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Oak Ridge National Laboratory review

THE FUSION MAGNETS: THE INSIDE STORY

State of the Laboratory—1985

THE COVER: Craftsman Maurice Love checks out the superconducting magnet made in Japan and now being tested in an international facility at ORNL. The story behind the six magnetic coils in the facility is told in the article on page 30.

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DEPARTMENTS

OAK RIDGE NATIONAL LABORATORY

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HERMIES, a robot being used to test artificial intelligence by ORNL's Center for Engineering Systems Advanced Research, delivers to ORNL Director Herman Postma the manuscript of his State of the Laboratory address. In a robotic monotone, Postma read aloud a note that he claimed was attached to the draft. It supposedly said, "Hey, boss, I would like a raise." Quipped Postma, "They're all alike."

State of the Laboratory—1985:
How Service Groups Support Research

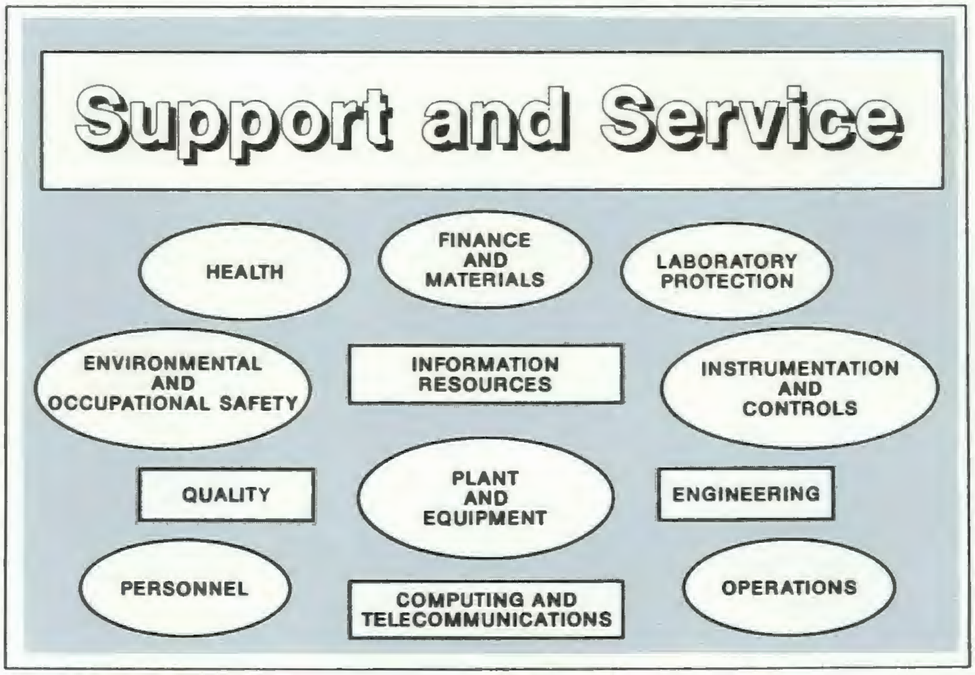
By HERMAN POSTMA

In this year's State of the Laboratory address, I salute the service and support personnel located at ORNL, who make up about 55% of ORNL's work force, including the personnel from the support organizations of Martin Marietta Energy Systems, Inc.—the Computing and Telecommunications Division, the Engineering Division, and the Information Resources Organization. Their high-quality work is important because it provides the support that research teams need to function effectively. In keeping with this theme, I have selected highlights that show various ways in which ORNL's support and service organizations have contributed to the Laboratory's success.

Staffing. Of the many vital personnel functions, none is more crucial to the Laboratory's well-being and mission achievement than our ability to attract and hire high-quality people. In 1985 ORNL achieved an outstanding record in attracting persons with Ph.D. degrees. About 72% of the outstanding candidates with doctoral degrees who were offered positions by ORNL decided to work at the Laboratory—a record Ph.D. acceptance rate in recent years.

ORNL's Personnel Division also helped find positions at ORNL for employees facing termination from the Oak Ridge Gaseous Diffusion Plant (ORGDP), where uranium enrichment and enrichment technology programs were halted because of low demand for U.S. enriched uranium for nuclear plants. The Personnel Division received more than 1800 resumes from ORGDP, interviewed more than 800 persons, and transferred 252 ORGDP employees to ORNL.

Under the leadership of Jim Barker, the Personnel Division not only met the challenge of keeping these qualified people from having to leave Energy Systems (which



In this updated report of his February 10, 1986, address to the staff, ORNL Director Herman Postma salutes the work of the Laboratory's support and services organizations in maintaining ORNL as a high-quality research facility. Services mentioned by Postma range from computerized library services and health risk information to the fabrication of large-scale breeder test equipment. Technical highlights include the development of a novel bioelectronic photosynthetic material for water splitting, an analytical technique to aid in the design of more efficient absorption heat pumps for heating and cooling buildings, a "smarter" robot, a method of using "bugs" to liquefy coal, and a computerized ultrasonic system for mapping "hot spots" on properties in the West having radioactive uranium mill tailings. Postma also notes ORNL's award-winning achievements.

operates ORNL, ORGDP, and the Y-12 Plant in Oak Ridge for the U.S. Department of Energy) but also matched them with jobs requiring their skills while offering them opportunities to learn new tasks.

Annual budget cycle. The budget cycle is a year-round process that involves and affects everyone at ORNL directly or indirectly; its annual product is the bread and butter of the Laboratory. Although the activity is continuous, it reaches its peak in the weeks preceding the Laboratory's formal budget submission to DOE in April. Throughout this period the monumental task of budget preparation is the responsibility of the members of ORNL's Finance and Materials Division, including financial officers assigned to research divisions and support and service organizations throughout ORNL.

Consider, for example, the work of three members of the Finance and Materials Division. John Hickey reviews the Laboratory's goals and missions and helps determine how much financial support is required to accomplish what ORNL sets out to do. Gus Testerman concentrates on the details, as well as the big picture, as he helps the Laboratory prepare the budget; he is primarily responsible for keeping abreast of DOE requirements and making sure that DOE guidelines are followed during budget development. Barbara Hall pulls all the budget segments together and makes last-minute corrections before the final ORNL budget is sent to Washington.

Formulating the overall budget requires teamwork. Financial experts must work with scientists and engineers to arrive at the numbers and justifications to be submitted to DOE and other funding agencies. Financial personnel also control costs to keep projects within budget and find satisfaction in the final products of their work, such as seeing a new research building or knowing that a scientific project has been authorized.

Environmental emergency response. Twice in 1985, in February and again in November, ORNL had to quickly identify unknown sources of radioactive discharge to the environment and then halt the releases. To help accomplish the task, a round-the-clock team made up of members of ORNL's Environmental and Occupational Safety Division (EOS), Operations Division, Analytical Chemistry Division (ACD), and Instrumentation and Controls (I&C) Division drew on new electronic data-gathering and analysis systems.

During the November release, the Department of Environmental Management (DEM) within EOS measured the concentrations of radioactive strontium on the Oak Ridge Reservation and at many points off-site and estimated the potential impact of the radionuclide on public health and the environment. DEM and Operations personnel then began sampling all ORNL stream outfalls into White Oak Creek, mainly surface waters and sewer systems, and pinpointed those that were contaminated. Analytical Chemistry Division personnel provided rapid analyses of the many samples brought in by sampling crews.

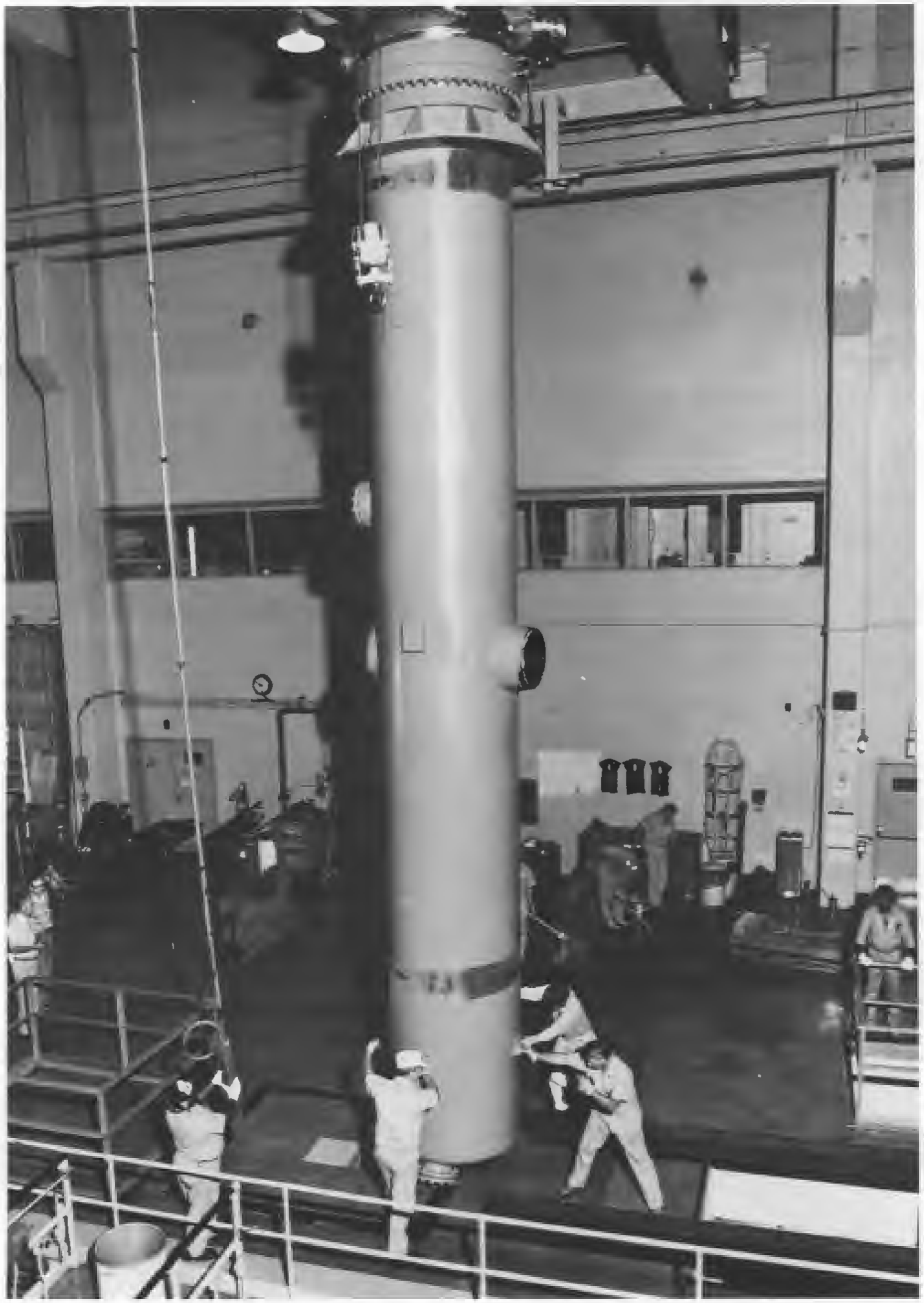
Operations Division personnel operated electronic systems that constantly sampled and monitored the White Oak Lake watershed and inputs to it; this information was telemetered back to a central computer. From all the information about locations of various contamination levels and from the data collected from the sampling, the team was able to narrow down the search area and concentrate on the most likely sources of contamination. Where contamination was found, ORNL personnel continued sampling upstream to locate the point where strontium entered each stream. Once this information was obtained, contaminated stream outfalls were plugged with sandbags and air bags, the water from these streams was pumped to a treatment facility for decontamination, and streams free of strontium were diverted to prevent further contamination. Remedial work was conducted where the contamination originated to prevent the transport of strontium from its burial site.

The flow from this storm drain south of a manhole where strontium-90 contamination was detected is blocked by sandbags added by ORNL personnel. Two pumps (one for high flow, one for low flow) pump the water over a wall to the compactment, the contents of which is pumped to the 3524 basin (feed basin for ORNL's Building 3544), where it is treated. The source of the contamination, which occurred in November 1985, was an exposed storm drain pipe at a construction site that broke during a heavy rain.

Quality assurance and large coils. Quality assurance and inspection play critical roles throughout a product's design, fabrication, and assembly to ensure the product's performance, reliability, and long-term service. An example of quality assurance in action was the careful scrutiny of the superconducting magnet coil built by Westinghouse Electric Corporation during its design, manufacture, shipment, and installation in the International Fusion Superconducting Magnet Test Facility at ORNL. Paul Burn, Ernie Childress, Jon Batey, and other members of ORNL's Quality Department did the surveillance work, checking out the progress at the Westinghouse manufacturing sites (as at the other two American suppliers of test coils—General Electric Company and General Dynamics-Convair Division) and relaying their concerns about the quality of the work to ORNL project engineers and managers. Their most important contributions were identifying problems, such as failure to meet certain specifications, and keeping the lines of communication open between each contractor and the Laboratory. They were motivated by the desire to see the last of six magnetic coils installed in the test facility's vacuum vessel so that the cooling and testing of the coils could begin. Results of these tests will be of interest because of the importance of superconducting magnets to the development of economical fusion power.

HFIR heat exchanger replacements. In 1985, for the first time since the High Flux Isotope Reactor (HFIR) began operation in 1966, two of its four heat exchangers were replaced in separate projects in July and November. The large maintenance project (two shifts a day, six days a week for a total of five weeks) involved a composite crew from the Operations and Plant and Equipment (P&E) divisions, with the Engineering Division and Quality Department providing assistance.

Because each new heat exchanger measures 11 m (35 ft) long and weighs 18,000 kg (40,000 lb), care had to be taken to ensure that the unwieldy equipment could be lifted by crane, carried, and fitted into what the workers call "the hole." The gargantuan task also involved removing the old heat exchangers and making sure that the new equipment met specifications and operated properly. Employees who played key roles in the project were Joe Arwood, Gene Hicks, Dave McGinty, and Bill Ward. Both



Primary heat exchangers are replaced at the High Flux Isotope Reactor as part of a continuous maintenance program to improve performance and safety. One heat exchanger was replaced in August; the other, in November 1985. This labor-intensive project involved detailed planning and the coordination of various divisions at ORNL.

projects were completed on time (in only 30 work days).

Forming helical field coils. The Advanced Toroidal Facility (ATF) under construction in the Fusion Energy Division is a type of stellarator designed to investigate the fusion plasma confinement properties of a novel magnetic configuration, basically a helical torus. The design and a major portion of the fabrication of the ATF helical magnetic field coils were done within the Oak Ridge complex using an array of unique capabilities. The challenge was to minimize the variations from the specified dimensions of the machined pieces to achieve very tight tolerances; to join the 24 complex segments of the two water-cooled, copper coils at the right places; and to accurately position the 1360-kg (3000-lb) segments with respect to each other. These tasks were considered by some to be impossible, but the ORNL team of computer programmers and engineers proved them wrong.

Support employees who have played key roles in this project are John Whitson of the Computing and Telecommunications Division (C&TD) and Mike Cole and Brad Nelson of the Engineering Division. They are driven by the challenge of confirming the predictions of theoretical physicists who say that the ATF should be superior to other toroidal concepts in confining the charged particles of fusion plasmas, thus raising the overall efficiency of energy production.

Upgrading security at a research reactor. Because of the increasing threat of terrorist attacks around the world, DOE has emphasized improving safeguards and security to prevent illegal entry to its facilities and avert any theft of nuclear materials. DOE has been assessing the vulnerabilities of various facilities to terrorist attacks and has increased physical security to protect against intrusion and diversion.

In 1985 ORNL improved safeguards and security at the Health Physics Research Reactor (HPRR) to meet DOE's new guidelines. The project was carried out under the leadership of Charlie

Library staff members at ORNL have been busy showing Martin Marietta Energy Systems employees how to use the new LION (Library Information On-line Network) system. At left, Allen Ekkebus provides LION training to Patience Ho of ORNL's Chemistry Division while, at right, Cathryn Nook explains the system's searching capability to Carl Petrich of the Energy Division.

Kuykendall, director of the Laboratory Protection Division, and Don Stallions, manager of the Laboratory's special nuclear materials. The goal was to develop and operate a protection system that can detect any intrusion and delay an outsider from gaining access to the reactor. By installing an adequate security system that meets DOE criteria, ORNL has saved an important program by avoiding the need to shut down HPRR for security reasons.

A LION in the library. The Library Information On-line Network (LION), or automated library catalog and circulation services, became operational in the library system of the three Energy Systems facilities in Oak Ridge a little more than a year ago. LION, which has replaced the traditional card catalog, has grown to include 55,000 books, 29,000 technical reports, and 6900 journals and book series. This data base, which is designed to save librarians and researchers considerable time, allows users to search quickly for reference material by author, title, subject, or key word.

Because LION integrates Energy Systems libraries and library functions, a user can go to any Energy Systems library and locate materials anywhere in the library system. Upon finding an item of interest, the user is told in which library the item is located and whether it is available or checked out. Some users can now remotely access LION from terminals in their offices—an increasingly popular service.

Support employees who played a key role in automating the Energy Systems libraries are Cathryn Nook, Nancy Norton, and John Phillips of the Information Resources Organization.

Heart-disease-risk information for employees. ORNL's Health Division took strides in 1985 to improve the quality of employees' medical information and to help them better understand it and benefit from it. The Division now makes available to employees videotapes produced by the American College of Physicians that discuss symptoms of arthritis and other common diseases and methods of disease prevention. In addition, the Health Division has an on-line computer system that each employee can use to estimate his or her own risk of developing heart disease.

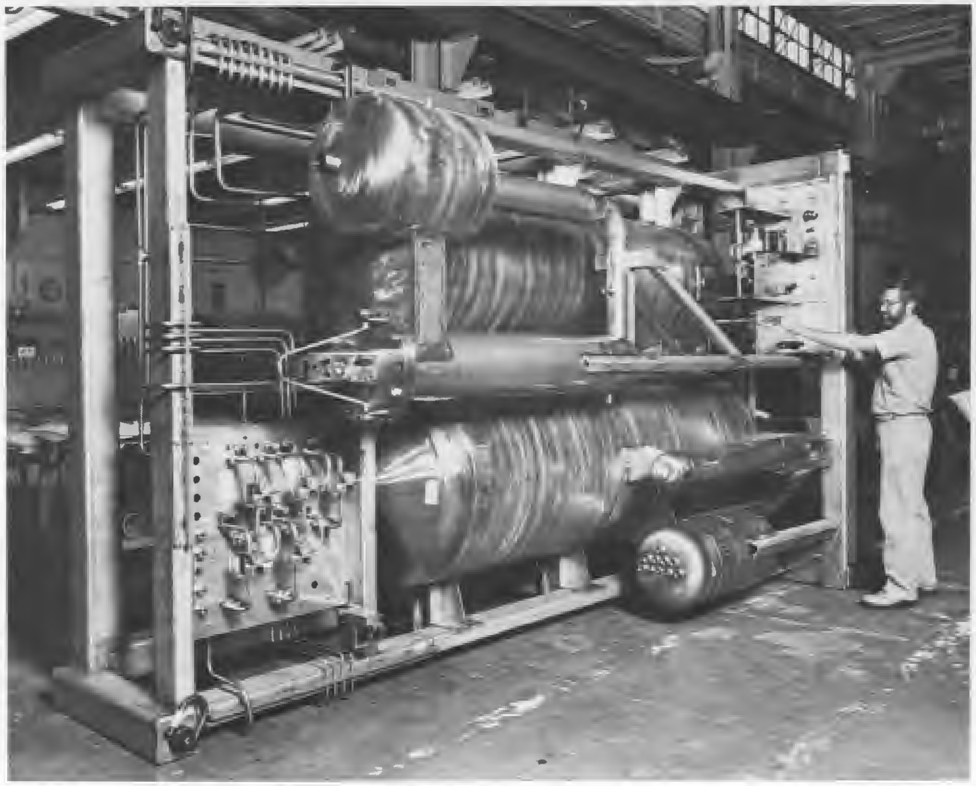
When employees have their regular physical examinations, the Health Division takes blood samples and measures concentrations of blood lipids such as triglycerides and low-density lipoprotein cholesterol, which raise the risk of heart attack because they obstruct arteries and reduce blood flow to the heart, and high-density lipoprotein cholesterol, which lowers the risk because it ties up low-density cholesterol in the blood and keeps it away from the arterial walls. These blood-lipid measurements are recorded in a computer file for each employee. Also recorded are other factors affecting coronary risk such as the employee's age, weight and height, smoking habits, and data on heart action (electrocardiogram results). A computer program developed by Roy Simpson of the I&C Division weighs all these factors and calculates the coronary risk for each employee, and a physician reviews the information with the employee. This method of patient education may motivate some employees to alter their lifestyles—eating, smoking, and exercise habits—to increase their resistance to heart disease.

Personal Computer Support Center. Personal computers are becoming an increasingly valuable tool for research. Although many employees have learned to use PCs at home, many researchers lack the time on the job to determine which hardware and software can best meet their research needs. To help employees stay abreast of what is available and particularly useful to them, the Personal Computer Support Center formally opened in February 1985. Initially under the direction of Ray Adams of the I&C Division, the center is now operated by C&TD.

The PC Support Center provides information to employees about new hardware and software through several avenues. Its staff publishes a newsletter (*The RAMbler*), maintains a wide variety of on-line news items, answers technical questions, suggests applications of PCs to research projects, and provides typical PC configurations and software for users to try out at the center.

Fuel-recycle equipment fabrication. ORNL's Consolidated Fuel Reprocessing Program has developed an Advanced Integrated Maintenance System that can remotely manipulate components and make repairs in hazardous environments, such as a highly radioactive area in a fuel reprocessing facility. Craft personnel in the P&E Division spent more than 10,000 hours in support of this project by fabricating advanced servomanipulators, equipment racks, and components that simulate a large-scale nuclear fuel reprocessing system.

Working in close coordination with their supervisors and employees of the Fuel Recycle and Engineering divisions, machinists, millwrights, and other skilled craft workers in P&E's Fabrication Department fabricated large components to very close tolerances and assembled state-of-the-art prototype equipment. This equipment greatly exceeded the size of components normally fabricated by the P&E Division. The equipment racks, for example, are almost a meter higher than the shop crane can reach. Because of the scope of the project, almost all of the Fabrication Department's 165 employees were involved in some phase of the work.



The lower equipment rack for an experiment to simulate large-scale nuclear fuel reprocessing lies on its side. A skilled craftsman works on the final details of this part of the project.

Coal-yard runoff and performance improvement. When ORNL's Quality Department first sought a project for applying the J. R. Juran approach to improving performance, it selected ORNL's coal-yard runoff problem for its first project using the "performance improvement process" (PIP). ORNL's coal pile, which stores fuel for the steam plant used to heat Laboratory buildings, poses an environmental problem: water from precipitation running off the pile is highly acidic and can pollute the stream into which it drains. In order to comply with state and federal water quality regulations, ORNL must treat the wastewater runoff from the coal pile to remove the acids.

PIP allowed ORNL managers to define the magnitude and complexity of the coal-pile-runoff problem and to use their technical skills to examine the issues involved: the treatment required to comply with regulations, the technical alternatives available for providing the required treatment, the cost of each alternative, and safety concerns for each alternative. Members of the Engineering, Operations, and EOS divisions worked together to identify which treatment processes could achieve the desired results efficiently, economically, and safely. After some important decisions were made, the contract to design and build a treatment facility was awarded to Alar Engineering Company. Key personnel implementing this recommendation were Eric Harrington, Bill Simon, and Ken Winsbro. The facility is now in operation.

The following technical highlights discuss the ongoing research and new results in the sciences and technologies at ORNL.

Acidification of Streams Depends on Land Processes

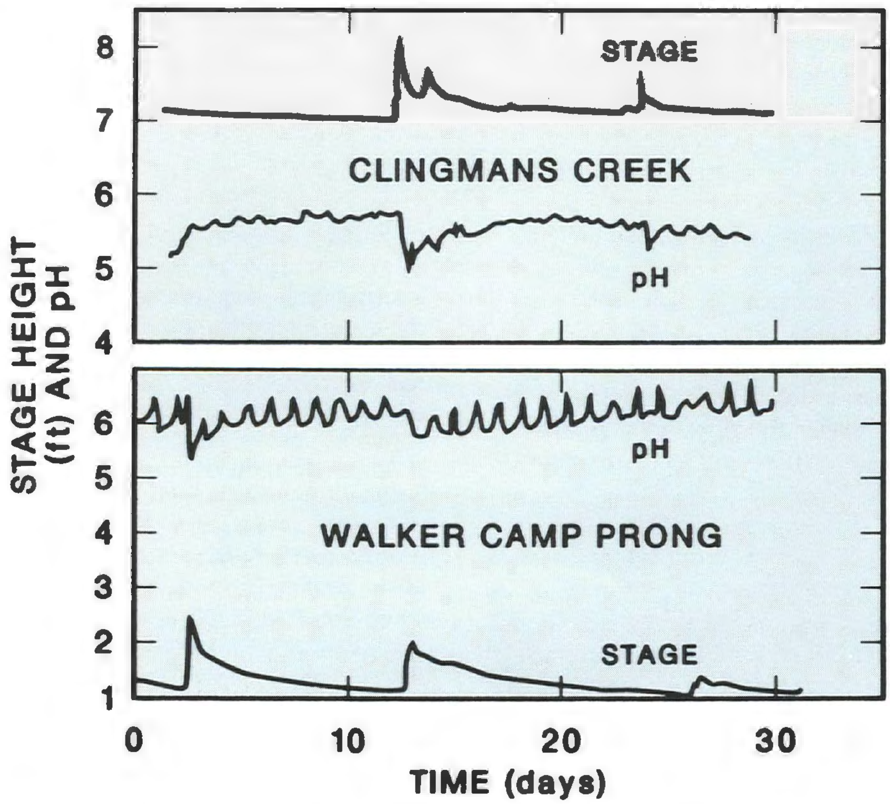
Acids deposited in some watersheds are believed to cause some mountain streams to become so acidified that fish cannot live in them. In the eastern United States, many watersheds subjected to atmospheric deposition of sulfuric and nitric acids have poorly buffered streams—that is, the surrounding soils and underlying rock contribute little to preventing acidification of the water. In these cases, scientists believe that chemical and biological processes on land play an important role in hastening—or inhibiting—the acidification of nearby surface waters.

Human activity contributes to the acidity of streams. Sulfur dioxide from coal-fired power plants and nitrogen oxides from industrial facilities and transportation vehicles combine with moisture in the atmosphere to form acids that are later deposited on the earth's surface. Hence, studies are now under way to determine if limiting these emissions would prevent acidification of mountain streams.

At ORNL the Environmental Sciences Division (ESD) is conducting a three-year project supported by the Electric Power Research Institute to investigate how chemical and biological processes affect the acidification of streams in the southern Appalachian Mountains of Tennessee and North Carolina—the Great Smoky Mountains—and in the Adirondack Mountains of New York. Results of this study show that multiple factors—watershed disturbances by heavy rainfalls and rapid snowmelts, soil characteristics, and geological features—can combine to increase or decrease the acidity of material migrating to surface water.

In the Smokies ORNL researchers found that the most acidic streams drain unlogged watersheds that have an internal source of sulfuric acid. Sulfuric acid is formed within the watershed by

Pat Mulholland of the Environmental Sciences Division collects a sample from a mountain stream at Clingmans Dome in February 1985 as part of a project to evaluate the effects of acid rain on surface water and the role of watersheds in hastening or inhibiting the acidification of streams.



Two streams in the Great Smoky Mountains show acid peaks at high flow.

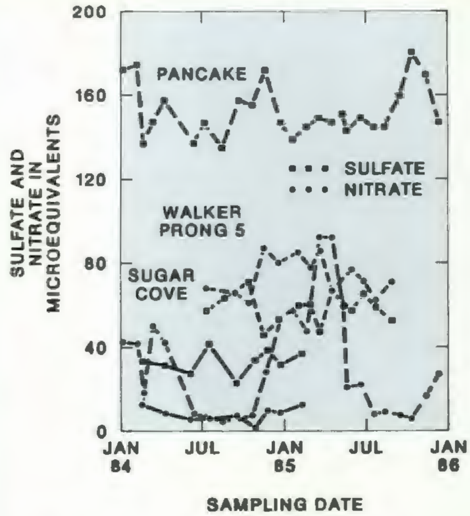
oxidation of pyrite (iron disulfide) contained in the bedrock. The pyrite has been exposed to weathering—that is, oxidation—at natural outcrops of pyrite-bearing rock or where natural landslides have uncovered the rock. They also found that nitric acid contributes at least as much as sulfuric acid to the acidification of streams in unlogged watersheds. Because nitrates in streams have no geological source, the researchers concluded that the nitrates came from atmospheric nitric acids and remineralized organic nitrogen that had been fixed by vegetation (a kind of nitrogen recycling).

In logged Appalachian watersheds having second growth and no internal source of sulfate, the input of both sulfate and nitrate to streams was found to be low, resulting in little, if any, acidification. In these watersheds, most of the atmospherically deposited sulfate appears to be retained by the soil, and most of the nitrate appears to be taken up by vegetation. The demand for nitrate appears to be especially high in recently logged and replanted watersheds because the many young, fast-growing trees require more nitrogen than mature ones. Since nitrate is a more mobile anion and is in greater biological demand than sulfate in most soils, biological processes play a more important role in limiting the transport of atmospherically deposited nitrates from soils to streams than they do in controlling sulfate transport.

In the Adirondacks, sulfuric acid was found to be the major cause of stream acidification in the logged watersheds, except during snowmelts when nitrogen input to streams increases. During these episodes, the ORNL researchers conclude, the biological demand for nitrogen is low; thus, uptake of nitrogen by vegetation is minimal. The Adirondack watersheds have no known internal source of sulfate, but retention of sulfate by their soils was observed to be less than that in the southern Appalachians. As a result, a high proportion of atmospherically deposited sulfate migrates through the Adirondack soil into the streams.

The research was conducted by Jerry Elwood, Patrick Mulholland, Ralph Turner, Maryanne Bogle, Donna Genung, and Anthony Palumbo, all of ESD.

The ORNL results are significant because they suggest that spending large amounts of money to reduce sulfur emissions from coal-fired power plants may not dramatically decrease acidification of mountain streams in poorly buffered regions having unlogged watersheds. In these areas, deposition of nitric acids may contribute at least as much as sulfuric acid to the acidification of surface waters because of the low uptake of nitrate by vegetation on land.



Acid inputs to streams in the Smokies and Adirondacks vary according to season, the nature of the watershed, the ability of the soil to retain sulfates, and the ability of the vegetation to take up nitrates.

Skin Can Aid Passage of Chemicals into Body

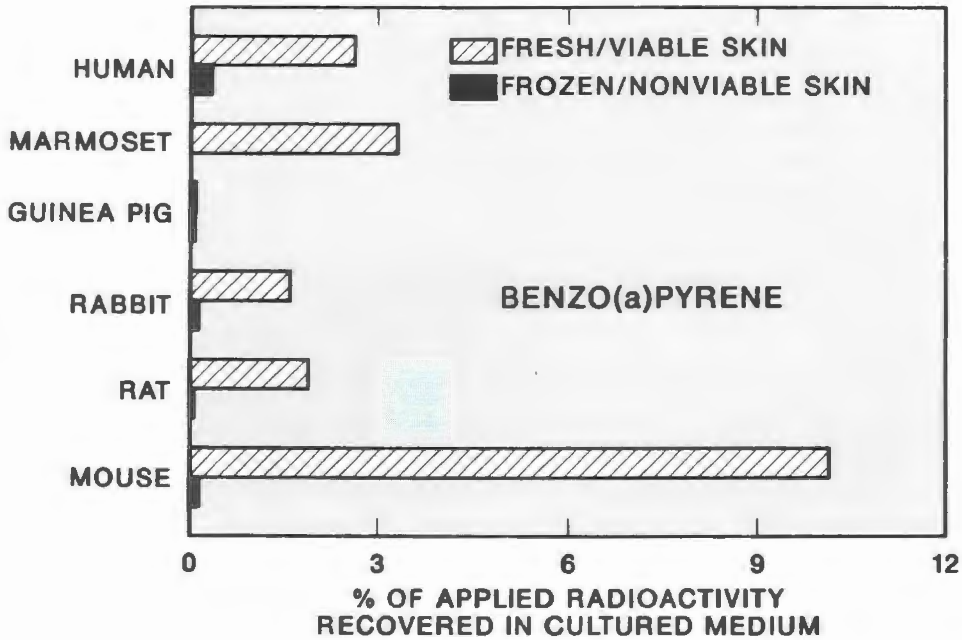
John Kao (left) and Jerry Hall prepare to analyze the effluent cultured medium from skin samples treated topically with benzo(a)pyrene

The skin has long been considered a passive protective barrier limiting the passage of chemicals into the body. Recently, however, John Kao (formerly of ORNL's Biology Division) has demonstrated that the skin can absorb chemicals, transform some into different substances (including potentially toxic ones), and serve as a pathway by which chemicals can invade the body.

Working with Mike Holland (formerly of the Biology Division), Kao also has developed culture systems for studying the effects of chemicals on circular slices of skin in an artificial environment outside the body (*in vitro*), thus permitting comparative studies of human and animal skins to be carried out under controlled laboratory conditions.

Using their *in vitro* methods for maintaining mammalian skin as short-term organ cultures, they examined the fate of chemicals in the skin following topical application. In their studies of skin preparations from mice, rats, rabbits, guinea pigs, marmosets, and humans, they found that topically applied model compounds were metabolized to a varied extent in all skin samples as the compounds passed through the skin to the culture media. One such model compound was benzo(*a*)pyrene (BaP), which is found in cigarette smoke and coal conversion fuels and discharges. The researchers found that the skin metabolism of BaP greatly facilitated its absorption and permeation through the cultured skin preparation.

In their studies of benzene, however, they observed no evidence of skin metabolism; benzene appeared to pass through the skin by diffusion, the major



The viability of the skin and the species affect the absorption of the carcinogenic chemical benzo(a)pyrene.

pathway by which chemicals are thought to enter the body by way of the skin.

In another experiment, Kao and Jerry Hall applied three closely related estrogens—estrone, estradiol, and estriol—to mouse skin. They found that the skin absorbed estrone easily and converted most of it to estradiol. However, only a small amount of the topically applied estradiol was converted to estrone; the amount of topical estradiol permeating the skin was twice as high as the amount of topical estrone. Estriol did not appear to be metabolized by the skin, and the amount of it permeating mouse skin was low (20% that of estrone).

These results support Kao's contention that, in skin absorption of chemicals, both diffusional and metabolic processes are intimately involved. Whether certain chemicals pass through the skin into the body seems to depend on the properties of the chemicals and how the skin responds to them.

The ORNL findings suggest that to protect the health of workers in coal conversion and chemical facilities, clothes should be changed frequently and skin should be well protected to limit its exposure to and contact with potentially hazardous natural and man-made chemical agents.

Chemical and Radiation Health Effects: Oxygen's Role Confirmed

The primary cause of cancer is not the array of agents produced by industrial activity, argues John Totter, a former member of ORNL's Biology Division. Totter has accumulated evidence showing that no relationship exists between the number of deaths from cancer in the United States from year to year and the changing levels of industrial pollution, including ionizing radiation. Instead, Totter believes, the primary cause of cancer is an all-pervasive, naturally occurring component of the environment. He suggests that the culprit is oxygen.

Why oxygen? Because during normal metabolism of oxygen in the body, an intermediate formed is the superoxide radical, $O_2^{\bar{\cdot}}$, which is essentially the same as the cancer-causing radical produced by radiations. Totter believes inhaling oxygen exposes a person to the equivalent of between 7 and 30 rads per year because of the formation of the highly reactive oxygen species. By comparison, the average person is exposed to a lifetime dose of 7 rads of background radiation.

Others have proposed that reactive oxygen is formed in response to exposure to some classes of chemicals, in addition to radiations, and that it causes not only cancer but also other adverse effects such as gene mutations and aging. But the reactive oxygen–mediated mechanism for biological damage has not been fully supported in the laboratory until recently.

Abe Hsie and his colleagues in ORNL's Health and Safety Research Division have produced convincing experimental evidence supporting the hypothesis that reactive oxygen species mediate the mutagenic and toxic effects of radiations and certain chemicals.

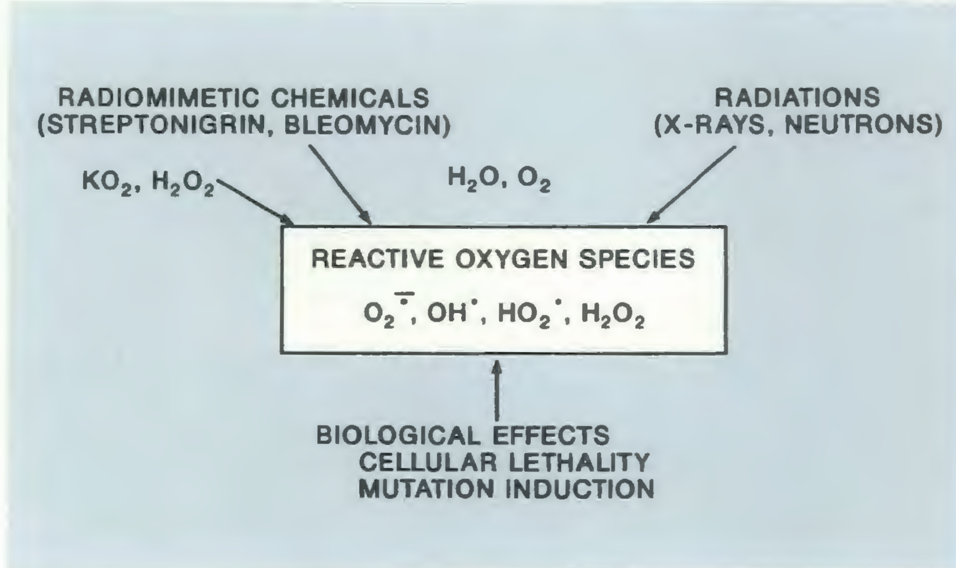
In his experiments, Hsie exposed wild-type Chinese hamster ovary (CHO) cells and their "radiation-hypersensitive transformants" to two types of

Abe Hsie (left) and Bob Schenley discuss the results of experiments showing that reactive oxygen species produced by radiations and certain chemicals play a role in inducing mutagenic and toxic effects in cells exposed to these radiations and chemicals.

radiation—X rays and neutrons—and two radiomimetic chemicals, streptonigrin and bleomycin. It is known that both the radiations and the chemicals produce two reactive oxygen species—superoxide ($O_2^{\cdot -}$) and hydrogen peroxide (H_2O_2). Hsie found that the toxicity exhibited, or the percentage of cells killed by these agents, was similar in both cell types. However, both the radiations and chemicals induced a much higher number of gene mutations in the hypersensitive cells than in the CHO cells. Potassium superoxide and hydrogen peroxide themselves exhibit similar effects.

Hsie hypothesizes that reactive oxygen species produced by the chemicals and radiations break strands of DNA, causing deletions, detectable only by sensitive DNA technologies, that could lead to mutations and cancer. He believes that use of his two cell lines will provide a way of identifying a variety of environmental agents that produce toxic and mutagenic effects by generating reactive oxygen species.

Hsie proposes that the possible role of reactive oxygen in inducing biological effects in response to radiation and chemicals could be used in developing a new common system of dosimetry. Such a system might be able to correlate biological effects with levels of chemicals or radiation known to produce the same levels of effects. Once this information is known, it might be possible to use measurements of biological damage in cells to determine the level of radiation or dosage of a known chemical to which an organism was exposed. Using reactive oxygen species as the common denominator, the toxicity and mutagenicity of various levels of radiation and doses of known chemicals could therefore be compared.



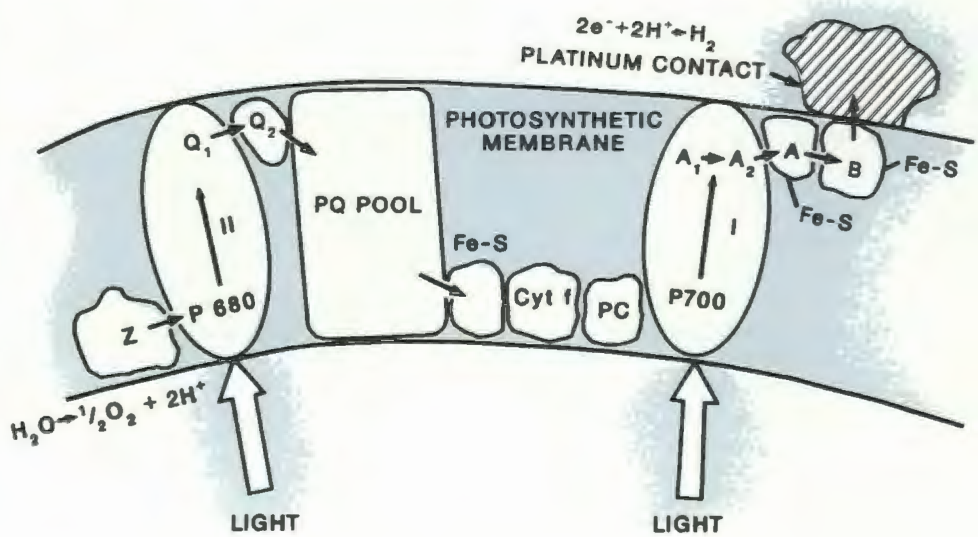
Reactive oxygen produced in the body by radiation and chemicals appears to break strands in DNA, leading to biological damage.

Novel Photocatalytic Material Produced at ORNL

A new bioelectronic material combining platinum with a chlorophyll-containing spinach membrane has been developed at ORNL. With this material researchers have demonstrated artificial photosynthesis and have split water, producing oxygen and the fuel hydrogen.

Eli Greenbaum and Perry Eubanks of the Chemical Technology Division made the composite "platinized chloroplasts" by precipitating colloidal platinum onto the photosynthetic membranes. The moistened material can produce oxygen and hydrogen when visible light is shone on it. According to Greenbaum, this system is among the simplest known for photosynthetically splitting water into molecular hydrogen and oxygen.

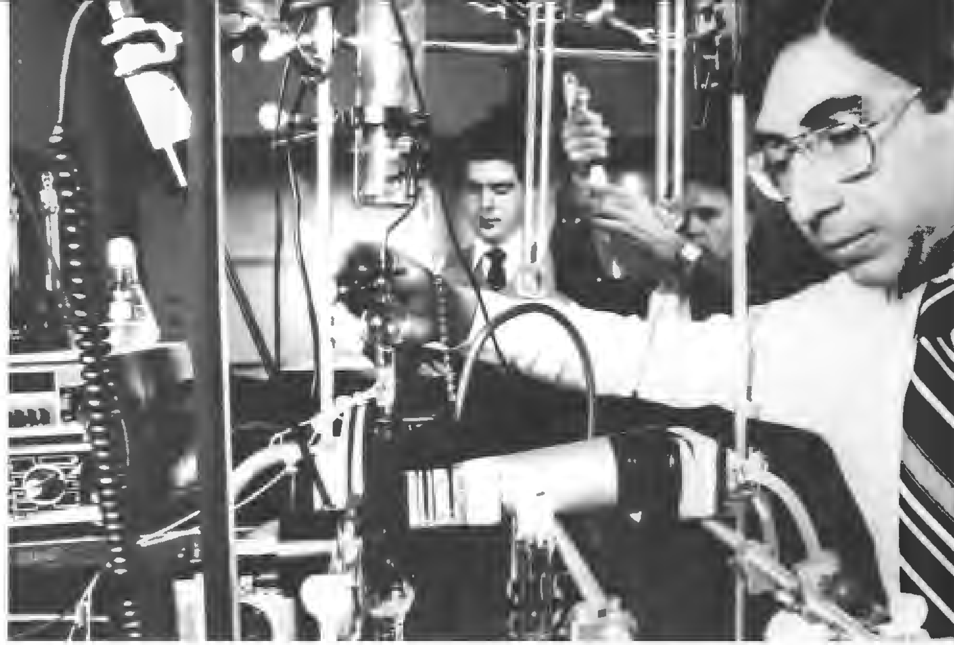
The platinum is important because it accepts electrons from the light-



Light-activated electrons flow across membrane-metal boundary.

activated thylakoid membrane so that, instead of causing carbon dioxide reduction, they split water, releasing oxygen and hydrogen. Thus, platinum serves as a catalyst for the photoevolution of energy-rich gases. Greenbaum and Eubanks are experimenting with different possible catalysts for the synthesis of other fuels.

Besides advancing the field of light-activated water splitting for producing molecular hydrogen and oxygen, the ORNL researchers have pioneered a new technology for making bioelectronic materials. Their work has drawn much attention, especially since late 1985 when platinized chloroplasts were featured on the orange-and-green cover of the Christmas issue (December 20, 1985) of *Science* magazine.



Eli Greenbaum works in the experimental facility used at ORNL to study photosynthetic water splitting. Behind him are Mark Reeves (left) and James Thompson.

Structure and Atomic Interactions Studied in Metallic Surfaces

One goal of materials research is to tailor metals, alloys, and ceramics to meet the demands of advanced energy systems. For example, efficient transportation engines require materials that can resist damage from high temperatures. In addition, materials that resist corrosion are needed in coal conversion technology. Although many usable materials have been developed by trial and error, it would be less costly to develop systematic ways of improving the properties of materials needed for harsh environments.

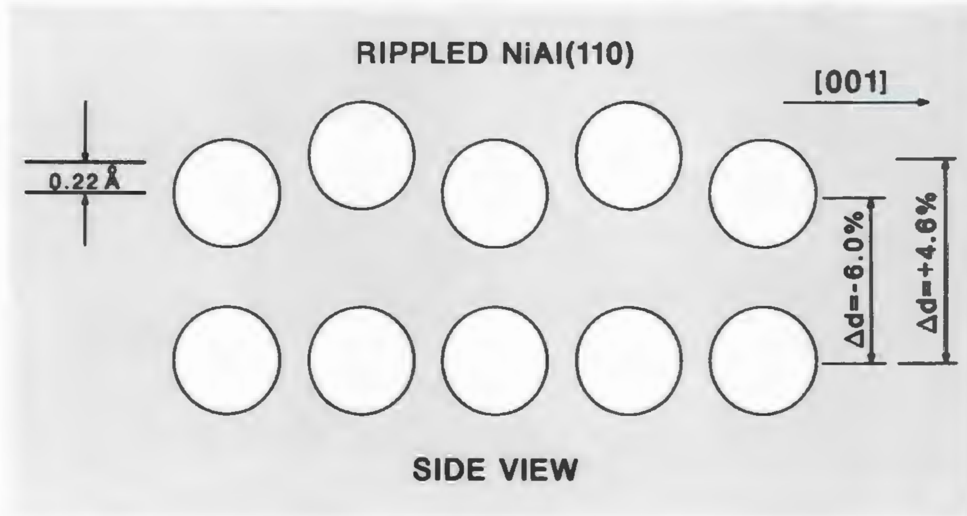
At ORNL, experimental and theoretical research on the atomic structure of surfaces is under way to understand the characteristics of materials that have desirable properties. Results of such studies could guide researchers in determining what changes are needed to tailor materials for specific needs and in developing metallic catalysts (i.e., surface agents which help produce desired chemical changes).

Harold Davis and John Noonan of the Solid State Division have been using low-energy electron diffraction (LEED) to study interactions between pairs of atoms in nonuniform environments. Because of recent improvements in theoretical techniques by Davis and new developments in experimental techniques by Noonan, LEED analyses can now be used to determine separations between atoms in surfaces to a sensitivity better than 0.02 Å. In fact, these state-of-the-art investigations at ORNL are recognized throughout the surface physics community as the most precise surface structure research in the world.

Harold Davis (left) and John Noonan plan a surface structure experiment using low-energy electron diffraction.

Davis and Noonan's past studies of one-atom-thick (monatomic) layers at the metallic surface have shown that the arrangement and proximity of atoms in the surface layer and in several near-surface layers differ from that of the atoms in the bulk of the material. The results of these studies also established that a simple universal trend appears to exist in all monatomic layers at or near the metallic surface: the distance between the outermost two atomic layers of such surfaces is always less than the distance between layers in the bulk, whereas the distance between the next two layers is always greater than in the bulk.

Recently, the researchers investigated the (110) surface of the ordered binary alloy of nickel aluminide (NiAl). Davis and Noonan's study of this surface has provided some very intriguing results, which clearly illustrate how atomic interactions change at a surface. The bulk (110) atomic layers of NiAl consist of equal numbers of Ni and Al atoms, which all are exactly in the same geometric plane. However, the atomic structure of the actual NiAl (110) surface is quite different from that of a bulk plane. The ORNL research has shown that the surface has a large



Ordered alloy (nickel aluminide, or NiAl) shows a "rippled" surface structure.

"atomic rippling" in which the Ni atoms have contracted toward the bulk, whereas the Al atoms have moved outward. The separation between the planes containing the displaced Ni and Al atoms was measured by LEED to be about 0.22 Å. A way to remember this rippling effect in NiAl, says Davis, is to think of the heavier nickel gravitating toward the bulk and the lighter aluminum rising to the surface.

The ORNL results for NiAl (110) suggest that any future research on the surfaces of ordered and disordered alloys or single-crystal and polycrystalline alloys should consider the possibility of such atomic rippling. These findings also have significance for materials scientists attempting to design new alloys for advanced technologies or to develop new metallic catalysts.

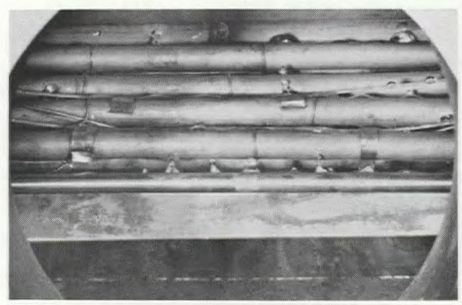
Technical Highlights—Technologies

Advanced Absorption Heat Pump Studied at ORNL

More than 50% of all the energy consumed in residential and commercial buildings in the United States is used for space heating, air conditioning, and water heating. A promising technology for cutting this energy use in half is the advanced absorption heat pump, a concept now under investigation at ORNL's Energy Division.

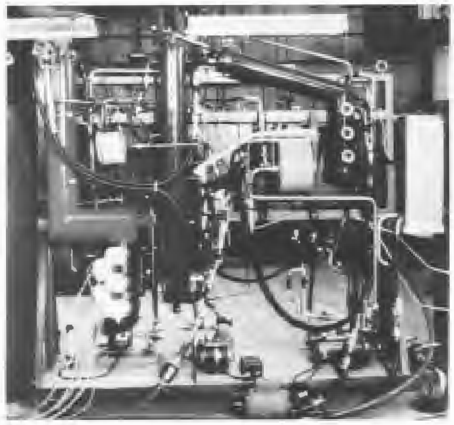
An absorption heat pump differs from a conventional electric motor–driven heat pump in the way it recompresses the vaporized refrigerant. The refrigerant, which transfers heat from outside to inside for space heating or from inside to outside for air-conditioning, is recompressed in an electric heat pump by a motor-driven compressor. However, in an absorption heat pump, the refrigerant is recompressed by dissolving it in an absorbent fluid and then recovering it by boiling it out of the absorbent at a higher pressure. Because only external heat is needed to operate the absorption heat pump—to boil the refrigerant out of the absorbent—an absorption heat pump can be run on natural gas. A motor-driven heat pump, on the other hand, requires electricity; thus, because of electricity's conversion losses, this type of pump consumes more primary energy than an absorption system.

Using DOE funds, ORNL has



The refrigerant-absorbent mixture condenses on cooling tubes in small-scale absorber experiments. The condensed fluid then flows over the fiber-optics refrigeration cycle monitor developed at ORNL. This instrument measures the local concentration of refrigerant in the fluid.

ORNL researchers examine the results from the new fiber-optic refrigeration cycle monitor to better understand the performance of advanced absorption heat pumps for heating and cooling buildings. From left to right are Leon Klatt (Analytical Chemistry Division), Michael Kuliasha (Energy Division), Robert DeVault (Energy Division), and Debra Bostick (Analytical Chemistry Division).



This advanced absorption cycle laboratory prototype is now operating at Phillips Engineering, a contractor whose development work in this area is being guided by ORNL. The contractor's first breadboard advanced absorption heat pump has achieved heating performance that is about double that of existing gas furnaces. The cooling performance of Phillips' laboratory device is comparable to that of the best air-conditioning equipment now available.

contracted with a number of industrial firms to develop advanced absorption heat pumps through the Building Equipment Research Program managed by Michael Kuliasha of the Energy Division. Three advanced cycles are being pursued by ORNL industry subcontractors, under the technical direction of Robert DeVault of the Energy Division.

Recently, Phillips Engineering, Inc., an ORNL–Energy Systems contractor, developed the first breadboard advanced absorption heat pump. The Phillips device has achieved a heating performance about double that of existing gas furnaces and a cooling performance comparable to that of the best air-conditioning equipment now available.

In support of the advanced heat pump work, ORNL has developed a unique instrument using fiber optics to measure precisely the refrigerant concentration in the refrigerant-absorbent mixture in an operating absorption device. This fiber-optic refrigeration cycle monitor measures the refractive index of fluids. Because most refrigerant-absorption fluids are binary mixtures, the refractive index of the fluid is directly related to the concentration of its individual components.

The refractive index of the solution is determined by measuring light loss from an unclad segment of fiber-optic cable that is immersed in the fluid. Changes in the fluid composition cause changes in the angle at which light rays are totally internally reflected at the core-fluid interface, thereby altering the light transmission efficiency of the fiber.

The unclad portion of the fiber is placed at the point within the refrigeration system where measurement of the fluid composition is desired. A thermocouple junction adjacent to each exposed fiber measures the local fluid temperature. Any number of modified optical fibers can be installed within a system.

Combining measurements of local concentration and temperature allows on-line monitoring and control of the refrigeration system, as well as a detailed study of heat and mass transfer processes occurring within these systems. This new measurement capability will improve the design of new absorption systems and increase their operating efficiency.

Developed by Horacio Perez-Blanco of the Energy Division and Leon Klatt and Debra Bostick of the Analytical Chemistry Division, the instrument can measure the local refrigerant concentration to an accuracy of 0.1% as the fluid condenses and flows over the cooling tubes.

A prototype of the ORNL instrument is being developed and will be sent to the industry subcontractors to assist them in developing their heat pumps. ORNL researchers will continue to use the instrument to increase their theoretical understanding of the absorption process.

Although recent advances in absorption technology have been made, further research is expected to find ways of increasing both the heating and cooling performance of these advanced cycles, cutting in half the amount of primary energy needed for heating and cooling buildings. DeVault has identified new advanced absorption cycles that promise even higher performance than the cycles now under study. His new concepts may form the basis for the next generation of advanced absorption heat pumps.

Development of Intelligent Machines Under Way at ORNL

Intelligent robots that can learn from experience and handle objects with dexterity are needed to perform work in the hazardous, unstructured environments found in fuel-reprocessing and waste-handling facilities, coal mines, off-shore oil drilling, places where explosives must be handled, and space exploration. Among the laboratories in the United States now conducting basic research in intelligent machines is ORNL's Center for Engineering Systems Advanced Research (CESAR), a multidivisional program including research staff members from the Engineering Physics and Mathematics, the Instrumentation and Controls, and the Computing and Telecommunications divisions.

CESAR's goal is to develop operational systems capable of autonomous decision making and action by merging concepts of artificial and machine intelligence with advanced control theory. By enabling the human to move as far out of the control loop as possible, intelligent machines could react more quickly, avoid potential mistakes resulting from operator fatigue, and minimize the health risk to humans who perform tasks in hazardous settings. CESAR is one of only a few U.S. multidisciplinary groups that is developing machine intelligence for real-time closed-loop navigation and manipulation with sensor feedback.

CESAR's experimental testbed is HERMIES-II, a motor-driven, untethered robot that senses its environment using sonar and machine vision and responds to computer commands sent to it by radio waves. Lately, it has demonstrated the ability to move toward, detect, and navigate around obstacles that may be moving as the robot moves and to "learn" from the experience so that it can minimize sensing on subsequent trips. HERMIES contains minimal on-board computing; much of its complex decision making and world modeling is now performed by an immobile computer that communicates with HERMIES through a radiofrequency link.

CESAR's achievements in 1985 included

Bill Hamel (left) and Chuck Weisbin examine the HERMIES-II robot, which is used by the Center for Engineering Systems Advanced Research for concept demonstration of artificial intelligence planning and learning algorithms.

- Upgrading HERMIES-II with a phased array of sonar sensors and a new vision system.
- Demonstrating navigation algorithms to make HERMIES-II avoid obstacles and developing techniques by which it can record and synthesize information from multiple journeys and, thus, learn from experience.
- Designing and building a new research manipulator called CESARM, which will be used to experimentally verify CESAR's analytical work on modeling and controlling compliant manipulators.
- Acquiring a new NCUBE hypercube parallel computer (64 processors, which are designed to have the equivalent computing power of 64 Vax 11/780's) to provide HERMIES with more powerful on-board computing capability. Up to 1024 processors can be contained within a cubic meter of space.
- Publishing leading papers in the areas of (1) multiprocessor scheduling and load balancing, (2) operating systems for real-time planning, (3) modeling the functions of the human retina, and (4) sensitivity and uncertainty analysis.
- Conducting workshops in which some of the nation's foremost experts in robotics and artificial intelligence participated.

CESAR, which is directed by Chuck Weisbin, is primarily supported by DOE; three activities sponsored by U.S. Army and Air Force laboratories complement the base DOE program in the areas of concurrent computation, dextrous manipulation in hazardous environments, and machine vision. Jacob Barhen, William Hamel, and Matthew Hall serve as principal investigators.

Their long-term goals for HERMIES are to develop its intelligence and skills and enable it to learn from experience (e.g., selective forgetting, memory organization, retrieval) and systematically acquire "common sense."

Microbes Liquefy Coal in ORNL Demonstration

Conventional methods of converting coal to liquids that can be used as fuel require considerable pressure and heat in a corrosive chemical environment. Because of the potential hazards of these extreme conditions and the expense of heating and pressurizing large amounts of coal, the use of microorganisms to liquefy coal is

These liquid droplets were produced by the action of the lignite fungus Candida *sp. ML13 on Mississippi lignite.*

Chuck Scott (left) and Jerry Strandberg use the results from a microbial surface culture for planning tests on a small, tapered fluidized-bed bioreactor. Their goal is to harness microorganisms to produce useful liquids from coal.

an attractive alternative. Such bioprocesses normally require operating conditions that are much milder than those of thermal-chemical methods of coal conversion.

Chuck Scott, Jerry Strandberg, and Susan Lewis of ORNL's Chemical Technology Division have been investigating the coal-liquefying abilities of several fungi. They have found that certain fungi could substantially solubilize many of the lower-ranked coals, such as lignites. In their studies, they found that the liquefaction rate of the most active microorganisms depends on the various chemical characteristics of the coal, including the oxidation state.

The liquid product obtained by the microbial action on lignite is not well defined, but the ORNL researchers determined that it includes a large number of soluble molecular constituents, some of which have moderate to high molecular weights. These constituents may be suitable for fuels and industrial chemicals.

Scott, Strandberg, and Lewis have carried out most of their work using surface cultures in which coal particles are placed on the surface of fungal mats. However, they plan to do experiments with organisms that can be induced to attach to the solid surface of coal particles suspended in a culture medium. The suspension method may be the best way of operating a large-scale coal bioprocessing plant.

The ORNL researchers' goal is to discover which microorganisms are particularly suited to converting coal to useful liquid products. Their work will involve determining which temperatures and other operating parameters increase the speed and amount of liquefaction, characterizing the liquid products, and testing bioprocesses that could be scaled up for commercial production of liquid fuels.

Ultrasonic Ranging and Detection System Developed at ORNL for Locating Contaminated Properties in the United States

Thousands of homes and other structures in Colorado and other western states were built with materials containing slightly radioactive tailings from uranium mills, which pose a potential health hazard. DOE has the task of identifying the properties having these tailings and cleaning up the sites.

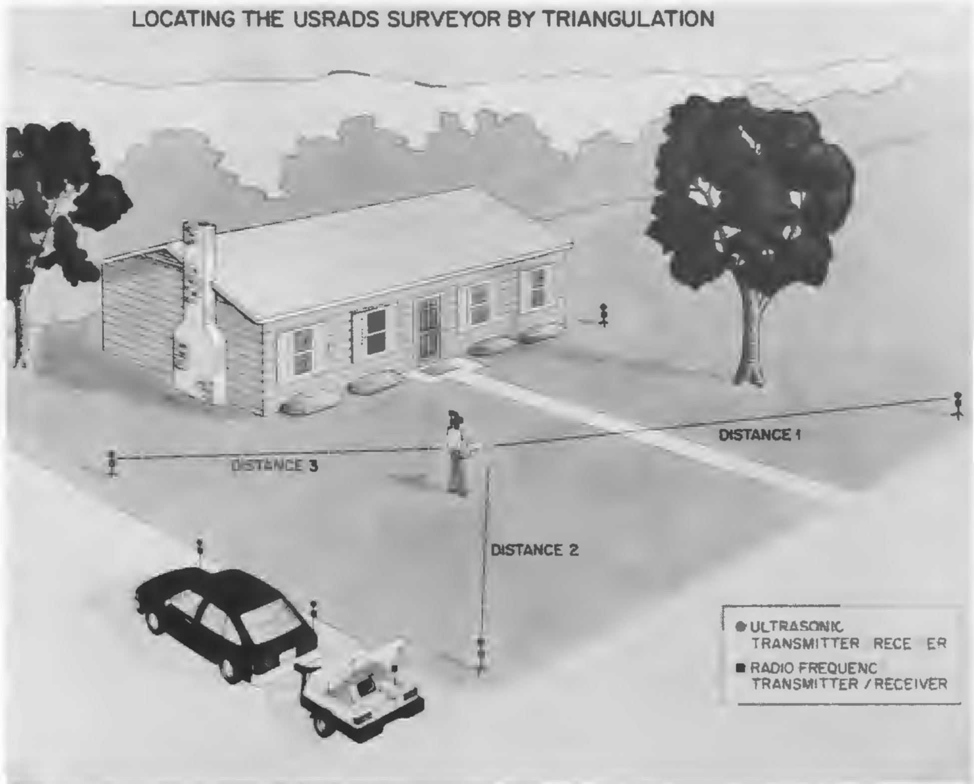
In 1986 ORNL must identify the properties to be included in the DOE Uranium Mill Tailings Remedial Action Project (UMTRAP). Information on the

Mike Blair demonstrates USRADS by conducting a radiological survey of an area near Building 3500 at ORNL.

location of radioactive properties is required to allow surveyors to return to all contaminated properties, inspect them, compare radiation levels at the different properties, and determine where action is needed first.

Because ORNL's job for UMTRAP involves surveying as many as 9000 private properties in nine states within a short time, automating at least part of the survey process was necessary to obtain the data in the most cost-effective manner. No commercial system was available that would meet this need. To speed up the compilation of information on the exact locations and radiation levels of contaminated properties for the DOE data base, ORNL researchers Michael Blair and Charlie Nowlin of the I&C Division and Barry Berven and Guven Yalcintas of the Health and Safety Research Division (HASRD) developed an ultrasonic ranging and data system (USRADS). Their system will save months of work and an estimated $14 million in labor costs.

Before USRADS was developed, surveyors who discovered radioactive properties using health physics instruments (such as gamma-ray



The USRADS surveyor, who takes radiation readings over an area suspected of having uranium mill tailings, is located by a computer, which triangulates signals sent each second from the surveyor's backpack to three or more receivers. The computer also receives signals from the portable instrument measuring radiation levels. It then processes these signals to correlate the surveyor's exact position with the radiation data collected.

Major contributors to the development of ORNL's ultrasonic ranging and detection system (USRADS) are, from left to right, Charlie Nowlin, Barry Berven, Guven Yalcintas, and Mike Blair.

scanners) had to determine their position by using tape measures and making estimates and had to maintain logs recording radiation measurements on each property as they walked around it. Using triangulation, the new ORNL system automatically correlates each surveyor's exact position with the radiation data collected.

The first field test of the engineering prototype of USRADS was conducted in March 1986 in Grand Junction, Colorado. Blair and Nowlin trained ORNL's Cathy Dickerson and Doug Pickering in two days to complete a radiation survey using USRADS on the third day. The team set up the entire system and used the data-reduction computer programs. ORNL staff members are evaluating the system and suggesting ways to improve the design and construction of field prototypes that will be used by all UMTRAP survey teams.

The advantages of USRADS include simplicity of set-up and operation, on-site verification of data quality, location identification within a third of a meter, operation by a two-person survey team, system flexibility allowing the solution of most problems in the field, computerized data reduction, integration of new data into existing data bases, and a low fabrication cost. The developers believe that the ORNL system could have broad applications and commercial potential.

ORNL Solidifies Uranium in Liquid Nitrate for Long-term Storage

From 1969 to 1985, ORNL stored 8000 L (about 1900 gal) of a radioactive uranium-bearing liquid nitrate solution that had been shipped here by truck from the Nuclear Fuel Services reprocessing plant in West Valley, New York. The plant, now closed, had reprocessed an experimental nuclear fuel core from Consolidated Edison's Indian Point reactor. The reactor had been operated in 1962–65 with fully enriched uranium-thorium fuel. The solution, which contains two fissioning isotopes (uranium-235 and uranium-233) was transferred to ORNL because it was the national uranium-233 repository. ORNL intended to recover the uranium experimentally as part of its fuel-recycle research; however, the decline of U.S. breeder reactor funding and the growing amount of highly radioactive decay products of uranium-232 (a nonfissioning isotope in the solution) made reuse of the material impractical.

The radioactive liquid was stored in a shielded tank. But in the late 1970s it was decided to investigate ways of solidifying it for permanent safe storage. One alternative under study was selected to convert the uranium from the liquid acidic solution into a solid oxide form to be contained in cylindrical stainless steel cans for storage in a shielded, secure repository.

The $28.6-million Consolidated Edison Uranium Solidification Project (CEUSP) began eight years ago. Designing, fabricating, and installing the complex process equipment required six years. Equipment and processing method development required a series of more than 200 "cold" tests using synthetic solutions of depleted uranium.

Actual solidification of the highly radioactive uranium solution began in April 1985, and 85% of the uranium had been solidified by late February 1986. The project was expected to be completed in June.

The remotely operated process used evaporation to concentrate 20-L batches of the solution to a volume of 8 L each. Then, a high-temperature denitration step converted the

Don Ferguson (left), Phil McGinnis, Rex Leuze, and Emory Collins examine some key components used in the Consolidated Edison Uranium Solidification Program (CEUSP). This project provides long-term safe storage of highly radioactive and fissile uranium.

concentrate to a solid oxide form. The solid oxide was doubly enclosed within stainless steel cans. After being sealed, the cans were stacked inside safeguarded storage wells by remote handling equipment.

Phil McGinnis, Emory Collins, and Rex Leuze of the Chemical Technology Division and Don Ferguson of the Central Management Offices directed the complex project. The complexities included the need for (1) totally remote operation and massive shielding to protect workers from the highly energetic radiation, (2) precautions against accidental criticality of the large amount of fissile uranium, (3) protection against corrosive conditions, (4) personnel training, and (5) special processing and handling equipment. Despite the complexities, the project met all DOE milestones.

Randy Kirk controls a remotely operated welder to seal a CEUSP can before storing it for a long time. This procedure is performed remotely because the solidified uranium inside the can is highly radioactive.

Milestones and Outlook

In planning for the future, we are now looking 15 years ahead. The year 2001 has been our focus for energy planning. By then, we believe, a serious shortage of liquid fuels will occur, the demand for electrical power will grow at a faster rate, and interest in fission energy for producing electricity will be revived; we think ORNL can help make future reactors safer, more economical, and more acceptable to utilities and the public. We foresee that a large, demonstration fusion device will be built through an international effort and that ORNL will play a major role in that project. We propose increasing our efforts to meet compelling national needs for improved waste-processing technologies, better defensive weapons, and basic-physics facilities open to users from industry, universities, and other national laboratories.

R&D initiatives. Our investment of discretionary funds in new initiatives (through our internal Exploratory Studies Program) continues to pay off. We are still attracting federal funds to expand our work on some new ideas that were originated at ORNL and nurtured by internal funds. For example, the President's budget for fiscal 1987 requests $2.5 million for preliminary R&D work on our proposed Center for Neutron Research (CNR), which would house the most potent research reactor in the world. If support continues, we plan to start construction of the $300-million reactor facility by 1989 and complete it in 1995. The CNR would replace HFIR.

In 1985 we approved six new "seed money" projects; we initiated another ten projects and continued to support four others through the Director's R&D Fund. The seed-money projects are:

- Ultrasonic diffraction tomography in medicine, a critical step toward the development of a medical ultrasound scanner.
- Microradiation detectors for gas and liquid chromatography, using waveguided solid scintillators, the development of which could be useful in bioengineering research, hazardous-waste management, and environmental analysis.
- Load balancing in hypercube multiprocessors by simulated annealing, which could have uses for machine intelligence and robotics.
- DNA assay of radiation-induced mutation, which could lead to a method for obtaining more reliable data for quantifying the mutagenic effects of radiation on humans.
- Stability and control of magnetically suspended, rotating fluid-mechanical systems, which could lead to the development of laboratory equipment for performing more precise measurements than are possible today.
- Visualization of complex flaws with pulsed-neutron activation, the results of which could draw funding for an experimental facility.

Bob Lauf and Walt Bond received an I•R 100 award in 1985 for their work in developing a compact metal-oxide varistor for use in protecting electrical equipment and power transmission lines from destructive surges. This development was originally sponsored by ORNL seed money.

New projects receiving support from the Director's R&D Fund are:

- Feasibility and implementation study for DOE's Advanced Control Test Operation (ACTO) project, a proposed facility for developing and testing advanced control systems for nuclear power plants. One goal of this work is to site ACTO at ORNL.
- A microbial ecology approach in treating hazardous wastes, a study of whether desired organisms that degrade wastes, including genetically engineered ones, will grow and function effectively where they are wanted—in bioreactors and open environments such as groundwater and surface spills.
- A study of the biomolecular electronics of platinized chloroplasts, a new composite material made at ORNL by precipitating platinum on a chlorophyll-containing spinach membrane (see page 10).
- Developing and using a scanning-tunneling electron microscope for physics experiments requiring atomic-scale resolution (submicron physics).
- Assessing liquid-metal boiling and two-phase separation characteristics under near-zero gravity in space by designing and building a two-phase flow system and instrumentation for an experiment to be put aboard a future U.S. space shuttle flight.
- Sintering of ceramic materials by microwaves from high-power gyrotron oscillators, using gyrotrons developed in ORNL's Fusion Program.
- Studies of the proton translocation and energy transfer between biological membranes, including the purple one from a halophilic ("salt loving") bacterium.
- Production of oxygen-consuming bacterial membranes and genetic characterization of *Clostridium acetobutylicum*, the oxygen-sensitive bacterium that produces the industrially useful chemicals acetone and butanol.
- Understanding the relationship between the effect of complex mixtures containing toxic agents (such as coal liquids and oils) and the speed of the agents' penetration through skin and distribution to and retention by body tissues.
- Exploring new short-contact-time coal liquefaction processes to see if overall hydrogen requirements can be reduced and energy efficiency of converting coal to liquid fuel can be increased.

Four projects that will continue receiving support from the Director's R&D Fund will be development of a preconceptual design for the CNR, protein engineering with an emphasis on site-directed mutagenesis, research in parallel computing, and application of artificial intelligence to operation and control of nuclear power plants.

We are proposing to build a synchrotron cooling ring at the Holifield Heavy Ion Research Facility to store beams of cooled, highly charged heavy ions for studies of atomic collisions. The device would allow precision spectroscopy using crossed and merged beams of ions, electrons, photons, and atoms. Several heavy-ion cooling rings are planned or being built in Europe, but the Oak Ridge ring is the first such facility proposed in the United States.

Waste-management issue. In August 1984 radioactivity was detected in two of three deep monitoring wells placed in the vicinity of the ORNL Hydrofracture Facility. These monitoring wells, which are placed 305 m (1000 ft) from the injection well, intersect the formation into which radioactive grout had been injected. The grout sheets are thought to extend no more than about 213 m (700 ft) from the injection well. Therefore, the finding of contamination 305 m from the injection well suggested migration of waste out of grout sheets.

The concern over the performance of the hydrofracture disposal concept was heightened still further in 1985 when the Tennessee Department of Health

Tony Malinauskas (right), director of ORNL's Nuclear Regulatory Commission programs, smiles as he receives a medal and a check for $10,000 from John S. Herrington, Department of Energy secretary. Malinauskas was a recipient in 1985 of one of DOE's Ernest Orlando Lawrence Memorial Awards.

and Environment issued regulations controlling underground injection of hazardous materials. Under the new rules ORNL must apply for and receive a permit to operate the Hydrofracture Facility; the permit application must identify all underground sources of drinking water in the vicinity of the Hydrofracture Facility. Staff members estimated that gathering the necessary data for a permit application would cost $5 million and take nearly a year.

Federal regulations issued in November 1984 require the EPA to publish guidelines on underground injection of hazardous materials by August 1988. Failure of the EPA to provide this guidance will result in a nationwide ban on underground injection. Little progress has been made by the EPA, and most experts think that the practice will be banned in August 1988. Therefore, DOE announced in November 1985 that the permitting of work on hydrofracture would be delayed until early 1989. Until then ORNL will focus on reducing the volume of liquid waste formerly earmarked for disposal by hydrofracture and solidifying it for later disposal.

Performance recognition. The Energy Systems facilities in Oak Ridge have received 52 I•R 100 awards from *Research and Development* magazine for developing innovations that have outstanding commercial potential, placing Oak Ridge DOE facilities fourth in the nation in terms of the number of all-time winners of these prestigious awards. ORNL has netted 46 of these awards, 25 of them in the last five years. Our innovations and innovators receiving awards in 1985 were a lead-iron phosphate glass (Brian Sales and Lynn Boatner), a pulsed-helium ionization detector (Rose Ramsey and Richard Todd), a biaxial high-temperature fatigue extensometer (Ken Liu), a metal-oxide varistor (Bob Lauf and Walt Bond), and an electronic image detector for biological applications (Art Case and Jack Davidson).

Of 100 *Science Digest* Innovator Awards in 1985, ORNL developments won 4. They were ceramic composites (Terry Tiegs), a spherical torus design for a fusion device (Martin Peng), a hyrid mass spectrometer (Gary Glish), and lead-iron phosphate glass (Sales and Boatner).

Tony Malinauskas, director of ORNL's Nuclear Regulatory Commission Program, received a prestigious Ernest Orlando Lawrence Memorial Award from DOE in 1985, largely for his work in explaining why emissions of radioactive iodine, a potential health hazard, were lower than expected after the 1979 Three Mile Island accident.

In December 1985 Energy Systems began honoring researchers who have made outstanding, sustained achievements in their fields by naming them Corporate Fellows. The new Corporate Fellows named are from ORNL: Thomas Carlson of the Chemistry Division, Eric Hirst of the Energy Division, C. T. Liu of the Metals and Ceramics (M&C) Division, and Peter Mazur of the Biology Division.

In May 1985 Energy Systems held its first annual Award Night. Among the 144 honorees from Energy Systems, 75 were ORNL employees. Twenty-four awards went to ORNL authors of publications. Four of the ORNL honorees also received Jefferson Cup Awards from Martin Marietta

Recently, Martin Marietta Energy Systems, Inc., named five Corporate Fellows, four from ORNL. They are, from left, Eric Hirst (ORNL), Thomas Carlson (ORNL), John Barber (ORGDP), C. T. Liu (ORNL), and Peter Mazur (ORNL). Third from right is Ken Jarmolow, Energy Systems president.

Corporation: Peter Mazur (Author of the Year), Brian Sales (Inventor of the Year), C. T. Liu (Scientist of the Year), and Phillip Thompson (Technical Achievement).

The quality of the people and research at ORNL has helped attract Distinguished Scientists to work jointly at the Laboratory and the University of Tennessee. ORNL-UT Distinguished Scientist Jerry Mahan, who has been at the Laboratory more than a year, was joined in 1986 by six new Distinguished Scientists: David White, formerly of Florida State University, who specializes in microbial ecology; J. Alan George, University of Waterloo in Ontario, Canada, numerical analysis; Robert Uhrig, Florida Power & Light Company, artificial intelligence for nuclear power plants; Robert Hatcher, University of South Carolina, structure of the earth's crust and causes of earthquakes; David Joy, AT&T Bell Laboratories, electron microscopy; and Philip Siemens, Texas A&M University, physics of nuclei at high temperatures.

I'm proud that ORNL work has been highlighted on the covers of six issues of *Science* magazine since 1983; two of those issues appeared in 1985 and called attention to our CNR proposal and our pioneering work in bioelectronic materials. Between early 1983 and early 1986 ORNL researchers have published 14 articles in *Science*. Because *Science* is an important source of information for the decision makers in Congress and federal agencies, we receive much attention from our sponsors in Washington when we publish in this respected journal.

Technology transfer. Several important advances in licensing ORNL technologies took place last year. In December, Energy Systems and Cummins Engine Company signed an exclusive license agreement for joint development and commercial use of ORNL-developed nickel and nickel-iron aluminide alloys in the manufacture of components for high-temperature diesel engines. This agreement marked the first commercial licensing by Energy Systems (rather than DOE) of a patented ORNL development. Also in 1985, the first Energy Systems licensing of a copyrighted ORNL technology occurred when the company licensed to Environmental Systems Corporation of Knoxville the exclusive rights to manufacture and distribute ORNL's fiber-optic luminoscope, which detects skin contamination by potentially cancer-causing chemicals.

To stimulate innovation at ORNL and its other facilities, Energy Systems began offering financial incentives to inventors who apply for patents. In June 1985, 31 former or current ORNL employees (and 11 other Energy Systems employees) received cash awards of $100 to $1000 for filing patent applications with the U.S. Patent Office.

Progress on new facilities. Construction of the High Temperature Materials Laboratory (HTML) was "inaugurated" in March 1985. The work has moved at a fast pace: the structure itself was completed in just twelve months. According to current plans, materials researchers will begin occupying offices and labs in the east wing by October 1986. The HTML will house elegant equipment and make ORNL the world leader in high-temperature materials research. We can be proud of this user facility, and we expect that the work coming out of it will be magnificent.

The International Fusion Superconducting Magnet Test Facility at ORNL now contains its full array of six large superconducting magnet coils. The coils were designed and built under ORNL's direction over the past 10 years by groups in Japan and Switzerland and within the European Atomic Energy Community, and by three U.S. firms—the General Dynamics-Convair Division, General Electric Company, and Westinghouse Electric Corporation.

In late 1985, the last of the magnetic coils was installed in the vacuum vessel, the lid was fitted on the vessel, and cooling began—that is, liquid helium was introduced to the vessel to cool the magnets so that they reach a superconducting state (i.e., a condition of virtually no resistance to the flow of electricity needed to create magnetic fields to contain fusion plasmas).

This photograph of the Walker Branch Watershed is one of six Science *magazine covers between 1983 and 1986 that drew attention to ORNL research. The other five covers are shown at right.*

In the tests planned over the next year or so, the six coils, weighing between 35 and 50 tons each, will be energized by electrical currents of between 10,000 and 25,000 amperes. The coils' ability to withstand thermal, mechanical, and electrical stresses will be evaluated to determine whether using superconducting coils to confine fusion plasmas is practical. The test results will be collected in a data base that could guide construction and operation of larger superconducting magnets for plasma confinement in commercial-scale fusion devices. (See article on page 30).

The Radiofrequency Test Facility (RFTF), which uses superconducting magnets, was brought on line in 1985 ahead of schedule and at a lower cost than expected. It will be used by international researchers to advance RF heating techniques for raising plasma temperatures in large fusion devices. The RFTF will first be used this year to test a

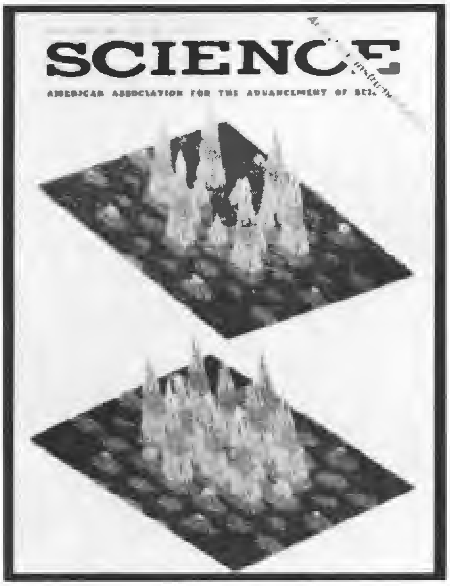
prototype antenna for the DIII-D experiment at the GA Technologies facility in San Diego.

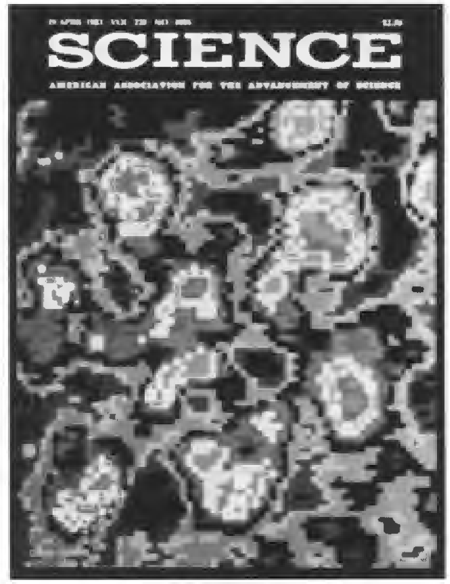
A soft X-ray spectrometer developed by Tom Callcott and Ed Arakawa of the Health and Safety Research Division was installed at the Synchrotron Radiation Facility at the National Bureau of Standards (NBS). The device, built as a joint project of the University of Tennessee, ORNL, and NBS, has a measuring efficiency 10,000 times greater than conventional soft X-ray spectrometers. It is being used for experiments at NBS before being moved to a higher-energy X-ray source—the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, which began operation last year.

At the NSLS in 1985, Gene Ice and Cullie Sparks of the M&C Division installed an ORNL X-ray beam line. The beam line, which was an I•R 100 award winner, focuses the synchrotron X rays to 5 to 30 times the intensity of the original beams, thus speeding up the yield of experimental data. The ORNL beam line at NSLS is the highest-flux X-ray source in the world.

Researchers working under the direction of Bob Luxmoore of ORNL's Environmental Sciences Division began innovative environmental field studies at two watersheds which will use recently completed subsurface weirs to allow groundwater samples to be taken from various positions in the soil profile, both laterally and vertically. The purpose of the study is to understand how inorganic contaminants such as cadmium, arsenic, and manganese are transported through the soils of watersheds having shallow (<5 m) and deep (about 30 m) bedrock.

We are pleased that we received funds in FY 86 to continue our Environmental Restoration and Facilities Upgrade Program (ERFU). The important goals of this comprehensive program for improvements of waste treatment, disposal, storage, and monitoring systems are to reduce our discharges of hazardous chemicals and radioactive materials to the environment and to accelerate compliance with state and federal environmental regulations. Expenditures for ERFU projects have increased from more than $4





million in FY 85 to $22 million in FY 86.

In 1985 several significant actions took place to remedy our environmental problems and determine their extent. The new sewage treatment plant was completed, underground piping carrying liquid wastes was lined to prevent contact with groundwater, work was begun on a facility to treat acidic runoff from the steam plant coal pile, and the migration of radioactive strontium-90 from Solid Waste Storage Area 4 into the watershed was reduced by about half through the use of a surface-water diversion structure that routes the runoff around the old burial ground. A comprehensive plan for monitoring ORNL's toxic releases to the environment was also developed. Additional monitors are to be installed on stacks and vents, and about 800 monitoring wells will be drilled over the next few years to indicate whether hazardous chemicals, heavy metals, and radioactive materials are entering area groundwater.

Looking Ahead

Because of conservative spending at the beginning of FY 86, ORNL should avoid serious problems for the remainder of the fiscal year, even though many programs will have to be cut 3.8% because of the Gramm-Rudman-Hollings Balanced Budget and Emergency Deficit Reduction Act of 1985.

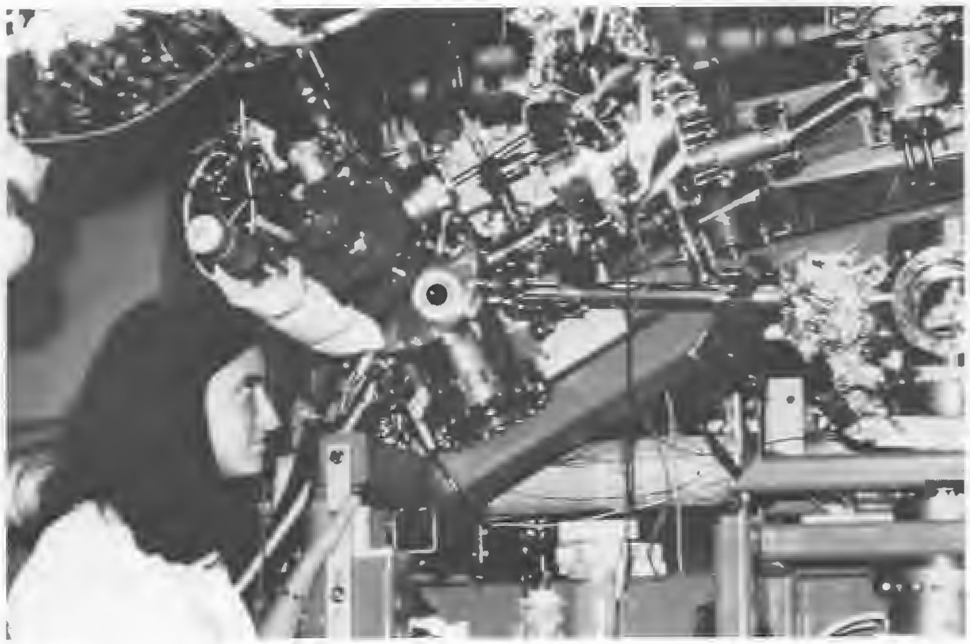
The President's FY 87 budget is not expected to have a large adverse effect on us, except in fission and fuel recycle R&D. We were pleasantly surprised because the budget for ORNL turned out better than we expected. We will have problems as always, but they will be manageable. At worst, we may have to allow the employment level to drop by 200, a reduction that we can probably accomplish by retirements and job transfers.

A high point in the FY 87 budget proposed by the President is the $2.5 million in preliminary R&D funding for the CNR. Low points are that ORNL's reprocessing R&D budget was cut from $12.5 million to about $1.5 million and that funding for our Reactor Technology Programs was reduced from $9 million to $6.5 million (of which only $700,000 was allocated for high-temperature gas-cooled reactor R&D). We have reason to believe that Congress will increase the funding for these important fission programs. In March the House Energy Research and Production Subcommittee authorized an additional $5.3 million for reprocessing R&D (on remote technology) and $5 million for HTGR work at ORNL.

ORNL has made preliminary agreements to collaborate with groups in Japan on HTGR fuel testing and on remote technology for breeder-reactor fuel reprocessing. The HTGR work would involve irradiating HTGR fuels made in the United States and in Japan at the HFIR to examine retention of fission products. The joint project on reprocessing would focus on a pilot plant to be built in Japan to extract new fuel produced in its JOYO and MONJU breeder reactor plants. Such a collaboration could provide the focus for ORNL's reprocessing program for the next 15 years and could allow the United States to positively influence the emerging worldwide trend of recovering and reusing plutonium from reactor fuel.

Although we were not allocated as much money as we wanted for ERFU projects in FY 87,

Donna Fitzpatrick, acting Assistant Secretary for Conservation and Renewable Energy for DOE, and Alex Zucker, ORNL Associate Director for the Physical Sciences, prepare to cut the ribbon at the March 1985 inauguration of construction of the High Temperature Materials Laboratory.



ORNL's soft X-ray spectrometer is now being used for experiments at the Synchrotron Radiation Facility at the National Bureau of Standards. The sample, grating, and detector chambers are visible left to right at the top of the picture. The synchrotron light is piped through the tubing at center. Janet Kahn, a summer research student in the UT-ORNL Science Alliance program, looks on.

The Radiofrequency Test Facility at ORNL is now in operation to test RF techniques for heating fusion plasmas.

environmental cleanup work and facility-related projects will nevertheless proceed at a healthy pace next year. The remedial efforts will focus on detailed characterizations and assessment of the highest priority sites. These include Solid Waste Storage Areas 4 and 6, a variety of process ponds, and the White Oak Creek–White Oak Lake drainage basin.

Facility decommissioning will continue at the Metal Recovery Facility and Fission Product Development Laboratory. Inactive equipment at these facilities will be dismantled, and they will be decontaminated so that they could be reused.

To upgrade other facilities, we will prepare comprehensive, long-range strategy documents for solid-waste management, water pollution control, air pollution control, and environmental monitoring, as well as for remedial actions. We will begin improving nonradiological wastewater collection and treatment systems to comply with new discharge regulations; for example, we will replace old surface impoundments with tanks. Several air pollution control systems will be improved to allow continued operations in compliance with DOE's "as low as reasonably achievable" policy for radionuclide emissions.

This year I am presenting the second Director's Annual Award to the materials sciences at the

Tuan Vo-Dinh (right) uses the fiber optics luminoscope that he developed to check whether D. A. White's hand is contaminated. This instrument, now being manufactured by Environmental Systems Corporation in Knoxville, can monitor the skin of workers who are exposed to oil and tar materials containing potentially carcinogenic compounds.

Construction of a French drain at ORNL to demonstrate collection and diversion of groundwater to prevent its contact with down-gradient buried radioactive waste.

Laboratory. Last year I honored the Fusion Energy Division; this year I decided to honor a field instead of a single division. To honor the field of materials sciences, I am presenting the 1986 Director's Annual Award to the people of the M&C Division (directed by Jim Stiegler) and the Solid State Division (directed by Mike Wilkinson until April 1, 1986) for all the work they have done to make ORNL one of the best materials research facilities in the world. In fact, a recent study by Jim Roberto of the Central Management Offices indicates that ORNL is the largest performer of nonclassified materials research in the DOE system and probably at any single site in the United States. Our distinction in materials research stems from the nature of our work in the materials sciences—its importance, its quality, and its performance by capable people working in teams.

In fact, ORNL as a whole is distinguished by the nature of its work. First, the work we do is important and worth doing; our employees are motivated by the knowledge that they are making a contribution to society, to the nation, and to their areas of expertise in science and technology or related fields. Second, our work is characterized by quality. Sometimes our work is a little behind schedule or costs a little more than anticipated, but no one ever accuses us of doing poor work. When our researchers come to a conclusion, their statements are true and factual. Our work is known for its integrity and credibility because we place such a high premium on quality research. Third, because our projects are difficult and complex, teamwork is required. Our projects succeed because of the well-managed work of multiprogram and interdisciplinary teams including not only scientists and engineers but also service and support personnel. I congratulate you all for the work you have done—and are doing—to bring greatness to Oak Ridge National Laboratory. ornl

BOOKS

Global Energy: Assessing the Future, *James E. (Jae) Edmonds and John M. Reilly, Oxford University Press, New York (1985). 317 pages. Reviewed by Alfred M. (Bud) Perry, Energy Division.*

The message of the energy crisis of the 1970s was that energy consumption could not continue to grow as rapidly as it had during the previous two decades. The past dozen years have seen a flurry of studies endeavoring to show how human societies could continue to grow and prosper by using energy much more efficiently and by turning from the limited resources, such as oil and gas, to the more abundant energy sources, such as coal, the atomic nucleus, and the sun. These studies included Project Independence; the National Academy of Sciences *CONAES* study (in which many ORNL staff members participated); *Energy in a Finite World*, carried out by the International Institute for Applied Systems Analysis; Amory Lovins' studies promoting the "soft path"; and ORNL's *A Desirable Energy Future*.

While facing up to a changing outlook for energy supply, people throughout most of the world were also becoming aware of the growing impact of energy production and consumption on the environment. We learned, for instance, that carbon dioxide produced in the burning of fossil fuels may cause great changes in climate, affecting temperatures, rainfall, and even sea level. But major uncertainties still remain concerning (1) the fate of CO_2 released to the atmosphere; (2) the climate effects that would, in fact, be produced by a given CO_2 increase, such as a doubling; and (3) the effects of such changes on human affairs. One of the largest uncertainties is the actual amount of CO_2 that will be produced because no one knows how much fossil fuel will be consumed.

In this context, Jae Edmonds and John Reilly of Oak Ridge Associated Universities' Institute for Energy Analysis (IEA) have attempted to model the evolution of global energy demand and supply over the 75-year period from 1975 to 2050. Their book describes the progress of their work from 1979 through 1982.

Surely, no one can predict with confidence what people will be doing far into the future, but the nature of the CO_2 problem requires us to try, however cloudy our crystal balls may be. Edmonds and Reilly explicitly deny that their glimpses of the future are predictions. Rather, they call them "conditional forecasts," contingent on the values chosen for a large number of parameters that, along with the structure of the model, determine the future course of energy supply and demand. With several dozen tunable knobs at their disposal, the modelers could generate any number of possible futures, covering a very wide range from "high" to "low" energy consumption and from "high" to "low" CO_2 release. However, Edmonds and Reilly did not take this approach.

A major part of the book deals with the proper adjustment of the knobs and the presentation of a single, central scenario based on preferred values of the parameters. The authors also present two other scenarios ("high" or "low") based on plausible deviations from the preferred values for a selected set of the most important parameters.

The preferred, or "reference," scenario presented in this book will give little comfort to "soft path" advocates and persons worried about the CO_2 problem. Both primary energy use and CO_2 emissions increase sixfold from 1975 to 2050. Major contributors to this increase are coal (for electricity and synthetic fuels) and shale oil. Both coal and shale oil, especially the latter, produce much more CO_2 per unit of useful energy than do conventional oil and gas.

The rapid expansion in the worldwide use of coal in this scenario (tenfold from 1975 to 2050) occurs, in part, because of the treatment of coal in the model as an "unconstrained" resource: if the rate of expansion does not exceed a specified value (an exogenous input), then annual coal production can become arbitrarily large without increasing price. In later work, Edmonds and Reilly have changed the method of describing the supply of coal, specifying production cost as an increasing function of cumulative production. Similar supply parameters have also been specified for oil and gas. Thus, two versions of their model now exist, with important differences in the treatment of energy supply.

It is unfortunate, I think, that no hint of the later version of the model appears in the book.

Nevertheless, the Edmonds-Reilly model is one of the leading documented, transportable models available for long-range energy studies. The earlier version has been adopted for a number of studies outside the IEA. This book (which is available in ORNL's Central Research Library) provides a clear, comprehensive, and well-written presentation of that model.

In the authors' static equilibrium model, energy demand and supply both depend upon prices. These are iteratively adjusted until demand and supply are in detailed balance, within each of nine geographical regions of the world, for each of four secondary energy carriers (solids, liquids, gases, and electricity) and for each of nine primary energy sources (conventional and unconventional oil including shale oil, conventional and unconventional gas, coal, nuclear energy, hydroelectric energy, solar-electric technologies, and biomass). Demand is driven by population growth and increases in labor productivity (which are exogenous inputs to the model) and is modified by a full set of price and income elasticities.

More than half of the book (10 chapters, covering 173 pages) is devoted to a review of supply parameters: resources, costs, energy conversion technologies, and postulated technical improvements over time. After reviewing the literature extensively, the authors have proposed "supply curves"—quantities of energy available annually as a function of time and price for each energy source. (Exceptions are conventional oil and gas, which are delivered on a prescribed schedule; this significant simplification is justified, within the context of the CO_2 problem, on the grounds that conventional oil and gas can make, at most, a relatively small contribution to the ultimate production of CO_2 from fossil fuels.)

The reader may not agree with all the authors' assumptions. Photovoltaics, for example, might turn out to be a greater supplier of electricity than Edmonds and Reilly assume. Nevertheless, the assumptions are clearly stated and the structure of the model permits any readers interested in using the model to substitute their own assumptions.

Books in Print

The following books were authored or edited by ORNL staff members (whose names appear in boldface print).

Indoor Air and Human Health, Proceedings of the 7th Life Sciences Symposium (held in Knoxville, Tennessee, October 29-31, 1984), ed. **R. B. Gammage** and **S. V. Kaye**, Lewis Publishers, Inc., Chelsea, Mich., 1985.

Immobilised Cells and Enzymes: A Practical Approach, ed. **Jonathan Woodward**, IRL Press, Oxford, England, 1985.

High Temperature Alloys: Theory and Design (conference proceedings), ed. **J. O. Stiegler**, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, 1984.

The Three Mile Island Accident: Diagnosis and Prognosis, (ACS Symposium Series 293), ed. **L. M. Toth, A. P. Malinauskas**, G. R. Eidam, and H. M. Burton, American Chemical Society, Washington, D.C., 1986.

Gas Transport in Porous Media: The Dusty-Gas Model (Proceedings of Symposium on Separations Science and Technology for Energy Applications), E. A. Mason and **A. P. Malinauskas**, Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 1983.

Measuring Culture: A Paradigm for the Analysis of Social Organization, Jonathan L. Gross and **Steve Rayner**, Columbia University Press, New York, 1985.

Capture Gamma-Ray Spectroscopy and Related Topics-1984 (Proceedings of International Symposium-1984), ed. **S. Raman**, American Institute of Physics, New York, N.Y., 1985.

Principles and Applications of Stirling Engines, **Colin D. West**, Van Nostrand Reinhold Company, New York, N.Y., 1986.

ORNL's $19-million High Temperature Materials Laboratory, which could be ready for partial occupancy in September, makes extensive use of skylights for interior lighting (inset).

ORNL-Japan fuels-testing program

In late March, DOE and the Japan Atomic Energy Research Institute signed an agreement for a five-year, $4-million collaborative testing program for high-temperature gas-cooled reactor (HTGR) fuels, to begin immediately. The agreement builds upon an existing plan, adopted by the two agencies in 1985, for cooperative HTGR research and development.

According to the March agreement, both countries will fabricate their own HTGR fuel particles and fuel-rod specimens. The fuels will be shipped to ORNL for irradiation in the High Flux Isotope Reactor and for subsequent testing to determine how well they retain fission products under normal and abnormal operating conditions.

John Jones, director of reactor programs at ORNL, says the tests will provide both countries with early data on the performance capabilities of HTGR fuels—data essential to the goal of designing passive safety features that would ensure "walk-away safe" reactors and preclude the possibility of an accident involving a fission-product release serious enough to require evacuation of the area surrounding an HTGR facility.

ORNL-Japan reprocessing program

Also in March, U.S. and Japanese officials continued discussions seeking a broader collaboration on fuel reprocessing R&D at ORNL and in Japan. Technical exchanges in the areas of experimental criticality and remote technology had previously been negotiated and are under way, with more than $6 million in support of the criticality program from Japan. According to Fuel Recycle Division Director Bill Burch, the broader collaboration would become the focus for the U.S. reprocessing program, which is centered at ORNL, for the next decade.

Japan is preparing to build a pilot plant to recycle spent nuclear fuel from its breeder reactors, JOYO and MONJU. The pilot plant will begin operation near the end of this century. The joint R&D program would complete development of technology needed for the pilot plant. The overall collaboration is envisioned to involve U.S. participation in all phases of the pilot plant project, including plant operation. Through a major funding contribution from Japan, ORNL's fuel reprocessing work could be maintained at approximately current levels.

Isotope facilities named landmark

ORNL's isotope development and production facilities, which in 1946 shipped the first medical radioisotope for use in a U.S. hospital, have been designated a "Nuclear Historic Landmark" by the American Nuclear Society. The new ANS designation, which was awarded also to eight other facilities throughout the nation, recognizes facilities that have contributed significantly to the development of peaceful applications of nuclear energy. (ORNL's Graphite Reactor, which in 1943 produced the world's first gram-size quantities of plutonium, is on the U.S. Department of the Interior's list of National Historic Monuments.)

ORNL serves as DOE's national center for isotope development, production, sales, and distribution. Over the past four decades, the Laboratory has made some 400,000 isotope shipments, valued at approximately $187 million, to industries, hospitals, universities, and government agencies throughout the world.

Currently the three best-selling ORNL isotopes are:

- tritium, mainly for radioluminescent emergency lighting and for remote airfield landing lights;
- gadolinium-153, for detecting osteoporosis, or bone mineral loss, in elderly people; and
- iridium-192, for industrial radiography of welds in heavy section steel, oil rigs, and pipelines.

technology transfer briefs:

Technology open house sparks industrial interest

Three firms are interested in obtaining rights to ORNL's whisker-reinforced ceramics, eight companies want more information on the Laboratory's continuous annular chromatograph, and two venture-capital firms plan to explore investments in Oak Ridge technology. Those developments are among the results of a March technology-transfer conference and open house in Oak Ridge, the first of its kind involving a DOE national laboratory.

Some 160 representatives of U.S. and Japanese companies attended the program, entitled "Getting Research Down to Business." The agenda included general briefings on ORNL R&D programs, descriptions of specific technologies that have commercial potential, and meetings with individual ORNL inventors.

According to Don Jared, manager of Energy Systems' technology applications program, the conference was aimed not just at large companies, which are the traditional focus of technology transfer efforts, but also at medium-size companies, which lack many of the R&D capabilities of large firms. "The large companies know we're here and they know what we're doing," says Jared. "Now we're aiming also for the smaller ones, because we can do more for them."

The keynote speaker for the conference was Nils Dailey, a proponent of "intrapreneurship," encouraging the growth of new ventures within existing companies. On a related note, Jared points to one case of "internal technology transfer" that may result from the conference: high-efficiency motors developed for uranium-enrichment centrifuges may have other applications at ORNL, including uses in caustic and high-radiation environments and in advanced heat pumps. Because the variable-speed motors are entirely sealed, they are immune to caustic chemicals; because they are designed for high efficiency and reliability, they could help reduce the operating costs and maintenance needs of heat pumps.

"If two research facilities are located more than a few hundred meters apart, they might as well be located on opposite sides of the continent," notes Jared. "Conferences like this highlight what's going on to people within the organization as well as to people from other companies."

ORNL's Jim Roberto briefs conference participants on current R&D in ion implantation at the Surface Modification and Characterization Collaborative Research Center, one of ten ORNL "user" facilities available to industrial, government, and university scientists.

Inventors honored

Forty-two Energy Systems inventors, more than half of them from ORNL, were honored for 1985 patents at an Energy Systems Inventors' Forum luncheon in April. Seventeen of the honorees were given "silver acorn" awards for receiving their first patents; one inventor, Richard Fox of ORNL's Instrumentation and Controls Division, received a "golden acorn" for his tenth patent.

The Inventors' Forum consists of the approximately 500 Energy Systems staff members who hold U.S. patents. ornl

Paul N. Haubenreich has been manager of the Large Coil Program at ORNL since it was established in 1975 and has been the U.S. project officer in the International Large Coil Task since 1977. He is responsible for the operation and maintenance of the International Fusion Superconducting Magnet Test Facility at ORNL and the coil testing now under way in collaboration with the foreign participants in the Large Coil Task. He came to the U.S. fusion program in 1973 after more than 20 years in fission reactor development at ORNL. He received B.S. and M.S. degrees in mechanical engineering from the University of Tennessee and was a full-time student at the Oak Ridge School of Reactor Technology in 1950–51. He also taught part-time at the University of Tennessee during the establishment of the Nuclear Engineering Department. After several years of working on the

Superconducting Magnets for Fusion Energy:

By PAUL N. HAUBENREICH and MARTIN S. LUBELL

To produce electricity, they would use an inexhaustible source of energy obtained from ordinary water. They would harness the highest temperatures on earth—and some of the lowest. More specifically, in such systems, hydrogen plasma at the temperature of the sun—millions of degrees—will be held within magnetic "bottles" produced by electromagnets that operate at temperatures only four or five degrees above absolute zero. These are some of the amazing aspects of fusion reactors now envisioned for the next century.

As the late David Rose, an articulate pioneer in fusion power development from the Massachusetts Institute of Technology, aptly remarked, "Controlled fusion has, during this scientific stage, been the most challenging and difficult of all such assignments ever given to physical scientists, and they deserve credit for doing so well. But there is much more to controlled fusion than applied plasma physics, and now controlled fusion shows signs of becoming, in addition, the most difficult and challenging assignment given to technologists and engineers."

The challenges are indeed great, but so is the reward for success. Consequently, all major industrial nations of the world are devoting significant resources to fusion power development. These nations include the United States, the European Community, Japan, and the Soviet Union. In the U.S. fusion program, Oak Ridge National Laboratory has a prominent role. On the physics side, scientists at ORNL have been working for more than two decades on methods of confining plasmas—hot ionized gases—with magnetic fields. For the past 15 years, a closely related effort has been under way at ORNL to develop the most efficient electromagnets conceivable for ultimate use in producing "man-made solar energy" from magnetically confined plasmas. These magnets will employ superconductors—a class of materials that can, when cooled to very low temperatures, carry massive electrical currents without any resistance whatever.

Why Superconducting Magnets?

Superconducting magnets are needed to ensure economical generation of electrical power from magnetically confined fusion. Net energy production from a fusion development and operation of aqueous homogeneous reactors in ORNL's Reactor Experimental Engineering Division, Haubenreich was placed in charge of the Molten Salt Reactor Experiment during its five years of operation. Following the successful conclusion of that experiment, he became associate director of the Molten-Salt Reactor Program and then transferred to the fusion program.

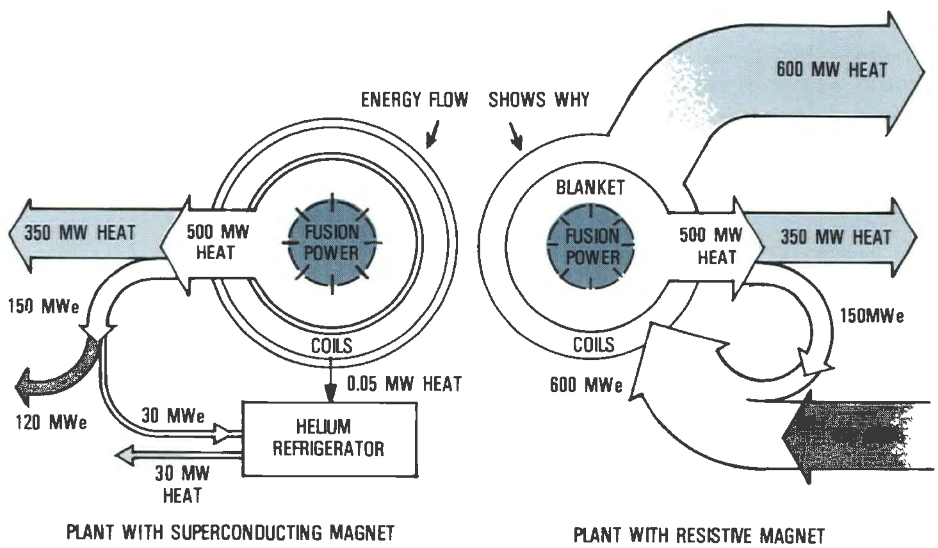
Martin S. Lubell is head of the Magnetics and Superconductivity Section of the Fusion Energy Division. His responsibilities include directing the research and development needed for the fabrication of the large superconducting magnets that will be required for future plasma experimental devices and tokamak fusion reactors. He also serves as deputy manager of the Large Coil Program (LCP); he is in charge of the testing and analysis of the large coils. Lubell, who holds an S.B. degree from the Massachusetts Institute of Technology and an M.A. degree in physics from the University of California at Berkeley, came to ORNL in 1967. He was appointed to his current position in 1976 following two years as assistant manager of the Division's Superconducting Magnet Development Program. He assumed his duties in the LCP in 1984. Lubell is a member of four national boards that are concerned with applied superconductivity, cryogenic engineering, cryogenic materials, and fusion technology. He was also a member of the International Organizing Committee for the International Magnet Technology Conference. Here, in the control room of the magnet test facility, Haubenreich (standing in back) and Lubell (standing in front) watch as ORNL engineers Stewart Shen (foreground) and Richard Stamps check facility operations.

The International Fusion Superconducting Magnet Test Facility at ORNL now contains its full array of six large superconducting magnet coils. The coils were designed and built under ORNL's direction over the past 10 years by groups in Japan, Switzerland, the European Atomic Energy Community, and three U.S. firms. This article presents the story behind the coils and the status of the testing program designed to compare the technical performance, reliability, and economics of using different coil designs to contain plasmas in fusion devices that could generate useful electrical power.

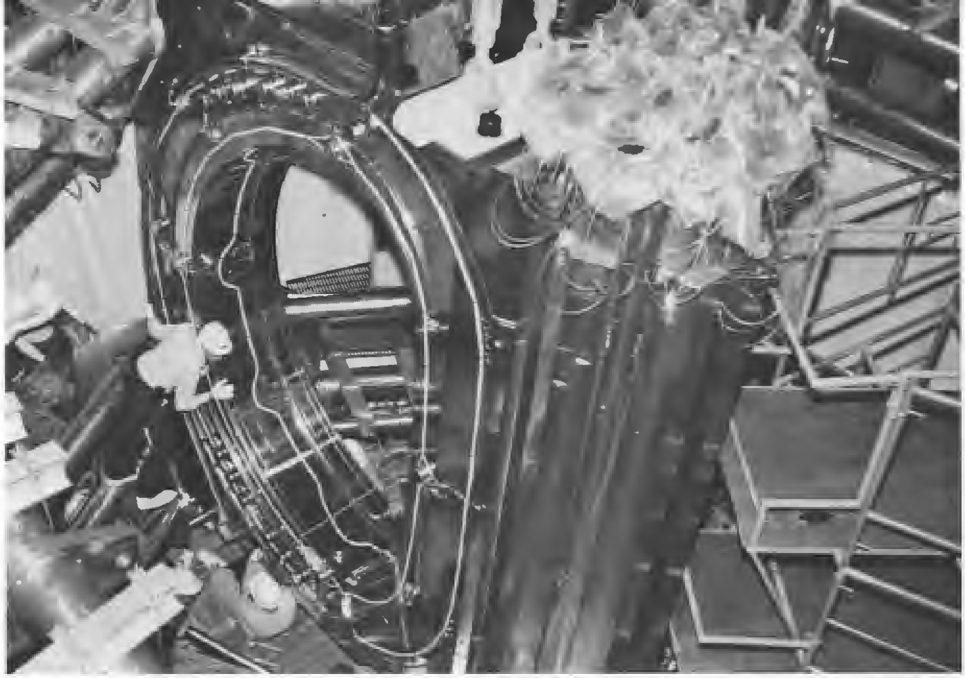
The Story Behind the Coils at ORNL

reactor employing power-hungry copper magnet coils is far less than that from a reactor having superconducting coils (see figure at right).

The early workers in the controlled thermonuclear fusion program were, of course, aware of the energy-gobbling nature of resistive magnets. However, back in the 1950s practical high-field superconductors had not been discovered, so researchers could only hope to invent a device that could use the confining magnetic fields with full efficiency (i.e., the plasma pressure could approach the equivalent pressure of the confining magnetic field). In this ideal case, the magnetic field generated by the electrical coils would be used so efficiently and the plasma would yield such tremendous returns in fusion energy that the energy expended in driving current



For efficient production of electric power from magnetically confined fusion, superconducting magnets are essential, as shown by comparing the energy flow of a plant with superconducting magnets with that of a plant with resistive magnets.



The Japanese coil was lowered into the test facility at ORNL in August 1983. It was the first magnet to arrive at ORNL.

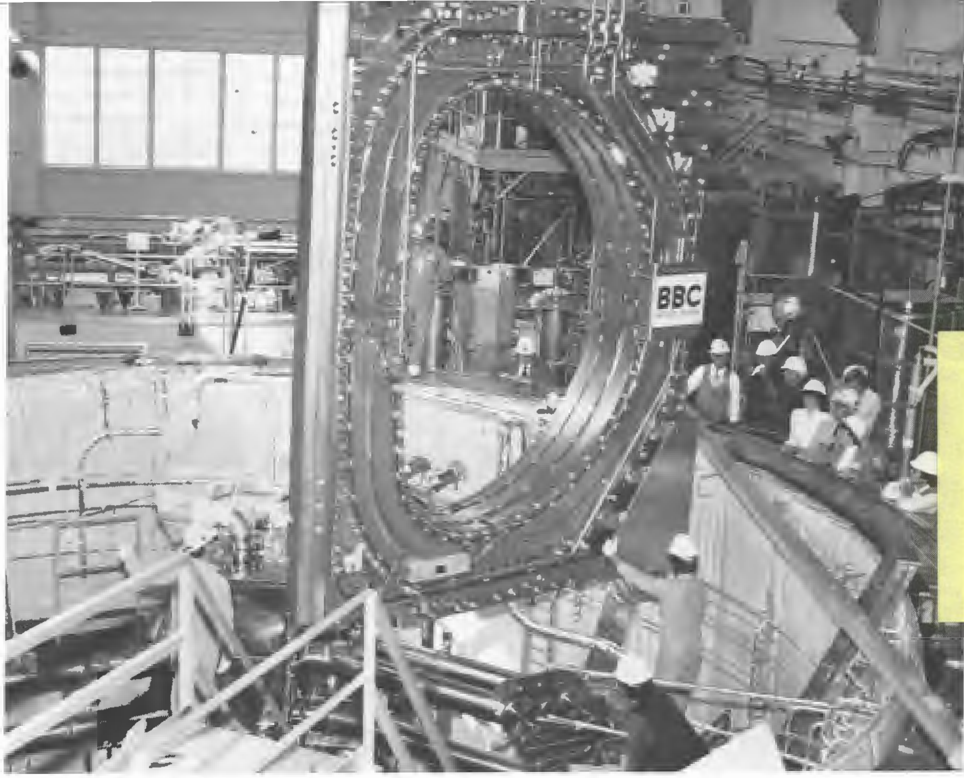
The General Dynamics coil (shown here), along with the Japanese coil, was subjected to an early test in the summer of 1984. Tests on both coils were successfully carried out to the full design current of 10,000 amperes.

through copper conductors would be comparatively small. That hope has not been abandoned but has been greatly diminished because the combination of stability and efficiency in the use of magnetic fields for plasma confinement has proved to be elusive.

Today the doughnut-shaped tokamak is the "mainline" fusion concept in the United States, Europe, and Japan, as well as in the Soviet Union, where it was invented. However, in the tokamak it has been impossible to raise the plasma pressure to more than a few percent of the magnetic pressure. The best achievement so far is about 5% and, in reasonably optimistic concepts, would reach only 10%. To make a tokamak reactor that has reasonably high power density in the plasma, the toroidal field (TF) magnet must produce field strengths in the plasma on the order of 3 to 6 teslas (T), over volumes on the order of a hundred cubic meters. (Such field strengths are about 100,000 times the earth's magnetic field.) The power requirements of such large, high-field magnets, if made with copper conductors, would be hundreds of megawatts, about the equivalent of the entire output of the Tennessee Valley Authority's Bull Run generating station. Fortunately for the future of fusion power, during the same decade that saw the birth of the tokamak concept, practical superconducting magnets began to make their appearance in various laboratories around the world.

Superconductivity had been discovered early in this century by Kamerlingh Onnes, a Dutch physicist who found that frozen mercury abruptly lost all resistance to the flow of electricity when its temperature was reduced below about 4 K (-452°F). Fifty years passed, however, before materials were discovered that could remain superconducting in the presence of high magnetic fields. In 1961, researchers at Bell Laboratories showed that an intermetallic niobium-tin compound (Nb_3Sn) would superconduct at rather high current densities in fields close to 10 T. Over the next several years, ductile, superconducting alloys, including niobium-titanium (NbTi), were discovered. By the time the news of the tokamak invention broke, several practical superconducting magnets had been built in laboratories around the world, including ORNL.

Tokamak reactors with superconducting TF coils were soon conceived both at Princeton and at Oak Ridge. In 1971, Marty Lubell and others in the Controlled Thermonuclear Division, in collaboration with engineers from ORNL's Reactor Division and Engineering Department, conducted a study that formed the basis for a development program that grew slowly over the next several years. They envisioned high-current, compound conductors designed to operate at high magnetic fields. Such superconductors were indeed credible, but the technology was still in its infancy. Thus, when Lubell and co-workers depicted TF



The Swiss coil arrived at ORNL in February 1984 and was then lowered into the test stand.

coils using NbTi superconductors at a peak magnetic field of 8 T in magnets with bores of 11 m, they were counting on further development of superconductors and magnet technology to successfully solve a host of problems, some of which were known and some only anticipated. When the paper on their work was presented at the 1971 International Atomic Energy Agency (IAEA) meeting at the University of Wisconsin, it created quite a stir—especially when the plasma physicists heard that a minimum of two months would be required to cool down the magnet system to make it superconducting. Lubell's talk prompted so many questions and discussions that, in his review of the conference, the science editor of the *New York Times* highlighted the ORNL paper as a significant contribution and step forward in fusion research.

Problems and Solutions

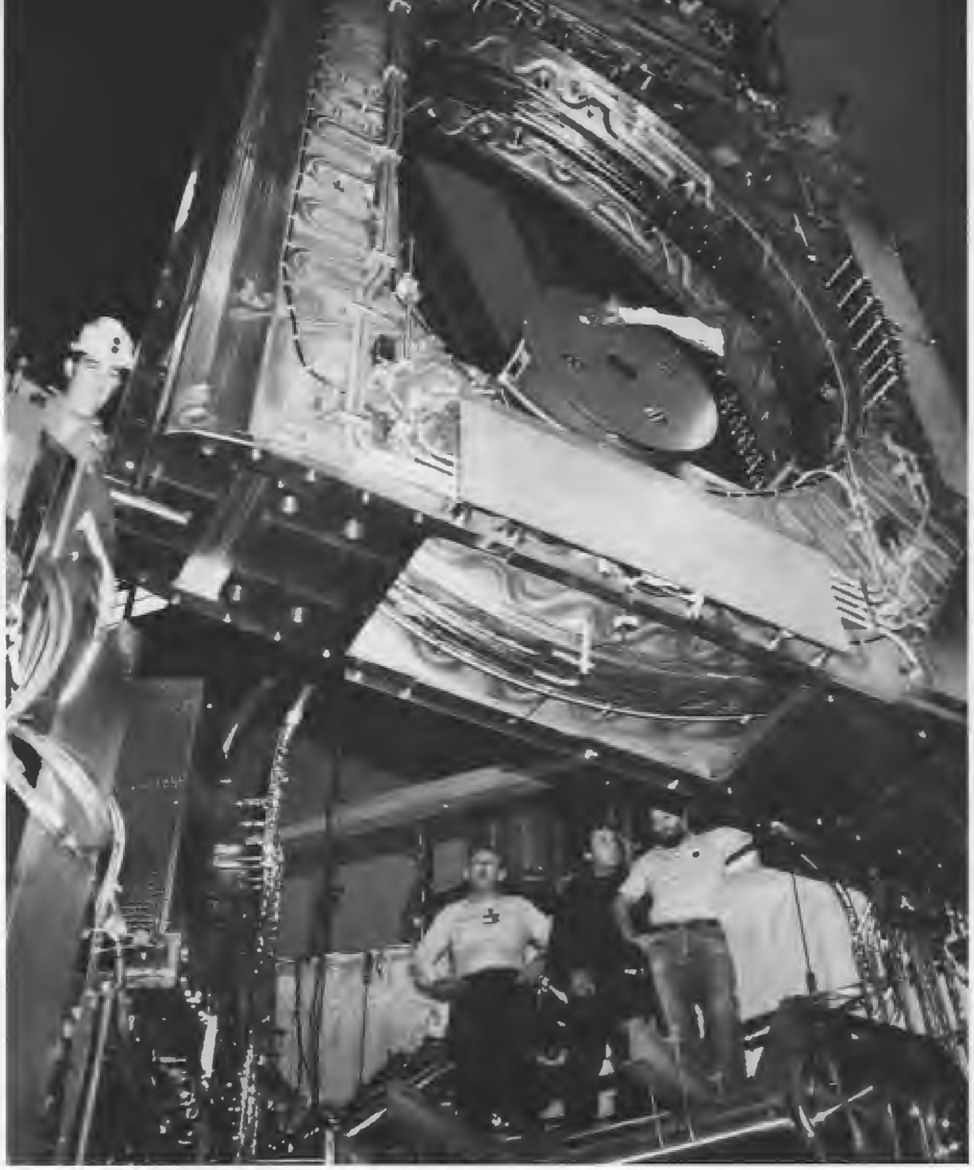
In the early days of superconducting magnets (the 1960s), discoveries came rapidly, including some disagreeable ones. For example, it was found that even if the rate of current rise was very slow, a magnet would undergo a spontaneous loss of superconductivity. One cause proved to be a phenomenon called "flux-jumping," and the solution was to reduce the transverse dimensions of the superconductor. NbTi rods were mounted in holes drilled lengthwise in a copper billet, which was then extruded and drawn into wire strands containing thin filaments of NbTi in a copper matrix. Nb_3Sn conductors were made at first by plating tin on a niobium strip that was reacted at high temperatures (around 700°C) to create a thin layer of Nb_3Sn at the interface. More recently, multifilamentary Nb_3Sn has been produced by extruding and drawing Nb filaments in a bronze matrix and heat treating (typically 700°C for about 24 h) to allow the tin in the bronze to react with the niobium.

Other problems of magnet stability cropped up. At the extremely low temperatures required for superconductivity, everything but helium has vanishingly small specific heat. Thus, a tiny amount of heating (typically a few mJ/cm^3), as by friction between two wires that slip [illegible]nts induced [illegible]ic field, [illegible] the [illegible] critical [illegible]

[illegible] a dramatic [illegible]. The [illegible]conducting [illegible]ut electrical resistance and ohmic heating would suddenly develop a resistance about like that of nichrome heater wire. In the early magnets, this event immediately produced an abrupt shutdown as the high current in the resistive filaments heated up the conductor and boiled off the liquid helium needed to take away the heat. (At the temperature of practical superconductors, every substance other than helium is frozen solid.) One simple answer to this problem was devised by magnet designers at Argonne National Laboratory and Avco-Everett Laboratories. They included sufficient copper in parallel with the superconductor in a composite conductor so that, if a brief heating event like a conductor slippage drove the superconductor into the resistive range, the current would simply be diverted through the copper. With enough copper and surface area in contact with helium, ohmic heating would be low enough that cooling by helium would quickly bring conductor temperature back down into the superconductivity range, terminating the event without any collapse of magnet current.

Superconducting Magnet Development Program

When Bill Gauster came to ORNL in the 1950s, he organized a



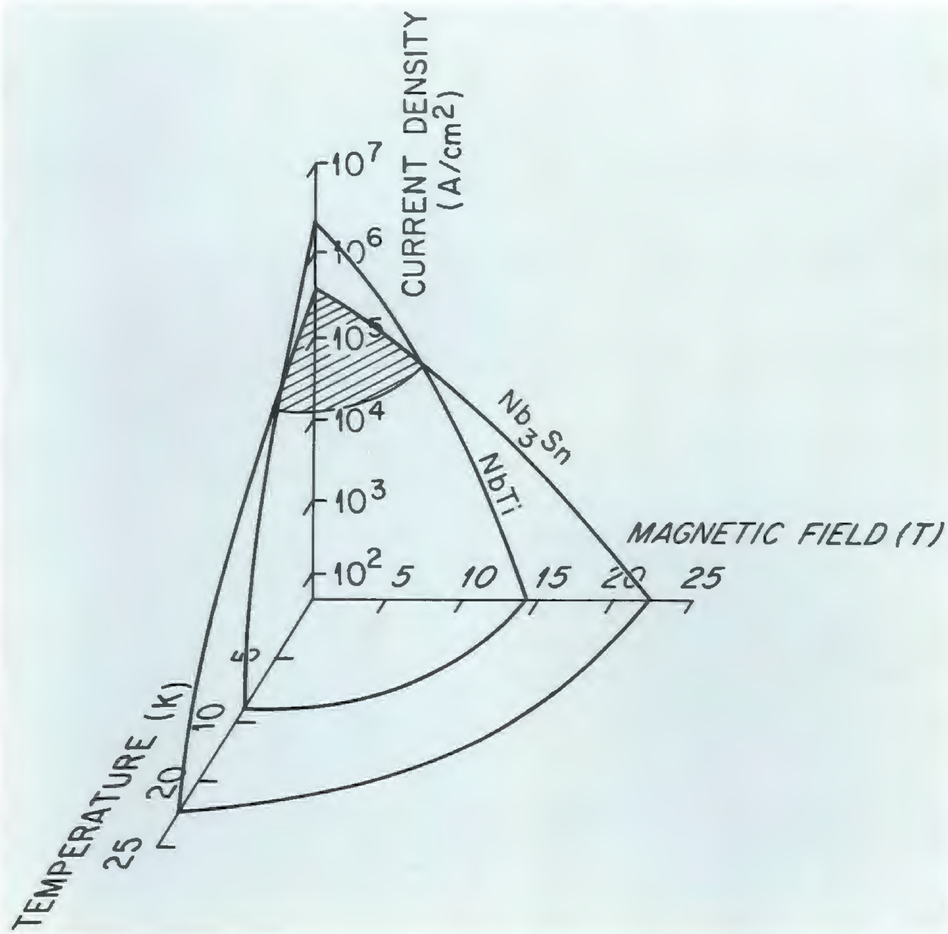
On December 17, 1985, the EURATOM coil was lowered into the ORNL test stand.

The Westinghouse magnet was delivered to ORNL in August 1985 and was superconducting, along with the five other coils in the test facility, by February 1986.

development team, consisting of engineers like Bob Brown and Jim Luton from other areas of the Department of Energy's Oak Ridge complex (which was then operated by the Nuclear Division of Union Carbide Corporation), to build better copper magnets to support fusion research. As the fusion program progressed, the machines became larger. For the larger "mirror devices", which require steady-state fields (as opposed to tokamak research machines, which can use pulsed TF magnets), it became necessary to use magnets whose power consumption would be prohibitively expensive if they were made of copper. Fortunately, the discovery of type II superconducting materials (high current density, high-field superconductors) coincided with fusion developments. Gauster promptly started a small research effort into superconductivity.

In the late 1960s Lubell joined the ORNL research team after five years of experience in superconductivity research at the Westinghouse R&D Center. A few years later, Hugh Long, a senior scientist in Carbide's Linde Division and a cryogenics expert, was brought in to take over the group upon Gauster's retirement. At about that time Gauster's group had completed the superconducting magnet for the Injection into Microwave Plasma (IMP) mirror machine. The IMP magnet was the first large superconducting magnet (a quadrupole configuration) to be made with Nb_3Sn ribbon conductor.

Over the next 12 years the Engineering Science Group (later the Magnetics and Superconductivity Section) designed and fabricated a number of devices embodying state-of-the-art advances in superconducting



Superconductivity—carrying electrical current without resistance—occurs only at extremely low temperatures and within the bounds of current density and magnetic field that depend upon the material. Shown here are the bounds for the two most widely used superconductors: niobium-titanium (NbTi) alloys, which are ductile, and niobium-tin (Nb_3Sn), a brittle, intermetallic compound that, in practical conductors, is formed within a matrix of ductile material.

magnet technology: a 14-T Nb_3Sn solenoid for Felix Obenshain (Physics Division); a magnet for the Coil Winding Test Experiment (CWTX) that had a 40-cm bore, 8-T working field and that received the 1980 Outstanding Engineering Achievement Award from the Oak Ridge Chapter of the National Society of Professional Engineers; and a 7.5-T high-current density, 40-cm bore magnet for the Elmo Bumpy Torus-P project. Also during this time, ORMAK, the first tokamak at ORNL, was nearing completion. Long was instrumental in solving a number of cryogenic problems associated with ORMAK's liquid-nitrogen-cooled copper TF coils. As a result of the ORMAK experiment, he became convinced that large steady-state magnets should be superconducting, not copper.

In 1972 at the behest of the Atomic Energy Commission (AEC), superconducting magnet specialists in the United States convened at ORNL to estimate the costs and time required to develop fusion magnets. The report presenting these estimates was prepared by representatives of the AEC laboratories under the direction of Lubell. It proposed that an eight-year program with a budget of $64 million (which seemed astronomical at the time, but turned out to be optimistic) was necessary to develop mirror and tokamak magnets. After this report came out, the need for a superconducting magnet development effort was generally accepted. Proposals were solicited. Lubell prepared an outline for a minimum development program specifically for TF coils, and Long presented it at the AEC Fusion Power Coordinating Committee meeting held in Princeton, New Jersey, in December 1972.

In 1973 Long prepared a more extensive plan and presented it to the AEC. In FY 1974 funding was provided, and the Superconducting Magnet Development Program for TF coils was launched at ORNL. Additional staff members were hired, and research was started according to the detailed program plan.

ORMAK-F/BX

By the spring of 1973 the concept of a large tokamak having superconducting TF coils appeared attractive enough for ORNL to propose that one be built at Oak Ridge. The AEC, which was pushing the development of fusion energy, directed ORNL to study the possibility of designing a tokamak that would achieve a significant level of fusion reaction in a deuterium-tritium (D-T) plasma. (Confinement experiments up to that time had used normal, light-hydrogen plasma.) Mike Roberts, who was active in getting ORNL's first tokamak built and operating, was to lead the study. Roberts' concept was to build a device large enough to reach the Lawson criterion (the minimum value of the product of the plasma confinement time and density that is required for fusion reactions to occur) using a nonradioactive hydrogen plasma, then to install shielding and a smaller plasma vessel for the D-T

What Size Magnets?—Weighing the Scaling Problem

In 1972–1975, when I was studying the options for testing large superconducting toroidal field coils, I pondered whether the results of any test would be scalable for a magnet of the size needed. Cost scaling was also important because no large, high-field superconducting magnets had ever been built anywhere. Our planning for the U.S. government had to include cost estimates for our test facility and for the test magnets, both of which had to be acceptable to the magnet community.

No one knew what the costs of these multi-ton magnets would be. The difficulty of making these cost estimates is underscored by the fact that, in 1979 when we built a facility magnet named the Coil Winding Test Experiment for use in our own laboratory, the largest magnet available to produce a central working field of 8 T had a bore size of only 40 cm and a total weight of only 2000 kg (2 tons). Thus, it is not surprising that in 1975 it was so hard to estimate with any degree of certainty the cost of constructing 3-m bore, 45-ton magnets.

It was also not easy in the 1970s to convince the fusion community that results from tests of these large magnets would scale up to the size needed for the proposed Experimental Power Reactor, which was anticipated to be three times larger than any test coils we might build. In fact, the ad hoc review committees in 1975 insisted that we increase the size of the test coils from our original proposal because they lacked confidence in any scaling rules.

We eventually got over this hurdle by developing the stored magnetic energy (vs current density) as a figure of merit. The stored magnetic energy (Es) in a magnet is a product of the square of the magnetic induction ($B^2/8\pi$) multiplied by the volume over which the field energy is stored (principally in the bore and winding). In a torus essentially all the flux is contained by the magnets; thus, very little leakage occurs. Both of the difficult scaling factors, field and size, are contained in Es.

When scaling magnets, the uncertainty arises because of the increased forces that must be handled. Handling increased forces requires the incorporation of more structural steel in the magnet and containment of the additional motion that is likely to occur. Because magnet winding motion causes friction and induced voltages, resulting in significant temperature rises because of low heat capacity of metals at 4.2 K, a dramatic loss of superconductivity can result. Reducing the possibility of such loss is a strong consideration in designing large superconducting magnets.—*M.S.L.*

burning experiments. The machine was called the Oak Ridge Tokamak-Feasibility/Burning Experiment (ORMAK-F/BX).

ORNL's first step toward an F/BX was to conduct a preconceptual design study. For this task Roberts assembled a small team to work with physicists in the ORMAK group. Included on the team were Lubell, whose job was to handle magnet design, and Haubenreich, who came over from the Reactor Division (now Engineering Technology) after 22 years in fluid-fuel reactor development programs.

After comparing various options for TF coils for the reference concept, the team chose superconducting coils using NbTi and operating at a peak field of 8.5 T and a temperature between 3 and 4 K. This concept soon encountered some powerful external opposition. The AEC scheduled a review of the F/BX concept in Washington, D.C., and arranged for staff members from the Princeton Plasma Physics Laboratory (PPPL) to participate. (Then as now, PPPL was the lead laboratory for U.S. experiments on tokamak confinement.) Although Bob Mills, an electrical engineering professor at Princeton University, Joe File, and others from PPPL had earlier produced a conceptual study of a power-producing tokamak fusion reactor having superconducting magnets, the plasma physicists at PPPL were quite uneasy about the prospect of the U.S. program jumping directly from the Princeton Large Torus (PLT), a relatively small, copper-magnet device, to a radioactive, superconducting tokamak, whether built at PPPL or elsewhere. The ORNL team members, accustomed to working with radioactivity and with superconducting magnets, were not unduly skeptical but were properly impressed with the difficulties inherent in a marriage of the two. Thus, when PPPL reviewers seemed to be pressing for guarantees that the F/BX development would not take long and that the magnet system would be highly reliable, the ORNL team's answers were qualified.

PPPL physicist Harold Furth thereupon pronounced the F/BX concept too uncertain and unveiled his counterproposal: the use of "conventional technology" to achieve D-T fusion in a so-called "wetwood burner." The idea was not to ignite a D-T plasma, but to get some burning (as it were, by playing a blowtorch on wet wood) by injection of high-velocity tritium atoms into a deuterium plasma. PPPL had already had engineers from Westinghouse Electric

Corporation sketch such a machine, showing copper TF coils like those in the PLT, only much larger. The idea of "cheap, quick" neutrons from fusion appealed to AEC fusion program head Bob Hirsch. He thereupon gave PPPL the go-ahead to do a preconceptual design, to be evaluated along with one from ORNL having the new reduced goals but with superconducting magnets.

Both studies were completed and reviewed together in July 1974. The choice was clear. The better "wetwood burner" would be PPPL's copper-coil machine, which clearly would be quicker to build. The resulting decision by the AEC was to launch the Tokamak Fusion Test Reactor (TFTR) project at PPPL—and to bury ORNL's F/BX project.

Origin of Large Coil Program

The F/BX study was not without effect, however. In the fall of 1974, the AEC started another year-long study, this time of a later-generation Experimental Power Reactor (EPR). AEC stipulated that the EPR should have superconducting magnets and demonstrate reactor technology (including a breeding blanket). Crucial decisions that had to be made included magnetic field strength, superconductor material and mode of cooling, magnet shape, and structural concept. After evaluating input from his magnet experts, Thermonuclear Division director John Clarke chose TF coils operating at a peak field of 11 T (with Nb_3Sn in the high-field regions and NbTi in lower fields) and cooled by forced flow of helium at supercritical pressure. Concurrent EPR studies at Argonne and General Atomic focused on quite different TF coils (i.e., NbTi at a peak field of 8 T, cooled by a "bath" of helium boiling at atmospheric pressure). Efforts to obtain a consensus of magnet experts on which of the two concepts was better were unsuccessful but convinced Hirsch that a major development effort on superconducting TF coils should be launched immediately.

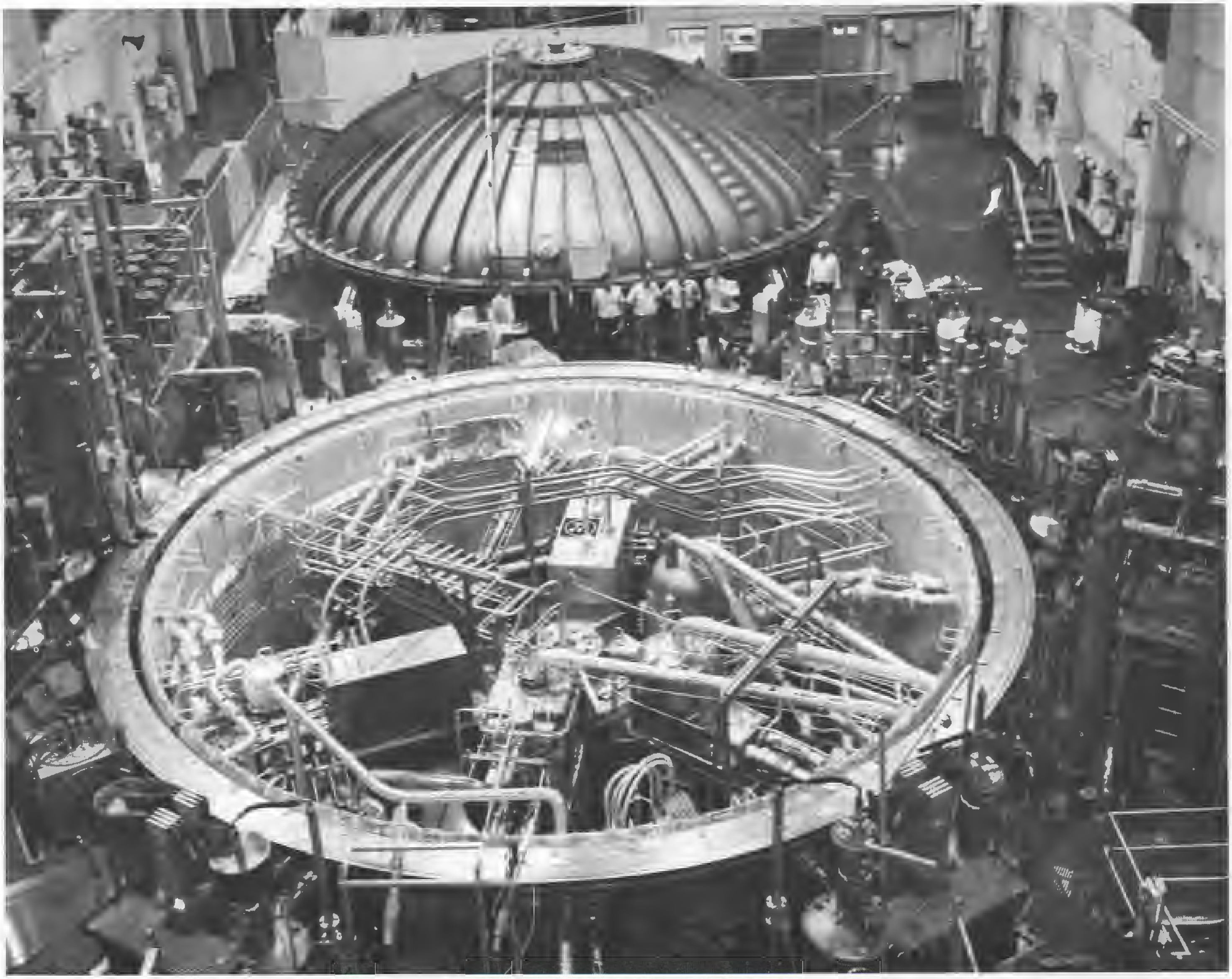
Having already come to the same conclusion, ORNL had prepared a proposal for a program to develop a series of test coils of sizes ranging from 1 to 6 m in diameter. One phase was a six-coil torus that had five background coils of conservative design and a slot for high-performance test coils. In recognition of the scope of this activity, then called the Compact Torus, John Clarke set up a project organizational structure that included heavy participation by Union Carbide Corporation-Nuclear Division Engineering staff members. Haubenreich was appointed manager; Jim Luton, deputy manager (with responsibility for involving magnet specialists); and Phil Thompson, principal engineer.

In the fall of 1985, AEC's successor, the Energy Research and Development Administration (ERDA), convened a panel of magnet experts from across the country to appraise the ORNL proposals. The panel recommended pursuing a version of the compact torus but not the other large-scale development tasks proposed by ORNL. Although ORNL was to manage the effort, it was to be a truly national program, accepting input from other fusion laboratories and using industry in design as well as manufacturing. The name was to be the Large Coil Program (LCP). A significant change was to make all coils test coils, enabling simultaneous testing of several concepts. Other criteria were set by the panel. For example, the peak field was to be specified as 7.5 T (later raised to 8.0 T by ERDA); the more conservative panel members felt that 7.5 T was likely to be the highest field that could be ensured using the NbTi conductor, which was viewed as the most reliable superconductor material. The program was also to consider the use of Nb_3Sn, which offered better performance but whose sensitivity to strain caused some experts to doubt its ultimate feasibility. To keep cost manageable, the overall dimensions of test coils were to be about one-third those of the EPR concepts. At the same time, the conductors were to be full-size (capable of carrying 10,000 to 20,000 amperes), so that no further scale-up of conductor design and production processes would be necessary.

In December 1975, ERDA authorized ORNL to prepare a preconceptual design of a test stand, prepare coil performance specifications, and develop a program plan that would include three industrial teams to design and build coils. This was clearly an undertaking of truly major proportions and one that Laboratory and company management did not enter into without extensive discussions.

In 1976 the technical aspects of the LCP took shape. Thompson, working with both engineering and magnet specialists, performed parameter studies that supported decisions on coil and test stand dimensions, vacuum topology, and many other features of the test facility. He and the project engineers made the cost estimates needed in the formal proposal to ERDA. After consulting magnet experts at ORNL and around the nation, Thompson and Luton then came up with a thick volume of technical specifications for the test coils. Later events proved that they did an outstanding job.

Because the purpose of the program was to solicit the best



The six large superconducting magnets are in place and the lid is ready to be put on top of the International Fusion Superconducting Magnet Test Facility at ORNL. Since this photograph was taken, the facility coils have been cooled and operated in a superconducting mode. Data is being collected to compare the technical and economic merits of each coil design.

ideas and test them, ORNL deliberately wrote the coil specifications to allow each coil design team to make some crucial design decisions, including structural concept, conductor configuration and materials, and the conditions of the helium coolant. To ensure that all the different coils would fit and work together, the performance parameters and external dimensions of the coils were, of course, included in the specifications. By the end of 1976, complete draft specifications were in the hands of interested industrial design teams.

Design of the test facility is quite a story in itself because of the extraordinary requirements that had to be met. The forces on the coils during high-field tests are enormous—equivalent to the weight of a 100-car freight train. Because of the extremely low operating temperature, thermal isolation of the six coils and restraining structure from the outside environment must be highly effective. The entire 400-ton array is placed inside an 11-m (35-ft) diameter vacuum tank, which is evacuated to one hundred millionth of atmospheric pressure. This vacuum must be achieved despite penetration of the tank wall by thousands of wires from sensors in the highly instrumented coils. The refrigeration system was

By October 1985, all six magnetic coils were in place and the lid was lowered and affixed to the vacuum tank of the International Fusion Superconducting Magnet Test Facility at ORNL. After minor leaks were repaired and major repairs were made on some of the cryogenic equipment of a huge complex refrigeration system, cooldown of some 400 tons of magnetic coils began in January 1986. All six magnets are now superconducting, and data are being taken on their performance.

complicated because three of the coil teams chose to use bath cooling while the other three chose to cool their conductors internally with flowing helium. Thus, the refrigeration facility had to supply up to 250 L/h of liquid helium to replace that being boiled off in the bath-cooled coils, while simultaneously circulating up to 300 g/s (about 35 gal/min) of helium at 15 times atmospheric pressure through the forced-flow coils. Perhaps the most difficult task was to design a pulsed coil system, in which electrical power and coolant must be supplied to a pair of coils that is moved remotely from one station to another within the sealed tank to produce field transients resembling those in a tokamak.

Construction of the test facility demanded adherence to the highest standards of quality assurance. Because it takes about three months just to warm up the test stand from operating temperature and then cool it back down, all components must operate reliably to minimize the need for maintenance in the tank. Experience has shown that these high standards have indeed been met.

That the facility has operated as well as it has to date is a tribute to all the people who designed and built it. This accomplishment was

Craftsmen, engineers, and scientists pose before the vacuum tank, which had just been closed (October 24, 1985) on the completed six-coil test array.

recognized by the Oak Ridge chapter of the National Society of Professional Engineers who awarded the test facility the title "Outstanding Engineering Achievement of 1985."

International Collaboration

While design studies of experimental power reactors were being carried out in the United States, staffs at major fusion laboratories in Europe and Japan were thinking along similar lines. In each country, fusion program managers recognized the need for a superconducting magnet development program and had people trying to decide how best to proceed. This situation resulted in intense information exchange through visits and correspondence.

By late 1975 we knew we would build some sort of test facility at ORNL. We also knew the test coils would have appreciable bore sizes (2 to 3 m) and conveyed this information to our foreign visitors from the United Kingdom and Federal Republic of Germany (FRG). They expressed their own desire to work on a comparable scale but said they were thwarted by limited budgets for superconducting magnet development. One day Professor Becker, a director of Kernforschungszentrum Karlsruhe (KfK), stopped by Lubell's office during a visit to ORNL to inquire about ORNL's plans. He mentioned how frustrated his people were because they could afford only a small test stand and magnets, yet they recognized that scale-up was essential. Lubell lightly suggested that the Europeans should spend all their magnet research money on building one large coil, which could be transported to Oak Ridge for testing in ORNL's test facility.

On further consideration, the idea of including foreign coils in Oak Ridge tests seemed worth pursuing. In late 1975, Lubell wrote to Werner Heinz, director of superconducting magnet development at Karlsruhe, and told him of his conversation with Becker about the possibility of international cooperation. The next initiative came from the Europeans to the U.S. government. Lubell then received a call from ORNL Director Herman Postma wanting to know what he had promised the Europeans. He sent a copy of his letter to Heinz; fortunately, it contained a caveat about the need for approval of ORNL management and our government sponsor (ERDA) before international cooperation could be arranged.

Birth of Large Coil Task

By mid-1976 ERDA had looked at ORNL's projections of schedules and costs for the U.S. Large Coil Program and began investigating the feasibility of international collaboration. Because of the effective communication network that characterizes multinational fusion research, people all around the world became aware of the rapidly evolving U.S. program of developing superconducting magnets for fusion. Because they had similar objectives, magnet people in all major countries were intensely interested in the U.S. Large Coil Program and met informally with program managers to learn about the program and exchange views on how a collaboration might work.

Lubell recalls vividly one such conversation that occurred during and after a dinner at an Oak Ridge restaurant early in 1976. The parties were Alberto Martinelli and Mauricio Spadoni from Italy, Gaston Bronca from France, Albert Knobloch from Germany, Susumu Shimamoto from Japan, and Lubell. Lubell was answering a lot of questions and talking rapidly, but the foreigners were having difficulty fully understanding his rather heavy New York accent. So Martinelli, who had spent two years at MIT and had an excellent command of English (and everything else!), would turn to Spadoni and explain it to him in Italian, then he would turn to Knobloch and converse in perfect German, and finally he would carry on a conversation in fluent French with both Bronca and Shimamoto (the latter had just returned to Japan from a seven-year stay at Saclay and felt more comfortable speaking French than English, and Martinelli didn't speak Japanese, at least not fluently). In later years in other international situations, Lubell remembered Martinelli's tour-de-force and wished for a similar ability to communicate in several languages.

In the fall of 1976, after an Applied Superconductivity Conference near Chicago that attracted many participants from abroad, a somewhat more formal meeting was held in Oak Ridge to discuss ideas for international collaboration. Out of it came the basic elements of what later came to be known as the Large Coil Task (LCT). The people at the meeting included Carl Henning from DOE-Washington, Knobloch from Germany, Martinelli from EURATOM, Ko Yasukochi from Japan, and Alfred Koch from Switzerland. Haubenreich went over the LCP plan and the draft coil specifications, which the foreigners found to be a quite acceptable technical foundation for collaboration. The idea that emerged was that the United States should serve as Operating Agent, building and operating the test facility as already envisioned in the LCP plan. Instead of the U.S. industrial subcontractors building two coils apiece, however, they would each build only one. Meanwhile teams in Japan, Germany, and Switzerland would each design and build a coil, all of which should arrive at Oak Ridge at about the same time as the three American coils. The interested parties had already decided to use the newly formed International Energy Agency (IEA) to help work out the formal agreement that would be required. Therefore, Niels de Terra, a lawyer from IEA, was present and took copious notes on the ideas evolving from the discussion. Afterwards he returned to Paris to rewrite them in legalese.

In April 1977 all prospective participants in the LCT got together at Garching (near Munich) to go over the draft and make it state as clearly as possible what the technical people wanted to accomplish. This was the real beginning of what was to become as much an experiment in international communication and collaboration as in magnet technology. The barriers of language were evident, but the participants, highly motivated by the potential benefits, reached agreement on a draft document which, after some further legal polishing, was acceptable to all parties. In October of that year, the United States (Secretary of Energy Schlesinger) and the European Atomic Energy Community (EURATOM) signed the agreement that formally established the Large Coil Task. The wheels of government moved more slowly in Japan and Switzerland, but in May and September 1978 respectively, they, too, became "original signatories" to the LCT agreement.

Taking the Magnets for a Ride: Humorous Stories about Transportation

Under the terms of the LCT agreement, each of the foreign participants was responsible for delivering its coil—by ship and truck—all the way to Oak Ridge. Here are several tales.

The longest voyage, that of the Japanese coil by way of Yokohama and the Panama Canal, was uneventful. So was the transport over the highways from New Orleans to the Oak Ridge test facility door, all arranged by Hitachi. Nothing was left to chance. An advance party drove from New Orleans to Oak Ridge, checking road clearances all the way. During righting of the coil, Japanese observers insisted that cables be attached to ensure that the coil would not fall over if an earthquake struck at the critical moment. The real secret of the smooth operation came out, however, when the coil was unpacked. The Japanese explained that the package fastened to the side of the coil was a "good luck charm" that had been blessed at a Shinto shrine to ensure a safe journey.

The Swiss coil departure from Basel down the Rhine was threatened by low water, but the rain and melting snow came in the nick of time. After that it was smooth sailing for the Swiss coil all the way.

The Germans, as might be expected, were also meticulous planners, but unexpected events delayed delivery of the EURATOM coil. The German ambassador to the United States, who came to Oak Ridge to celebrate the coil's arrival, spoke humorously of its serene passage by the castles of robber barons along the Rhine gorge only to be halted by Georgia state troopers because of a problem with the trucker's papers.

In the case of the General Dynamics/Convair coil, once Sacramento approved the 4-unit, 34-wheel highway transporter, the trip from California met no delay. Neither did the transport of the General Electric coil from Schenectady to Oak Ridge Gaseous Diffusion Plant and, 24 months later, the trip from there to the Oak Ridge test facility.

Delivery of the Westinghouse coil was a tight squeeze in more than one way. When Tennessee authorities approved movement of the Westinghouse coil in its 4-m- (13-ft-) wide box, they didn't mention that temporary bridge railings in a one-lane section of I-75 near Lake City were only a few centimeters farther apart (13 ft and 2 in.). At least that is the estimate of the trucker and escort who maneuvered the 30 m (99-ft) long rig through the bottleneck in the dark without scraping either side. Both were still wide awake, to say the least, when they arrived at Knoxville shortly before midnight with the coil for which, they were assured, the world had been eagerly waiting.—*P.N.H.*

To reflect the international nature of the LCG, the test facility at ORNL is now named the International Fusion Superconducting Magnet Test Facility.

The foreign participants who joined the venture were EURATOM, with KfK, Karlsruhe, as project manager; Japan, with the Japan Atomic Energy Research Institute (JAERI) as project manager; and Switzerland, with the Swiss Institute for Nuclear Research as project manager and Brown Boveri Company, as the industrial partner that would fabricate the conductor and magnet.

Industrial Involvement

Industrial competition is commonplace. What is unique about the LCT is the way the competition works. Ideas, designs, and workmanship of six industrial giants from all around the world are laid on the line, side by side, at Oak Ridge. (More precisely, they are nose-to-nose because the six different coils form a toroidal array.) This arrangement requires cooperation, because each coil contributes to the magnetic field in which all are tested. The arrangement also, however, emphasizes the competition, as it facilitates direct comparison of performance and reliability.

Because each coil is required to do exactly the same job, any coil that is better or worse stands out. There is no way to hide; each participant has access to data on the behavior of any coil, his own or any of the others.

From the beginning of the international program, it was intended that LCT participants could see for themselves which design features were most desirable, so that they could decide what to incorporate in their next generation of superconducting magnets. Comparison of the capabilities of the industrial firms and nations that produced the magnets was not talked about so much. Nevertheless, this subtle form of rivalry is a strong undercurrent, which occasionally surfaces in the discussions at international meetings and in reports on program results. However, rather than being a detriment to the collaborative efforts, the rivalry has been a stimulant to each participant.

From beginning to end, working with the U.S. industrial teams has been quite an experience for the Oak Ridge people. It began to heat up in 1976, when news of the LCP and its intention to involve industries was published in the *Commerce Business Daily*. Judging from the immediate activity that was generated, industrial managers must have viewed fusion energy as a program that was going somewhere important (translation: the government was going to spend big money on it for at least a couple of decades). At any rate, several firms began organizing teams to compete for the three subcontracts for coil design and manufacture that were promised.

During 1976, five leading industrial firms organized teams having the diverse capabilities they would need to do the complete job. ORNL kept all interested parties informed as the specifications took shape. The request for proposals went out in January 1977, and within a month we received five very thorough proposals. We felt gratified by such a high-quality response, but we knew the choice of three was going to be tough.

When the proposals were received, the local evaluation board plunged into their task and, after an exhausting two weeks, emerged with a decision. The three teams chosen were: Westinghouse Electric Corporation, with superconductor manufacturer Airco; General Electric Company (GE), with Intermagnetics General to produce superconductor and Chicago Bridge and Iron Nuclear to design and fabricate the structure; and the Convair Division of General Dynamics (GD), with Intermagnetics General to produce the key element of the conductor. When the decision was announced, we received questions from many people all the way up to the Speaker of the U.S. House of Representatives. But, after all was said and done, there was no doubt that the right choices had been made.

The subcontracts between UCC-ND and each industrial team leader had three phases: conceptual design, detailed design and development, and coil manufacture. In keeping with ERDA philosophy, the capabilities and experience of the teams were fully utilized by giving them a great deal of freedom to choose the best course to produce the superconducting magnets. At the same time, the management team at ORNL had to be strongly involved. At the beginning, the team reviewed and approved concepts and transferred special knowhow on superconducting magnet technology from ORNL and other government laboratories to the industrial partners. Review and technology transfer continued through phase two, with some of the development being done at Oak Ridge, where special facilities already existed. During this phase, Keith Kibbe joined the LCP and assumed responsibility for all technical and budgeting dealings with the coil teams.

In the manufacturing phase, ORNL people kept in close touch with the shop work and especially the quality assurance programs of the subcontractors. In some instances, ORNL had to intervene and participate actively in solving problems. An outstanding example was the multifrequency eddy-current inspection of the continuous welding process in Airco's production of the conductor for Westinghouse. The instrument used for this inspection was developed by a team in ORNL's Metals and Ceramics Division and received an I•R 100 award from *Research & Development* magazine.

Throughout the course of the industrial work, ORNL, of course, had other important tasks: to monitor spending, to project funding needs, and to interact with DOE either to get the money or to decide the best way to spend the money that could be found in each fiscal year's budget. These tasks took on major proportions, especially when the efforts required to design and produce the coil turned out to be more difficult and expensive than anyone could have foreseen. In the process, several heads of hair turned grey.

In the other three LCT countries, the relationships among government and industries were different from those in the United States.

In Japan, JAERI first conducted a six-month conceptual design study in which representatives of all interested firms participated. This led to proposals from three electrical equipment manufacturers. JAERI negotiated with all three to arrive at a fair price, then awarded the LCT coil to Hitachi, while giving contracts for other work to the other two. The Japanese take schedule commitments very seriously, so when Hitachi discovered that they had more work than they had expected in the manufacturing phase, they complied with JAERI's demand for multiple winding lines and around-the-clock work to avoid schedule slippage. How much of their own money Hitachi put into the project is unclear, but one outspoken Hitachi executive indicated in a meeting in Europe that it was considerable.

In the European Community,

the Germans took the lead. The participation of the French and Italians in LCT planning diminished after Germany agreed to provide the largest share of the EURATOM funding and almost disappeared after competitive bidding throughout Europe led to contracts to Siemens for coil design and manufacture and to Vacuumschmelze for the conductor. KfK played the same role in EURATOM as ORNL did in the United States, with a somewhat more direct involvement in design decisions.

The Swiss arrangement was distinctly different. The Swiss had no big program to develop fusion power. They did, and do, have a thriving business in providing hardware for others around the world, such as copper coils for Princeton and generators for the Tennessee Valley Authority. The Swiss Institute for Nuclear Research had developed special expertise in superconducting magnet technology and Brown Boveri Company was in the business of producing, among other electrical equipment, magnets. The result was a partnership of the Swiss government and Brown Boveri to produce an LCT coil that they expected to lead to further business.

Naturally the U.S. firms were looking ahead to future business as well. Westinghouse set up to do the work in its East Pittsburgh plant, in the midst of the huge operations of producing generators for large power plants. GD/Convair established a new department for magnets and prepared to produce the conductor and assemble the LCP coil in a cavernous building at Lindbergh Field in San Diego, formerly used for aircraft manufacturing. GE, which had contracts for other superconducting magnets (for magnetohydrodynamics research, for example), set up a separate department in an unused building across the street from its bustling turbine-generator operation in Schenectady.

The atmosphere and orientation of the six industrial design and manufacturing teams clearly reflected the differences in their origins. For example, GD, with its background in aerospace vehicles, immediately plunged into sophisticated structural analysis. Westinghouse became engrossed in conductor strand insulation. Teutonic characteristics were evident in the gleaming floors and tidy equipment in the refurbished building prepared by Siemens. Japanese and Swiss coil assembly projects were set up right along side beehives of production on other big jobs. Clearly it will be very interesting to see how these different environments affect the end product, the test coil performance at Oak Ridge.

Exchanges of visits among industrial teams is a unique feature of the LCT. The quest for controlled thermonuclear fusion has, almost from its inception, involved a high degree of international cooperation. This background was reflected in the international agreement establishing the LCT. To promote the strongest, broadest base for building fusion reactors, the LCT participants agreed to arrange for each other to visit and learn about the industrial production setups of all LCT teams. So it was, for example, that Westinghouse engineers visited the shops of Siemens, Brown Boveri, and Hitachi as well as GD and GE. This kind of interaction was almost unprecedented, but industrial managers' misgivings were allayed, and eventually they came to agree that the exchanges were quite worthwhile to each of them.

Although the relationships between U.S. subcontractors and ORNL were always correct and even cordial, there were times when the road became rocky. Several times it was necessary to slow the pace to stay within fiscal year budgets. This contributed in no small measure to the prolongation of the program. However, after the beginning of the LCP, the time frame for fusion energy development as a whole, as perceived by DOE and Congress, also stretched out, and this was reflected in support for the LCP.

At no time did any technical problem loom so large that it made a coil concept appear impractical. There were, however, occasions when DOE seriously reexamined the question of whether each coil project was worthwhile. At such times, ORNL assembled all the pertinent information and arguments and worked with DOE to arrive at the conclusion that the project should continue.

One coil project did not, however, turn out at all as expected. The GE coil was removed from Schenectady unfinished and, after extensive modifications to the structure, was finally assembled in shops at the Oak Ridge Gaseous Diffusion Plant. The reasons for the decision by ORNL to truncate the GE subcontract were complex and thoroughly examined both before and after the fact. The conclusion was that grave problems in their magnet fabrication operation had indeed justified the termination.

Aerospace manufacturers are accustomed to working closely with customers who have special needs that entail new technology. Heavy electrical equipment manufacturers, on the other hand, are used to working with standard designs, which evolve gradually and require little involvement of their utility customers. The consequent attitudes tended to carry over into the LCP coil projects, especially at first. In the case of Westinghouse, events along the way eventually led to a real partnership relationship between the corporation and the government in solving various problems.

The industrial involvement did not end with the coil deliveries. During the tests now under way at Oak Ridge, people from Westinghouse and GD are analyzing data along with engineers and scientists from each of the three foreign participants.

Coil Testing

From the earliest days of the international program it was envisioned that coil completion and delivery to ORNL would be spread over a considerable time schedule. Still, no one could foresee the musical chairs that would subsequently take place. The following is a recap of the steps leading to the Partial-Array Tests, which were undertaken in the summer of 1984.

The international project officers—representatives of all the participating government organizations—decided to have a shakedown test of the complete facility at the earliest possible date—right after three coils had been installed. At the onset of the program, the first three coils to arrive close together would be those from JAERI, GE, and GD. At the April 1982 project officers' meeting, a proposal was made by Haubenreich, the U.S. representative, to reduce the shakedown test to a two-coil test (JAERI and GE) because a delay had occurred in the GD coil fabrication. The project officers unanimously agreed to the two-coil test because no one wanted to see a delay in the start of the six-coil (compact torus) test.

After another year the two-coil test was still on but the coils to be used had changed—now it would be the JAERI and GD coils! GD had accelerated its fabrication and made up some lost time; meanwhile, the domestic testing of the JAERI coil and fabrication of the GE coil had been delayed. By September 1983, the JAERI and GD coils were installed, and the test was started in November 1983. Unfortunately, leaks in the GD coil ports (openings through which a urethane potting compound was injected to fill voids between the winding and structure) necessitated removal of the coil from the tank and rewelding of the port covers and reinstallation of the coil. While all this work was going on, the Swiss coil arrived (February 1984). Although the Swiss coil was installed in the tank, there was only time to make all the cryogenic connections—the superconducting bus power lines were not installed. The Partial-Array Test got under way in June 1984, and the tests on the JAERI and GD coils were successfully carried out to the full design current of 10,000 amperes (albeit not full field, which requires contributions from the other coils) in July through September 1984.

An encouraging series of two-coil tests was also carried out. One coil was dumped, or discharged rapidly, across a room-temperature dump resistor, which removes 98% of the stored magnetic energy, while the neighboring coil was maintained energized with current at 40% of its maximum value. Would the energized coil remain in the charged state when its neighbor was dumped? Could our quench detection system distinguish an induced current (when a magnet dumps or quenches, its neighbor has currents induced in it which try to maintain the magnetic flux) from a normal zone? If the quench detection system "sees" a voltage that is high enough, would a signal be given to dump the coil to protect it and prevent it from burning up? (Remember, the superconductor can carry 10,000 amperes when it is in the superconducting state but can't support *any* current in the normal state. The copper which is bonded to the superconductor can carry the current only long enough to permit either cooldown of the superconductor and recovery of the superconducting state or dumping of the magnet.) The two-coil tests proved successful and confirmed that our quench detection system and protection system would work as desired—one coil can be rapidly discharged or dumped while its neighbor stays energized.

After the Partial-Array Tests were completed, the system was warmed up and installation began on the remaining EURATOM, GE, and Westinghouse coils. The last coil (from Westinghouse) was delivered in August 1985. After an all-out effort by a large team led by Bob Bohanan and including Y-12 Maintenance and Engineering, installation was completed and the lid was on the vacuum tank ready for pumpdown by October 24, 1985, as promised. After the expected problems of repairing minor leaks and after some major repairs of some of the cryogenic equipment of a huge complex refrigeration system, cooldown of some 400 tons was under way on January 18, 1986. By February 13 the Westinghouse coil was superconducting, and on February 18 all the remaining coils were superconducting. (The Westinghouse coil uses Nb_3Sn conductor, which has a transition temperature at about 18 K, whereas the other coils all use NbTi conductor, which has a transition temperature of about 9 K.) Cooldown and operation of the facility for coil testing are in themselves experiments, which are performed by a group headed by Bill Fietz, who provides continuous coverage. Coil testing, by a group headed by Lubell, proceeds on two shifts for about 70 hours a week.

A detailed set of test plans has been prepared and approved by the project officers. These plans have been hammered out over the last six years with proposed revisions and additions discussed at six-month intervals. Yet, we have no doubt that we will find new results, which no one can fully predict or anticipate, when we measure the stability of each magnet, the mechanical stresses of the conductor and structure, the displacement of the windings under load, the losses and heating resulting from superimposed pulsed fields simulating a tokamak's magnet environment, the changing bore dimensions under load, the acoustic emission noise generated in the windings and structure (as a result of motion, flux distribution and microscopic crack growth), and the properties at temperatures lower than 4.2 K and fields higher than 8 T. Such has been the history of the development of superconducting magnets. Each new factor-of-ten step-up in stored magnetic energy has produced some unexpected phenomena.

Because of its magnitude and international significance, the International Fusion Superconducting Magnet Test Facility is included in the itinerary of many visitors to ORNL. Some, who are unacquainted with the program, have trouble grasping the fact that the experimental operation of the coils is the whole purpose of the program. They ask, "If there is no plasma, what are you going to do with the coils?" The answer was stated nicely by the French newspaper *Le Monde,* which in 1982 called the LCT "une experience technologique á Oak Ridge"—a technological experiment. The product is information that will enable designers of future toroidal fusion reactors to select magnet designs that will optimally combine performance, reliability, and economy. The entire investment in the program is expected to be recouped in the first big reactor because design can be optimized, making the magnet system that provides the confining field much more cost-effective than one would have dared without the benefit of LCT experience.

Looking Ahead

The planned coil testing program is still in its early phases. Some big hurdles are passed—cooling down the six-coil test array to the extremely low operating temperature without springing a leak or popping off sensors, for example. Now the magnetic fields and the consequent forces on the coils are being escalated while data are taken that allow a penetrating analysis of how well each design is working. The planned program next involves operation of each coil at its design point to verify its ability to ensure performance. Ultimately experiments will be done to explore the limits of operability. It is expected that these extended-condition tests will be completed and that facility operations will be terminated by the end of FY 1987.

The question of future use of the coils is a good one. All three foreign participants have plans to repatriate their coils, for use in providing background fields for testing more advanced conductors and coils in facilities in Karlsruhe and at JAERI's superconducting magnet laboratory in Ibaraki. Similar uses have been envisioned for the three U.S. coils, which will remain at Oak Ridge. One use might be individual testing of production coils before installation in a fusion reactor plant.

Will the future of superconducting magnet applications prove to be as unpredictable as the experience of the past two decades has been? When Lubell first started research into the nature of superconductivity 24 years ago, the magnets he worked with were no larger than a man's finger. He never for a moment imagined that he would someday be testing six magnets simultaneously, each of which weighs some 45 tons and has a bore large enough to stand inside. The path to this point has not been without purpose and direction, but it has proved to be very much an adventure, not of a day's or week's duration but of more than 20 years. There is undoubtedly much more yet to unfold that no one can predict with certainty. The future of fusion magnet development depends upon, among other factors, world leaders' views of the benefits and costs of pushing ahead vigorously with the peaceful utilization of fusion energy. Whatever may come, we trust that the LCT experience and the wealth of data from it will both encourage and guide the world's fusion programs in this quest. ornl

Epilogue

Although the telling of this story leaves the authors with a sense of achievement and a feeling of optimism, we also feel a tinge of sadness. Two outstanding persons, each of whom played a prominent part in promoting and organizing his country's participation in the Large Coil Task, did not live to see the full fruition of their labors. Professor Werner Heinz, of KfK, and Professor Ko Yasukochi, of Nihon University, died within a few months of each other in 1984, each at the age of 60.

take a number

BY V. R. R. UPPULURI

Last Digits of the Fibonacci Sequence

The sequence of numbers 1, 1, 2, 3, 5, 8, 13, 21, . . . is called the Fibonacci Sequence, after Leonardo Fibonacci, the 13th-century Italian mathematician who discovered it. Inspection of this sequence reveals that its third member, 2, is equal to the sum of the previous two members, 1 and 1. The fourth member of the sequence, 3, is equal to the sum of the immediately previous two members of the sequence, 2 and 1, and so on.

The Fibonacci Sequence has many interesting properties, which are discussed in the articles that appear in the journal *The Fibonacci Quarterly* (published by the Fibonacci Association).

One of the lesser known facts about the Fibonacci Sequence is the periodic behavior of the last digits of each integer (e.g., 3 for the seventh integer of the sequence, which is 13, and 1 for the eighth integer, which is 21). The last digits of the first sixty members of the Fibonacci Sequence are

1,1,2,3,5,8,3,1,4,5
9,4,3,7,0,7,7,4,1,5
6,1,7,8,5,3,8,1,9,0
9,9,8,7,5,2,7,9,6,5
1,6,7,3,0,3,3,6,9,5
4,9,3,2,5,7,2,9,1,0

Interestingly, this cycle of 60 final digits repeats itself for succeeding sets of 60 integers in the Fibonacci Sequence. Thus, the last digits of the members of the Fibonacci Sequence has a cycle with period 60.

Three Unusual Cubes

The number 512 has an interesting property. The cube of the sum of the number's digits is equal to the number itself; thus, $512 = (5+1+2)^3 = 8^3$. Only two other numbers have this property: 4913 and 5832. Thus, $4913 = (4+9+1+3)^3 = 17^3$ and $5832 = (5+8+3+2)^3 = 18^3$.

awards and appointments

Charles D. Scott has been elected to the National Academy of Engineering. He has also been appointed a member of the advisory committee for the new Division of Fundamental Research for Emerging and Critical Engineering Systems of the National Science Foundation.

Bill Appleton has been named director of ORNL's Solid State Division.

Bill Appleton, O. E. Schow III, and **C. Woody White** have received a Material Science Award from the Department of Energy for their work in ion-beam processing. They were cited for "research with significant implications for energy technology" in DOE's 1985 Materials Science Research Competition.

Annetta Watson has been named book review editor of the journal *Environmental Management.*

Robert N. Compton has received the annual Excellence in Research Award from ORNL's Health and Safety Research Division for his studies of the spectroscopy of negative ions using novel experimental techniques.

Edward H. Krieg, Jr., was presented an Engineering Service Award by the Tennessee Society of Professional Engineers at the 1986 WATTec Engineers Week Luncheon.

Robert A. Langley is chairman-elect of the Fusion Technology Division of the American Vacuum Society.

Barbara A. Lewis has received the Margaret Oakley Dayhoff Memorial Award in Biophysics.

David K. Trubey has been appointed a member of the American National Standards Institute Committee N17, whose secretariat is the American Nuclear Society.

J. H. Whealton and **J. F. Lyon** have been named fellows of the American Physical Society.

The International Fusion Superconducting Magnet Facility at ORNL received an Outstanding Engineering Achievement Award from the Tennessee Society of Professional Engineers at 1986 WATTec Engineers Week Luncheon. The award plaque was presented to U.S. Large Coil Program Manager **Paul Haubenreich**.

Two ORNL publications received awards in the International Technical Publications Competition sponsored by the Society for Technical Communication. The winning entries and entrants are *Water Chlorination: Chemistry, Environmental Impact and Health Effects. Volume 5*, **Robert L. Jolley, Vivian A. Jacobs,** and **Raleigh H. Powell, Jr.**, award of distinction in the books category; and "Photosynthetic Water Splitting," ORNL *Review*, **Elias Greenbaum, Carolyn Krause,** and **Martha G. Stewart**, award of achievement in scholarly/professional articles.

Twenty-seven entries of ORNL and Martin Marietta Energy Systems, Inc., staff members received awards in the 1986 publications competition of the East Tennessee Chapter of the international Society for Technical Communication. The winning entries and entrants are: *Transuranium-Element Production and Research*, **O. L. Keller, Cindy Allen,** and **Bill Clark**, award of excellence in the brochures category; *Research and Development Activities in the Instrumentation and Controls Division*, **R. A. Todd, LaWanda E. Klobe,** and **Jeanne Dole**, award of merit in brochures; *The Center for Neutron Research*, **Ralph Moon, Kathie McKeehan,** and **Jack Rich**, award of achievement in brochures; *The RAMbler, Support and Assistance on Personal Computer Selection, Operation, and Applications*, **Allyn Zerby, LaWanda E. Klobe,** and **Jeanne Dole**, award of merit in newsletters; Oak Ridge National Laboratory *Review*, **Carolyn Krause, Jon Jefferson,** and **Bill Clark**, award of excellence in house organs; *Martin Marietta Energy Systems 1985 Awards*, **Raymond S. Wiltshire, Cynthia A. Chance,** and **Alice D. Richardson**, award of excellence in promotional materials; *Oak Ridge*, **Bill Clark, Steven Wyatt,** and **Linda Jeffers**, award of excellence in promotional materials; *Trends and Balances 1985–1990*, **James W. Terry, Susan E. Hughes**, and Technical Publications Department staff members, award of achievement in promotional materials; *Career Opportunities*, **Bill Clark, Steven Wyatt,** and **Jack Rich**, award of achievement in promotional materials; *Chem Tech 1984: Plans, Programs, Prospects*, **R. G. Wymer, Luci Bell,** and **Betty Jo Williams**, award of excellence in periodic activity reports; *Technologies Applications Bulletins*, **Tina Sekula,**

Linda Jeffers, and **Bob Eldridge**, award of merit in periodic activity reports; *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1984*, ORNL Fusion Energy Division staff members, **Bonnie Nestor Johnson**, and staff members of the Fusion Energy Division Publications Office, award of merit in periodic activity reports; *Environmental Sciences Division Annual Progress Report for Period Ending September 30, 1984*, **Stan I. Auerbach**, **Ann L. Ragan**, and Technical Publications Department staff members, award of achievement in periodic activity reports; *Nuclear Safety Journal*, **Ernest G. Silver**, **Sharon H. McConathy**, and Jean S. Smith, award of excellence in whole periodicals; "Disposal of Hazardous Elemental Wastes," *Environmental Science and Technology*, **Charles W. Forsberg**, **Luci Bell**, and **Donna Brooksbank**, award of excellence in scholarly/professional articles; "Photosynthetic Water Splitting," ORNL *Review*, **Elias Greenbaum**, **Carolyn Krause**, and **Martha G. Stewart**, award of excellence in scholarly/professional articles; "Techniques for Controlling Fugitive Dust from Uranium Mill Tailings," *Nuclear Safety*, Monte R. Elmore, James N. Hartley, and **Sharon H. McConathy**, award of merit in scholarly-professional articles; "Environmental and Health Impacts of Water Chlorination," ORNL *Review*, **Carolyn Krause** and **Susan Hughes**, award of merit in trade/news articles; "A Question of Impurities: ORNL Examines a Persistent Fusion Problem," ORNL *Review*, **Carolyn Krause** and **Cindy Allen**, award of merit in trade/news articles; *Water Chlorination: Chemistry, Environmental Impact and Health Effects. Volume 5*, **Robert L. Jolley**, **Vivian A. Jacobs**, and **Raleigh H. Powell, Jr.**, award of distinction in books; *Indoor Air and Human Health: Proceedings of the Seventh Life Sciences Symposium*, **Richard B. Gammage**, **Raleigh H. Powell, Jr.**, and **Vivian A. Jacobs**, award of merit in books; *Site Development Planning for Energy Management*, **Robert L. Wendt**, **Carl H. Petrich**, and **Alfred H. Voelker**, award of distinction in technical reports; *Detailed Thermal Performance Measurements and Cost Effectiveness of Earth-Sheltered Construction: A Case Study*, **Jeff Christian**, **Sharon McConathy**, and Technical Publications Department staff members, award of excellence in technical reports; *MFTF-Alpha Plus T Progress Report*, **W. Donald Nelson**, **Bonnie Nestor Johnson**, and **Jane Parrott**, award of merit in technical reports; *Air-Source Heat Pump: Field Measurement of Cycling, Frosting, and Defrosting Losses, 1981–83*, **Van D. Baxter**, **Carolyn Srite**, and **Leroy Gilliam**, award of merit in technical reports; *Comparative First- and Second-Law Analysis of an Absorption Cycle*, **H. Perez-Blanco**, **Sharon McConathy**, and **Leroy Gilliam**, award of achievement in technical reports; *International Topical Meeting on Fast Reactor Safety*, **George C. Battle, Jr.**, **Regina V. Clark**, and **Alan E. Levin**, award of achievement in technical reports; *A Precision Ion Vacuum Gage with Logarithmic Response*, **Michael G. Duncan**, **Stephen D. Parks**, and Y-12 Plant Publications Office staff members, award of achievement in technical reports.

ORNL and Energy Systems employees who received awards for industrial-technical graphics in the 1986 Art Competition sponsored by the East Tennessee Chapter of the Society for Technical Publication are **Larry H. Bohanan**, award of excellence in mechanical illustration line art for *Perspective of the Y-12 Plant Map*; **Judy C. Neeley**, award of merit in tone art (one or two colors) for *Spherical Torus Experiment (STX) with Neutral Beam Injector*; **Michael W. Darnell**, excellence in tone art (three or more colors) for *ORNL Centrifuge Pellet Injector*. Employees who won design graphics awards are **Sanda R. Schwartz** and **Cynthia H. Johnson**, award of merit in line art (one or two colors) for *Performance Planning and Review System Materials*; **Bill Clark**, illustrator, **Steven Wyatt**, coordinator, and **Jack Rich**, makeup, award of merit in tone art for the brochure *Career Opportunities*; **Bill Clark**, illustrator, and **Steven Wyatt**, coordinator, award of excellence in tone art (three or more colors) for the brochure *Oak Ridge*.

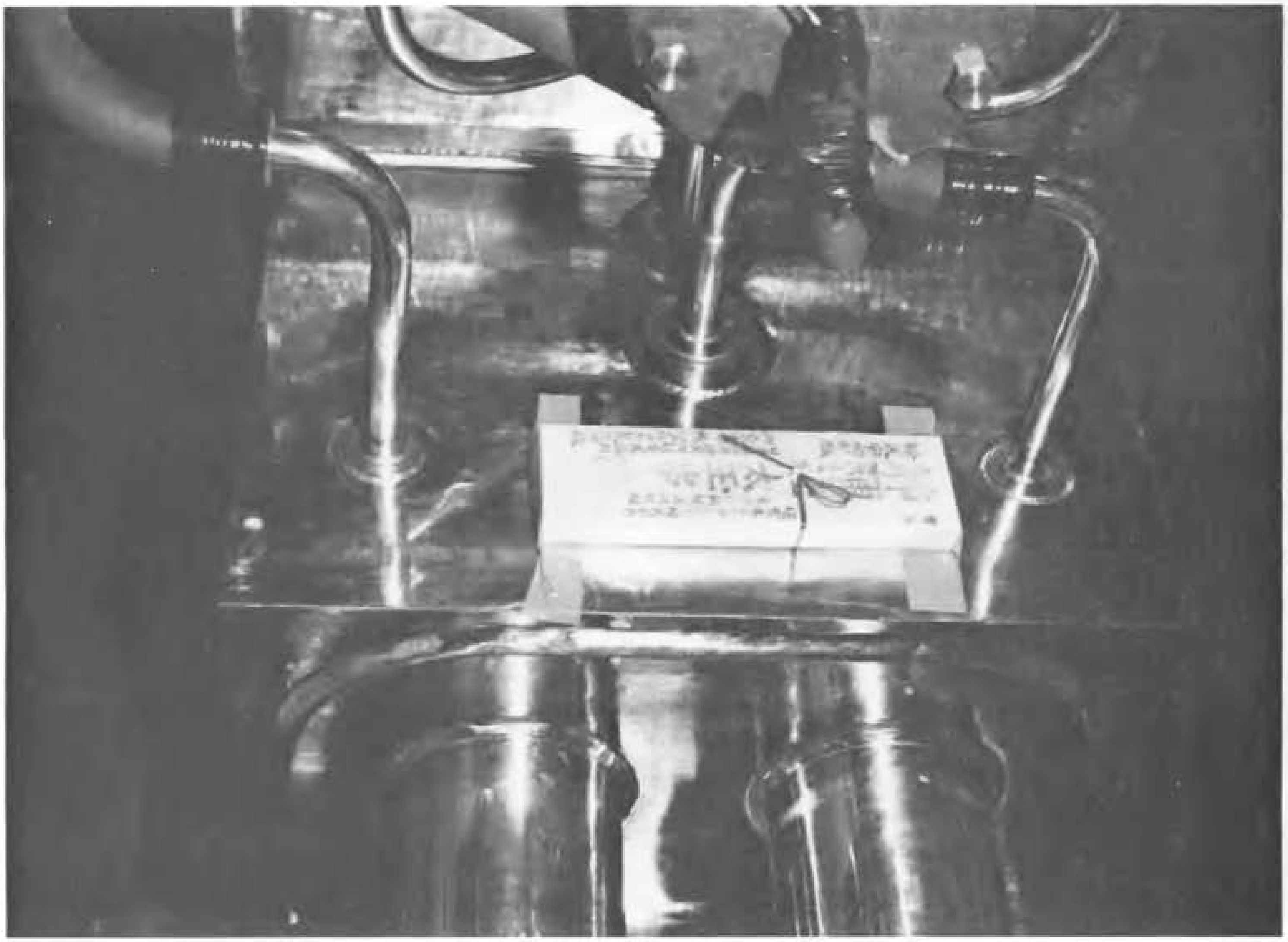
Electron micrographs taken by **P. J. Maziasz** were published on the covers of recent issues of *Journal of Metals* and the *Proceedings of a Conference on Optimizing Materials for Nuclear Applications*. The micrographs illustrate the defect structures produced in stainless steel by neutron irradiation.

Philip W. King III has been appointed coordinator of the Energy Systems Honors and Awards Program.

Claud Pugh has been named head of the Pressure Vessel Technology Section of ORNL's Engineering Technology Division. He replaces **Grady Whitman**, who has retired. Pugh is also manager of the division's Heavy Section Steel Technology Program.

Carolyn T. Hunsaker has been appointed to the advisory board of *The Environmental Professional*, the journal of the National Association of Environmental Professionals.

OAK RIDGE NATIONAL LABORATORY *REVIEW*
P.O. Box X, Oak Ridge, Tennessee 37831



To ensure its safe transport from Japan to Oak Ridge, the Japanese fastened to the side of its superconducting magnet a "good luck charm" that had been blessed at a Buddhist temple. For the inside story on the magnetic coils being tested at an international facility in ORNL's Fusion Energy Division, see the article on page 30.