responsible for special functions."

Woychik came to the Biology Division in 1987 and worked with technician Barbara Beatty to set up the division's transgenic mouse laboratory, which now has eight staff members. He learned the technique of producing transgenic mice at Harvard University in the laboratory where the first "patented mouse" was produced for cancer research.



Barbara Beatty and Bill Montgomery, both of the Biology Division, compare tail defects of two transgenic mice.

To produce transgenic mice for genetics research, Woychik and Beatty inject multiple copies of a cloned gene into the paternal genetic material of a single fertilized egg cell. The manipulated cell, which is removed surgically from a pregnant mouse, is cultured to the two-cell stage and implanted into another female mouse. After 20 days, a mouse is born to the foster mother and a small portion of the baby's DNA is analyzed to determine whether the foreign DNA is present.

Once it is confirmed that the mouse is transgenic, the researchers use standard genetic techniques to determine whether the integration of foreign DNA has interfered with the function of any normal genes. Using the inserted foreign DNA fragment as a molecular tag, Woychik and his associates can characterize the structure and function of both the mutated gene and its normal counterpart and determine their roles in the development process.

Because diseases such as cancer and diabetes in the mouse are analogous to those clinical conditions in humans, the researchers expect to use this "transgenic mouse mutagenesis" approach to identify and study genes that are associated with inherited diseases in humans. ornl

ORNL Ceramic Technology Licensed to Coors

Clyde Hopkins (right), president of Martin Marietta Energy Systems, Inc., and Joseph Coors, Jr., president of Coors Ceramics, finalize the agreement that Energy Systems will license to Coors Ceramics the new ORNL "gel casting" method for making ceramics in complex shapes. Coors also announced plans to build a ceramics facility in Oak Ridge.

Oak Ridge is emerging as a national center of ceramics research and production, as suggested at an August 18, 1989, special ceremony at ORNL's High Temperature Materials Laboratory (HTML).

At that time, Martin Marietta Energy Systems, Inc., announced it had licensed to Coors Ceramics Company of Golden, Colorado, the new ORNL "gel casting" method for making ceramics in complex shapes. The Coors company also announced its plans to build a ceramics facility in Oak Ridge. Joseph Coors, Jr., president of Coors Ceramics, said ORNL's ceramics expertise and excellent facilities, which are shared with industrial users, are partially responsible for the location of the new plant here.

Until this time, Energy Systems had licensed the ORNL-developed technology for making alumina reinforced with silicon carbide whiskers to eleven companies (see following story). Two other ceramic-related technologies have been licensed to two companies. One of the companies licensed to use the toughened alumina, Hertel AG, a manufacturer of cutting tool inserts from the

Federal Republic of Germany, is also building a manufacturing facility in Oak Ridge as the first tenant of Martin Marietta Corporation's Commerce Park.

Gel casting is superior to current ceramic molding technology because it minimizes the final machining required after the part has been sintered (heated until hardened). If molded by the gel casting process, ceramic parts can be machined before they are sintered.

The casting process begins by suspending fine ceramic powder in a water solution containing an organic compound. The suspension is poured into a mold at room temperature, where it polymerizes—forms large organic molecules that trap water, making a gel.

After the resulting gelatin-like material is removed from the mold and allowed to dry and harden, it can be machined if necessary. It is then heated to remove the organic compound and reheated at higher temperatures to form the final ceramic product.

The gel casting process was invented by ORNL researchers Mark Janney and O. O. Omatete of the Metals and Ceramics Division. Their initial research in gel casting was sponsored by DOE's Office of Transportation Systems; subsequent development for industrial application was sponsored by DOE's Office of Industrial Programs in the Conservation and Renewable Energy Program.

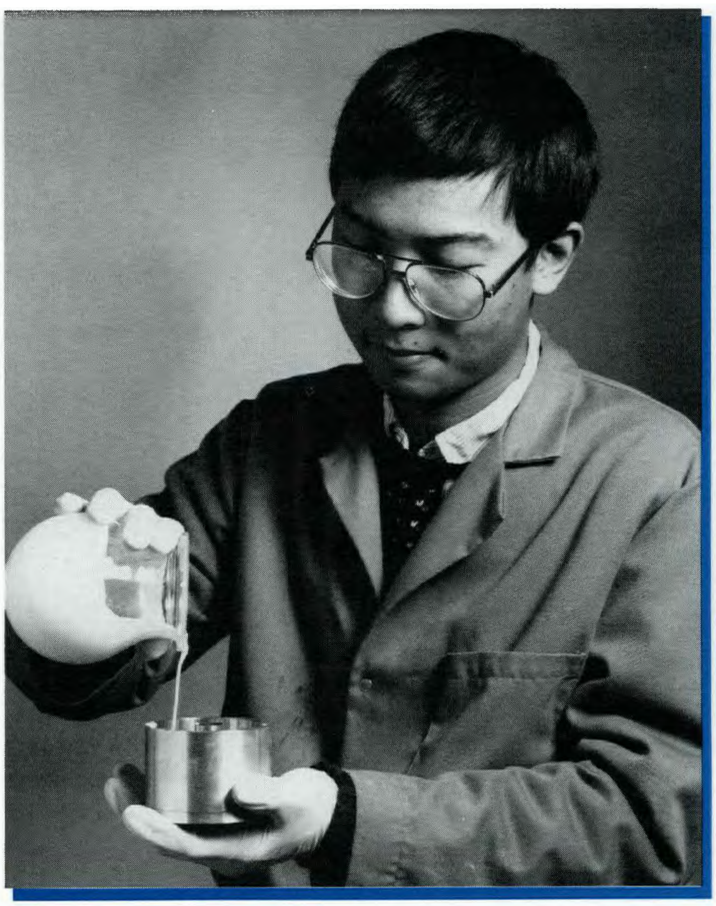
William W. Carpenter, Energy Systems vice president for Technology Applications, said the licensing agreement with Coors Ceramics and the company's decision to build a ceramics facility in Commerce Park in Oak Ridge "are evidence of the outstanding ceramics research and development capabilities of ORNL." These unique capabilities are concentrated in the HTML, a DOE user facility that can be shared with U.S. industries and universities (see p. 152).

Coors also has announced that one of its affiliates, Cercom, which is licensed to use a patented ORNL silicon-carbide–whisker-reinforced ceramic, will move some of its manufacturing activities to Oak Ridge.

The gel casting technology agreement is the 35th license Energy Systems has issued in the technology transfer program it administers as managing contractor for five DOE research and production facilities.

ORNL Ceramic Material Used by 11 Tool Makers

Eleven U.S. companies representing more than \$2 billion and 80% of the worldwide market in cutting tools now hold licenses to use an ORNL-developed ceramic composite material.



Albert Young pours a slurry of aluminum powder and pre-gel solution into a mold. Upon heating, the polymeric slurry sets into a firm gel body that can be machined, then heated to form the final ceramic product.

This human hair, magnified 2000 times, dwarfs the silicon carbide whiskers placed on it. Used to reinforce ceramics, these whiskers supplied by American Matrix, Inc., are based on an ORNL development.

Tools made of the ceramic composite have dramatically higher strength and wear resistance than metal cutting tools, because the ceramic material contains rod-like silicon carbide reinforcing "whiskers"—fibers less than 20 millionths of an inch in diameter. Produced from rice husks, the embedded whiskers deter the growth of cracks, making the composite much less brittle, even at temperatures as high as 1000°C (1835°F).

The companies licensed by Energy Systems to use the ceramic are American Matrix, Advanced Composite Materials, Greenleaf, Sandvik, Dow Chemical, High Velocity Corporation, Iscar, Cercom, Inc., Hertel AG, GTE Valenite, and Kennametal, Inc.

William W. Carpenter, vice president of Technology Applications for Energy Systems, said, "These licenses demonstrate that the national laboratory has become a significant source of marketable technology for industry. This technology has helped U.S.-based manufacturers offer an improved product and recapture market share which had been lost in the world marketplace."

Carpenter said cutting tools made of the whisker-toughened ceramic can be operated up to 10 times faster than metal tools, making it possible to machine the extremely tough superalloys. Even at the higher cutting speeds, the tools last up to seven times longer than those made of conventional materials.

Motor Diagnostic Device Licensed to Two Firms

Energy Systems has granted Predictive Maintenance Inspection (PMI), Inc., of Madison, Alabama, and Performance Technologies, Inc., of Lynchburg, Virginia, nonexclusive licenses to market an ORNL-developed device that can diagnose motor-driven systems during operation.

The technology was developed by ORNL's David M. Eissenberg and Howard D. Haynes as part of the Nuclear Regulatory Commission's Nuclear Plant Aging Research Program to assess the aging of motor-operated valves used in nuclear power plant safety systems. The licenses to these firms are the second and third nonexclusive licenses Energy Systems has granted for this technology. The first was to Wyle Laboratories of El Segundo, California.

The technology monitors an electric motor and reads the load, which changes constantly as it reacts to conditions within the system the motor is driving. The load changes are reflected back into the motor, which responds instantly to them. By analyzing the weak signals caused by these load fluctuations, the device can determine any changes in the system's condition, such as deterioration or wear.

Comparisons can be made with the established load "signature" of a properly functioning system to determine whether similar systems are operating properly. Any fluctuation in the "signature" will reveal changes in the system's condition. ornl

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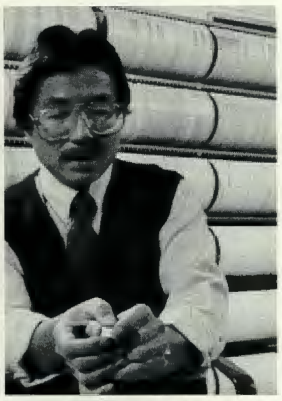

Next Issue

Invention, human behavior in emergencies, and advances in electron microscopy are among the topics.