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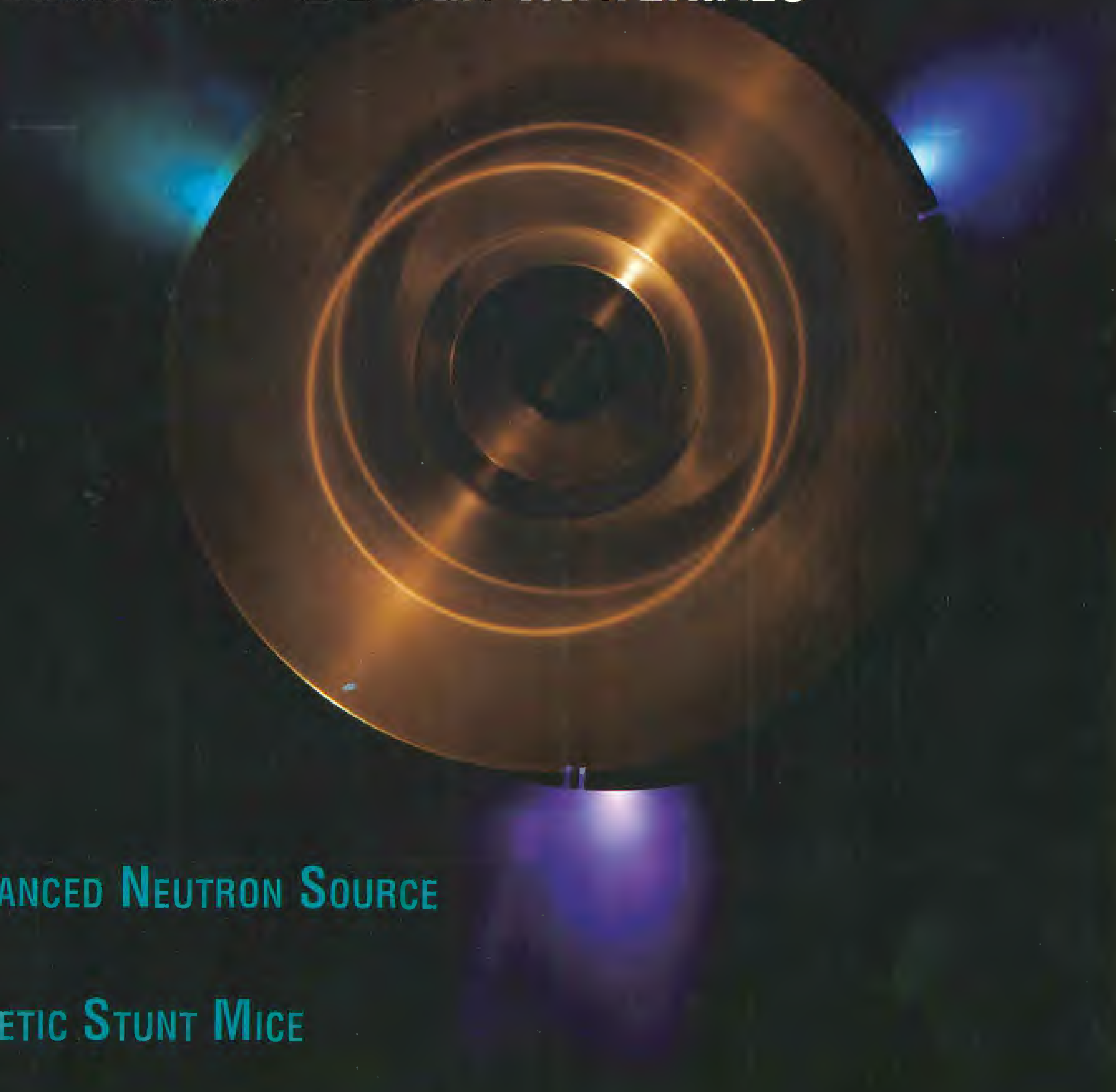
BEAMING UP BETTER MATERIALS



ADVANCED NEUTRON SOURCE

GENETIC STUNT MICE

ON THE COVER

View of a laser ablation system developed by ORNL's Douglas Mashburn. The multiple exposure photograph shows the color and intensity of plumes of light produced by a laser beam striking and "boiling" off atoms of different materials on a rotating target drum. The plume colors—green, purple, and blue-white—are characteristic of three target materials used for the photograph—copper, zinc, and a mixture of aluminum, copper, and zinc, respectively. To learn about Mashburn's laser machine, see the article on p. 40. *Photograph by Bill Norris.*

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REVIEW

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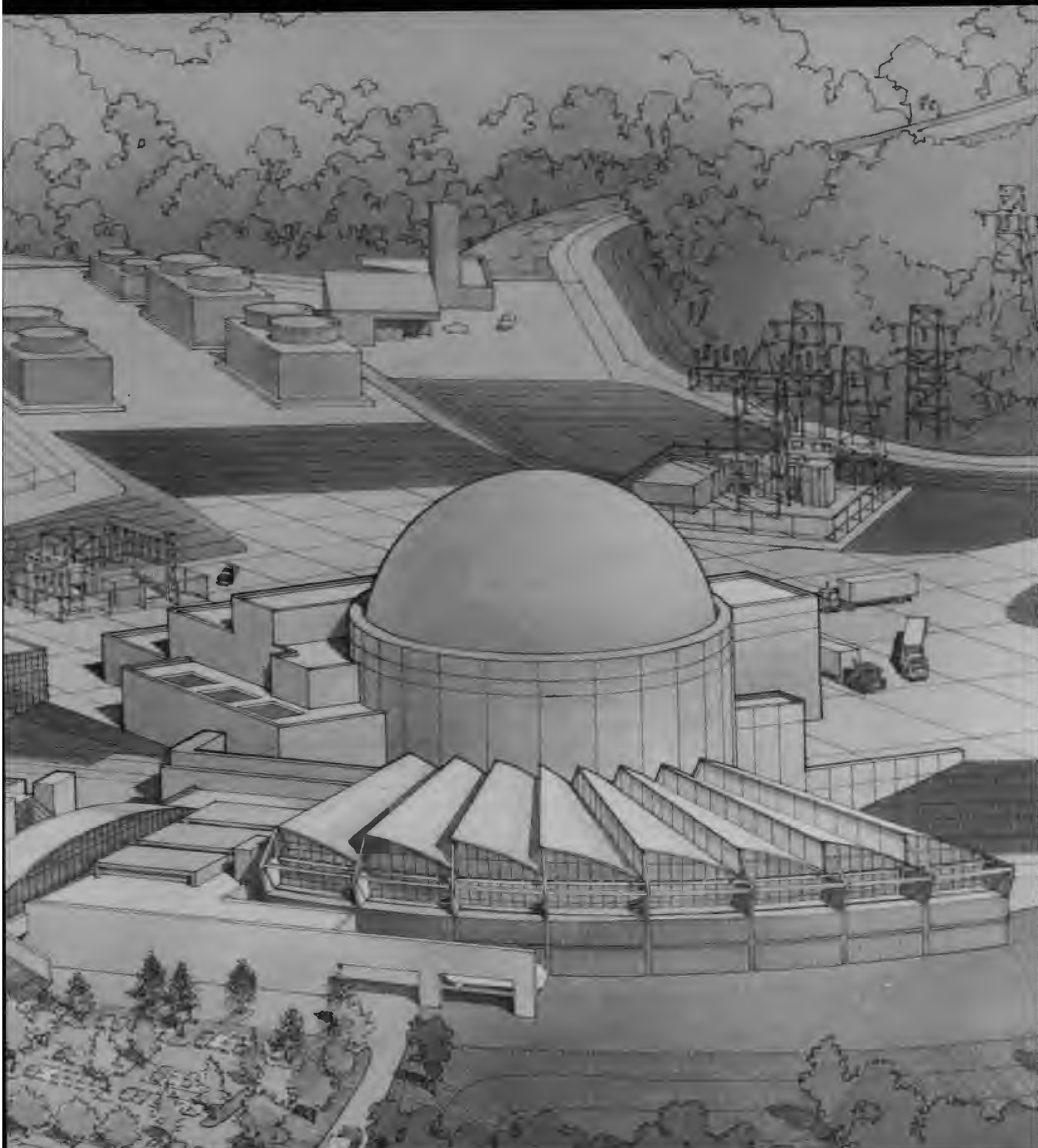
FEATURES

DEPARTMENTS

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

Research Reactor of the Future: The Advanced Neutron Source

By Bill Appleton and Colin West



Agents for cancer detection and treatment, stronger materials, better electronic gadgets, and other consumer and industrial products—these are assured benefits of a research reactor project proposed for Oak Ridge. Just as American companies have again assumed world leadership in producing semiconductor chips as well as cars and trucks, the United States is poised to retake the lead in neutron science by building and operating the $2.9 billion Advanced Neutron Source (ANS) research reactor by the start of the next century.

In the 1950s and early 1960s, the United States had the lead in neutron research. One reason was the work of pioneers like Ernie Wollan and Cliff Shull (winner of the 1994 Nobel Prize for physics). They performed some of the first neutron scattering studies in the late 1940s and early 1950s at Oak Ridge National Laboratory's (ORNL's) Graphite Reactor, the World War II pilot plant for the plutonium production reactors at Hanford, Washington. Another reason was the U.S. Atomic Energy Commission's (AEC's) support for construction of the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL) in 1965 and the High Flux Isotope Reactor (HFIR) at ORNL in 1966. A third reason was the variety of strong neutron science programs that were developed using these research reactors.

In 1969, the U.S. Department of Commerce's National Bureau of Standards built a research reactor specifically for neutron scattering experiments in Gaithersburg, Maryland. By the end of the 1960s, it had become apparent that a key to industrial leadership was the ability to produce neutrons for research aimed at development of new, improved commercial products and processes.

In 1971, Europe's new research reactor facility—the Institut Laue-Langevin (ILL) at Grenoble, France—began operation. Because it was a more powerful source of neutrons for research (including highly useful low-energy neutrons) and had more sophisticated instruments than the American reactors, researchers from all over the world were drawn to Grenoble to conduct neutron studies. In the 1980s, other neutron sources were built in Europe and Japan, and neutron research at these facilities also surpassed that at U.S. reactors. Furthermore, many American neutron scientists went abroad to conduct their research.

Although not obvious to many people, the fruits of neutron research include improvements in the range and quality of products used in our everyday lives. Examples are automobiles, jets, credit cards, pocket calculators, compact discs and magnetic

The United States is poised to retake the lead in neutron science by building and operating the $2.9 billion Advanced Neutron Source research reactor.

Bill Appleton (right) and Colin West discuss a strategy for gaining additional support for the Advanced Neutron Source, a unique reactor-based research laboratory that may be built by 2003 in Oak Ridge.

Depiction of the proposed Advanced Neutron Source complex at ORNL.

The fruits of neutron research include improvements in the range and quality of products used in our everyday lives.

recording tapes, computer disks, agricultural pesticides, geological maps of oil deposits, and satellite weather information for forecasts. (For a more detailed explanation of applications, see the article "Fruits of Neutron Research" on p. 19.)

In the past 20 years, neutron research brought about a revolution in plastics, once fragile materials that engineers considered useless except for toys. New high-tech plastics are lighter and stronger than steel. Examples of uses for these plastics are bulletproof Kevlar™-armored vests that have saved the lives of police officers and small bags that contain prepackaged foods or snacks (these extremely thin bags are now so strong they can be opened only by tearing at the precut notch).

For millions of people, neutrons provide a lifeline in the form of specialty radioisotopes produced by the HFIR and other sources; in the United States, radioisotopes are used in 36,000 medical procedures conducted each day and 50,000 treatment programs and almost 100 million laboratory tests conducted each year.

Neutrons are also an essential tool for researchers studying ways of improving materials that may have practical uses such as high-temperature superconductors and powerful lightweight magnets.

In 1985, the neutron community, led by ORNL researchers, proposed a pioneering project, later called the ANS. Scheduled to begin operation in 2003, the ANS is seen not only as a replacement for the aging HFIR and HFBR but also as the best laboratory in the world for conducting neutron-based research.

Why the Nation Needs the ANS

Since 1970, Western Europe has spent five times as much as the United States on new

Current Status of the ANS

The ANS was included in the 1994 and 1995 president's budgets as an enhanced infrastructure initiative and as a construction line item. However, in 1994 in the wake of the Superconducting Super Collider cancellation, the U.S. Congress appropriated $17 million of a requested $39 million for the research reactor project, specifying that this money be used to continue research and development and preliminary design. The line item was delayed to allow DOE time to perform a technical evaluation of the impact on ANS performance of using low-enriched fuel. This study is now complete; a draft report has been submitted to DOE.

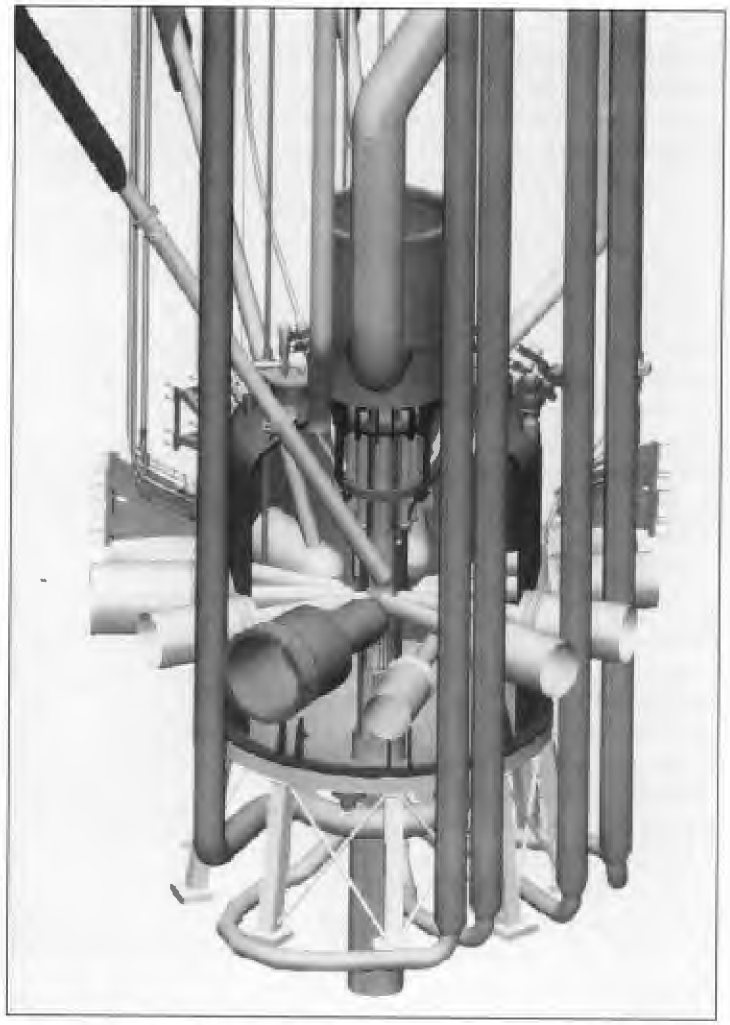
On December 3, 1993, for the second consecutive year, the Clinton administration again supported a line item for the ANS in the fiscal year 1995 budget for $40 million. In early June 1994 the U.S. House of Representatives approved $10 million in operating funds and $1 million in capital money to start construction on the ANS. However, on June 23, 1994, the U.S. Senate Energy and Water Development Appropriations Committee voted to continue ANS development by allocating all $21 million to operating money but deferred construction funding again. The committee's energy subcommittee stated in its report, "The project does not appear to be mature enough at this time to begin construction." It added that the project needs "a firm and mature conceptual design," a "streamlined management chain," and a final environmental impact statement. The differences between the House and Senate on whether to start construction were referred to a conference committee for resolution.

On August 11, 1994, the conference committee provided $21 million for design but no construction line item. However, the committee did provide language with the bill that allows ANS to engage industry in the design process, a necessary step toward actual construction.

neutron sources and instruments. The ILL, the world's best source for neutron scattering research, is being refurbished to make it last another 20 years. Germany has just improved its research reactors in Berlin and Geesthacht and is designing a new research reactor in Munich. Switzerland is constructing a steady-state spallation neutron source roughly equivalent to a medium-flux reactor.

In Asia, while South Korea is completing construction of a new research reactor, Japan has strengthened its position by building the new JRR-3M research reactor, Indonesia has brought a new reactor on line, and Thailand is planning a new one for completion in 1999. Interestingly, Japan's investment of $300 million exceeds all U.S. investments in research reactors in the past 20 years.

No world-class research reactor has been built in the United States since the 1960s. The HFIR and HFBR are approaching the end of their useful lives. In the western hemisphere, the HFIR is the only source of californium, a radioisotope critical to treatment of certain cancers, and other isotopes used for medicine and industry. Without a new world-class research reactor, the United States will no longer be competitive in neutron scattering research and radioisotope production and will have to turn to sources abroad.



Close-up of the ANS reactor assembly showing the core, control rods, neutron beam lines, source of cold, or low-energy, neutrons (tube at back left), and source of hot neutrons (large dark tube at front left). *Drawing by Barbara Smith.*

The ANS will reaffirm America's position as an industrial leader.

To make the United States more competitive in a scientific field that has such important applications, leaders in science and industry recognized the need for a new world-class research reactor 10 years ago. In 1984, a National Research Council committee ranked a new reactor-based neutron facility as one of the nation's top two needs in materials science and related disciplines. In December 1985, some 40 scientists and engineers, including ORNL researchers, met at Gaithersburg, Maryland, and the basic concept of the ANS emerged as the preferred neutron source for meeting the needs of the U.S. scientific community.

In 1989, Paul Fleury, director of physical research at AT&T Bell Laboratories, told a Department of Energy (DOE) panel, "We simply

The ANS will be far superior to even the best neutron facilities in Europe.

are not competitive with the rest of the world at this point." He called construction of the ANS "absolutely necessary." He added, "It is a sad fact that. . . over the last couple of years, I have spent more of my neutron-related research money on airplane tickets for our scientists to go to Europe than on direct support of collaborative work at U.S. facilities."

In a January 1993 report, *Neutron Sources for America's Future*, the Basic Energy Sciences Advisory Committee of DOE's Office of Energy Research deemed construction of the ANS as an "overriding priority" to prevent a serious decline in the U.S. neutron research community in the next decade. In early 1993, President Clinton urged Congress to build the ANS in his report *A Vision of Change for America.*

The ANS Project is incorporating European improvements so that the ANS will be the world's best neutron facility for fundamental science, for engineering, for isotope production, and for materials irradiation and testing. Such a remarkable facility will be made available to a broad spectrum of scientists and students.

The ANS will ensure America's future in neutron-based studies and will reaffirm its position as an industrial leader through the many products that will result. The list of businesses and organizations that already depend on neutron research to develop better products and services contains household names such as IBM and Xerox, Goodyear and Firestone, Ford and General Motors, General Electric and AT&T, Exxon, Amoco, and even the American Dental Association. The Smithsonian Institution, a popular tourist attraction in Washington, has used neutrons to assess paintings and ancient bronze sculptures. These and other organizations have been sending their researchers to the best neutron facilities, especially those in Europe, to conduct their studies.

However, the ANS will be far superior to even the best neutron facilities in Europe, allowing the United States to recapture the lead in neutron production and research. Once operational, it will have 5 to 10 times the useful neutron flux—the number of neutrons that strike a given area each second—of any existing research reactor. Such a position would not be new to ORNL if the ANS is located here: the Oak Ridge Research Reactor (ORR) and HFIR were, in turn, world leaders in neutron flux when they were new. Through improved design and instrumentation, the ANS will offer up to 10,000 times more usable neutrons for some experiments than the HFIR and HFBR. Hence, the path for neutron research will lead back to the United States.

The ANS will offer the nation several benefits. It will be the foremost center in the world for neutron science. It will have a record number of neutron beam lines and world-class, state-of-the-art instruments. It will have a user-friendly design for scientists all over the United States—that is, it will be designed from the beginning with user access in mind. It will be a national testing center for new materials, it will facilitate engineering development, and it will produce new radioisotopes that may be approved for medical use when the ANS begins operation.

The ANS also will offer regional benefits. It is estimated that every year about 1000 university, laboratory, and industrial researchers from around the world will come to Oak Ridge to use the ANS, which is designed to be a DOE user center. Most of these visitors will stay a few days to several weeks to conduct their experiments. In addition to making valuable research contributions, the visitors will help bolster the area's economy and will contribute to regional colleges and universities through lectures, seminars, and research collaborations.

In addition, the ANS will be a magnet for industrial firms in need of neutron research for product development. Just as Coors Ceramics Company located in Oak Ridge to take advantage of the research capabilities of ORNL's High Temperature Materials Laboratory, other businesses and industrial firms are likely to settle in the region because of the unique research offerings of the ANS.

Origin of the ANS Design

The basic ANS design emerged as the best choice from a number of technical alternatives at the 1985 workshop in Gaithersburg, Maryland.

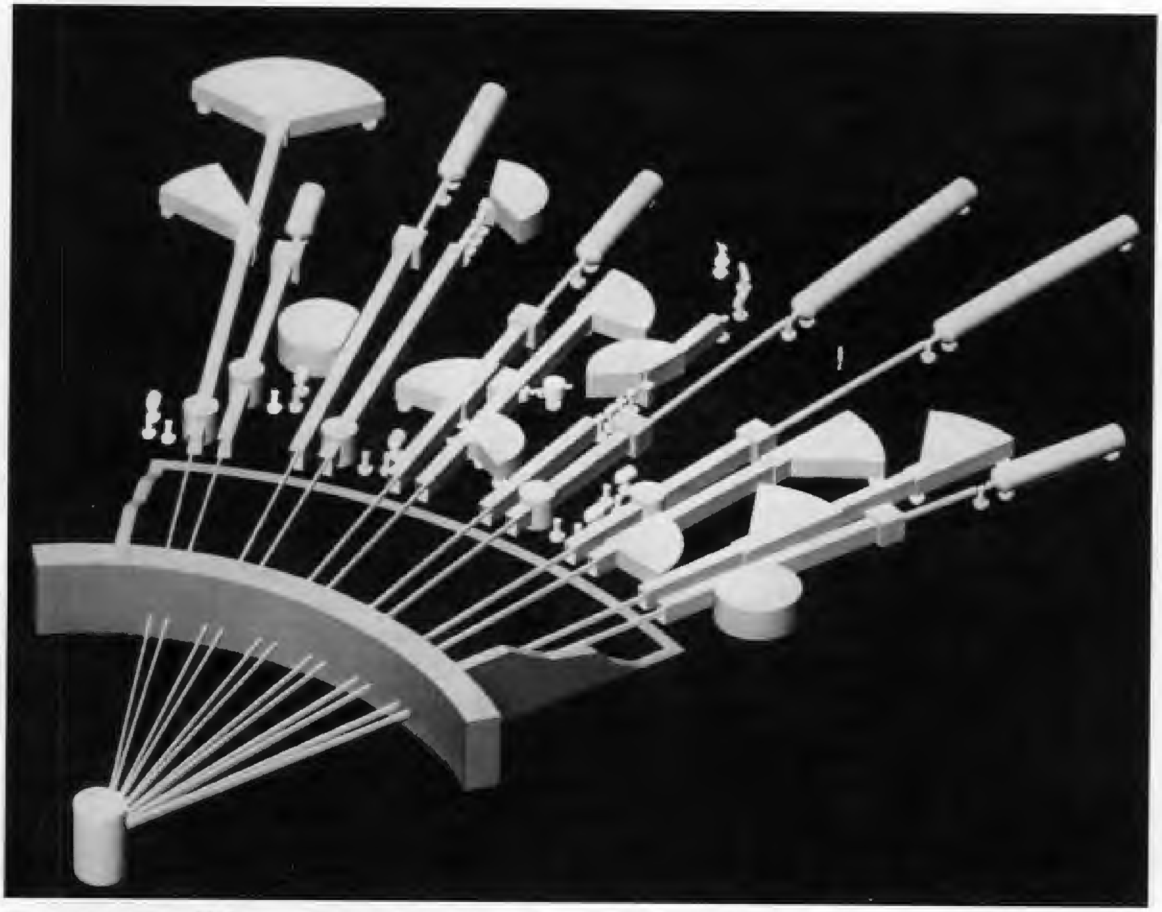


Illustration of the ANS neutron beam lines extending from the reactor core to the neutron scattering experimenters' stations. *Drawing by Paul J. Fogarty.*

(For the history behind this concept, see the article "A History of the ANS: Going Back to the Source" on p. 16.) Scientists and reactor engineers from around the world participated in a critique and evaluation of source concepts to determine the one that would best meet the scientific requirements. Because the ANS would use existing research reactor technology and because its technical risk and overall cost were considered relatively low, the Gaithersburg conferees recommended its further development.

The ANS design proposal was based on a concept initially proposed by Dick Cheverton of ORNL's Engineering Technology Division (ETD) and strongly endorsed by Ralph Moon of the Solid State Division. It was dubbed the HFIR-II at first and then was called the Center for Neutron Research (CNR). The ORNL researchers had proposed a heavy-water–moderated reactor because they considered it the best choice for high thermal flux, minimum technical risk, and reliability of operation. They proposed using heavy, or deuterated, water to cool the nuclear fuel core; to slow down, or moderate, neutrons to make them useful for research and isotope production; and to reflect them back into the core to promote additional neutron-producing fission reactions. By contrast, the HFIR uses ordinary water as the moderator and coolant and beryllium as the neutron reflector.

Colin West of ETD proposed that the ANS use uranium silicide (U_3Si_2) as its fuel rather than uranium oxide employed in the HFIR. The uranium would be enriched, as it is in all high-

ORNL has the longest tradition in the world for neutron scattering experi-mentation at nuclear reactors.

performance research reactors, to 93% of the fissionable uranium-235 isotope. Researchers at Argonne National Laboratory, who had been trying to develop nuclear fuel for research reactors that contained a lower percentage (enrichment) of fissionable uranium because of nuclear proliferation concerns, had discovered in the 1980s that U_3Si_2 is a good choice for a fuel that contains a lot of uranium. The reason: The molecular structure packs the uranium atoms more closely together, enhancing neutron production.

DOE has asked Brookhaven National Laboratory to assemble a group of experts to assess the impact on ANS performance of using U_3Si_2 fuel enriched in lower amounts of uranium-235 to address proliferation concerns.

As with the HFIR and other research reactors, the ANS fuel will be clad with an aluminum alloy that is an excellent heat conductor, thus minimizing the temperatures within the nuclear fuel. Zirconium, which is used in Zircaloy cladding for nuclear power plants, is not as good a cladding as aluminum for research reactors that generate heat because zirconium doesn't conduct heat away from the fuel as well.

The maximum neutron flux of the ANS will be $7.5 \times 10^{19}\ m^{-2} \cdot s^{-1}$, or about 100 billion billion neutrons per square meter each second. This flux will be 5 to 10 times that of the ILL.

Features of the ANS will include 30 neutron beam lines, 48 neutron scattering stations, 50 irradiation facilities for isotope production and materials testing, 10 materials analysis facilities, a gamma irradiation facility, and a positron production facility. A Joint Institute for Neutron Studies building (in association with the University of Tennessee) will provide classroom space, small conference rooms, and some on-site accommodations.

Scope of the ANS Project

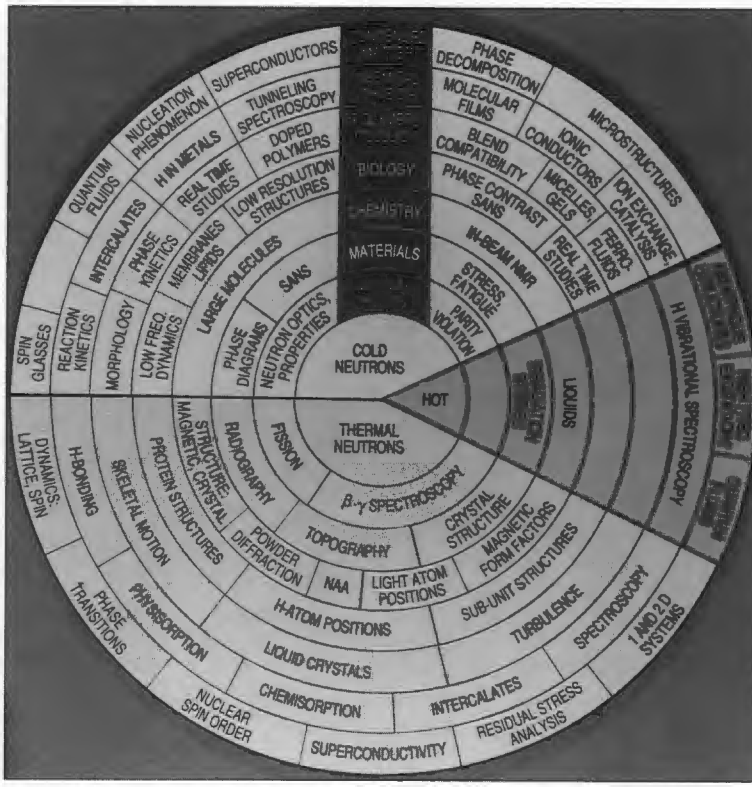
On July 1, 1985, Colin West of ORNL's Engineering Technology Division was named director of the new CNR Project, which continued the initial design of a new research reactor urged by Ralph Moon and led by Dave Bartine. The CNR Project, like the ORNL reactor design study initiated in 1984, was supported by the Laboratory Director's Research and Development Fund.

When Congress passed an appropriations bill providing DOE funds for the first time for an "advanced neutron source," ORNL began to have a larger source of financial support for its CNR Project. Because of the bill's language, the CNR name was changed to the Advanced Neutron Source Project.

Since 1985, much progress has been made. The ANS Project management team has been working closely with the National Steering Committee for the Advanced Neutron Source to ensure that the facility meets the requirements of the scientific community. In addition, more than 3000 applicable federal, state, and local environmental, safety, and health regulations have been identified and have been, or will be, addressed. In 1991, Gilbert/Commonwealth, Inc., was selected as the architect-engineer for conceptual design of the ANS, working with ORNL researchers and other members of the team. Using a concept developed by architect Hanna Shapira of the ANS Project, the team came up with a user-friendly facility design. In June 1992, the ANS team completed a fully documented conceptual design for development of a cost estimate and schedule for detailed design and construction; the conceptual design report contains 12,000 pages. Based on the design, which has been approved by DOE, an environmental report was prepared, indicating some of the potential impacts of the project. That report was aimed primarily at the Oak Ridge Reservation—DOE's preferred site for the ANS, subject to evaluation of the environmental effects. Some of the information will also be useful in preparing the environmental assessment, which will include sites at Los Alamos National Laboratory (LANL) and Idaho National Engineering Laboratory, as well as Oak Ridge.

The environmental assessment will be prepared on the ANS by an independent group contracted by DOE. This group will examine the environmental and socioeconomic impacts of the proposed research reactor on all three candidate sites, with particular emphasis on the acceptability of the preferred Oak Ridge site.

During the past few years, West has been reporting to Bill Appleton, formerly associate director for Physical Sciences and Advanced Materials. In October 1992, Appleton headed an ANS task force responsible for getting the ANS initiated as a construction project, and in 1994 he assumed the new position of associate director for the Advanced Neutron Source.



"Mayan calendar" of neutron research applications using hot, thermal, and cold neutrons. *Designed by John Hayter and Ralph Moon.*

The ANS will be used primarily for neutron scattering experiments.

Neutron Scattering

ORNL has the longest tradition in the world for neutron scattering experimentation at nuclear reactors. ORNL researchers have been conducting neutron scattering experiments since 1945 with the Graphite Reactor, ORR, and HFIR. Neutron scattering experimentation has progressed over the years partly because of advances at ORNL. For example, in 1970, Manfred Kopp and Cas Borkowski, both of ORNL's Instrumentation and Controls Division, pioneered development of a new type of gas-filled position-sensitive detector. Their detectors were used at the ORR and later at the HFIR. Kopp also developed the electronic circuitry to enable the detector to count and map the positions of neutrons or X rays scattered from the nuclei of target materials. The resulting pattern of dots of varying intensities now helps scientists determine the structure of metals, plastics, superconducting ceramics, biological tissues, and other materials. Such position-sensitive detectors will be used for neutron scattering experiments at the ANS.

In 1979, Wally Koehler of ORNL's Solid State Division obtained funding from the National Science Foundation to build a small-angle neutron scattering (SANS) instrument at the HFIR. The instrument was designed by William Taylor Clay and built by Charlie Fowler, both then of ORNL's Instrumentation and Controls Division. The instrument, combined with a small-angle X-ray scattering instrument designed by ORNL's Bob Hendricks, became part of the National Center for Small Angle Scattering Research at the Laboratory. Because industry is the nation's largest single taxpayer, Koehler invited representatives from American industry to make use of the center. Thus, the center became ORNL's first user facility, starting a tradition of government-industry partnerships that will continue to flourish with the operation of the ANS.

The ANS will be used primarily for neutron scattering experiments. Neutron scattering is used by a variety of scientific disciplines to study the

The ANS will have the most advanced source of cold neutrons in the world.

arrangement, the motion, and the interaction of atoms in materials. Neutrons for scattering experiments will come from the heart of the ANS facility, which will be the world's most capable research reactor. The heart of the ANS is the reactor core, which is about the size of a 57-liter (15-gallon) can and which produces neutrons by fission of uranium atoms. Neutron beam tubes and guides, which serve as pipelines, will carry some of the neutrons from the reactor to adjacent instruments, where samples of material will be placed directly in the path of the neutron beam.

Neutrons are well suited for unlocking the secrets of materials made of light elements and of complex molecular structures. These materials include living matter and synthetics that are composed of the light elements carbon, hydrogen, and oxygen. Neutrons, particles in the atomic nucleus that lack an electrical charge, are strongly diffracted, or scattered, by light atoms in a sample. Because they are uncharged, neutrons penetrate to much greater depths than other radiation such as X rays and charged particles that interact with electron clouds in atoms of solids. On the other hand, X rays—the type of radiation commonly used in dentists' offices and emergency rooms—tend to shoot past light atoms, although they are more strongly deflected by the electron clouds around the nuclei of heavier atoms. So neutrons are a preferred probe for many materials, including DNA and synthetic molecules such as polymers.

As neutrons travel through the sample, some will ricochet at an angle off atomic nuclei. By measuring the relative fractions of the neutrons scattered at different angles from a sample, scientists can decipher even subtle details of the material's atomic structure. It is possible to deduce, for instance, the kind of atom doing the scattering, its energy of vibration, and its position and motion in relationship to other atoms in the material. This knowledge is the key to improving the material, making it stronger, lighter, more wear resistant, or more flexible, to meet specific needs.

Neutrons are also valuable because they behave as tiny magnets. Thus, they can reveal details about the magnetic properties of certain materials that cannot be obtained any other way. Such information can help determine if a material can be used for magnetic storage or superconductivity. Virtually everything we know about the behavior of magnetic materials has involved neutron scattering, and much of this information has come from studies at the HFIR.

Types of Neutron Beams

Not all neutrons scatter in the same way, and some have too much energy and move too fast to be useful for scattering. By decreasing the temperature of the moderating environment, neutrons can be slowed down enough to be useful for scattering experiments. The ANS will produce all types of neutrons: fast, thermal, and cold.

Fast neutrons are the high-energy products of fissioning uranium atoms in the reactor core. By placing a sample of material very close to the core, where fast neutrons are most plentiful, scientists can study the effects of intense radiation on different materials. Thus, they can simulate in a few days or weeks the type of radiation damage that might be expected by long-term exposure of these materials to intense neutron radiation from fission and fusion reactions. Results from such studies help engineers select the best structural materials for fission and fusion devices being designed as future sources of electricity.

As fast neutrons leave the reactor core and pass through the surrounding heavy water, they lose energy through collisions with water molecules. As they slow down, they become thermal neutrons as their average energies reach the temperature of the water. Thermal neutrons can be used for scattering without altering the atomic structure of the target material. They are valuable also for neutron radiography for viewing the interiors of metallic components, such as aircraft wings, to identify signs of corrosion or hairline cracks. Unless these problems are detected and corrected early, they could lead to catastrophic failure under operational stress.

Very slow, or "cold," neutrons are desirable because they are even more sensitive probes than thermal neutrons for certain applications. For this reason, American neutron scientists have indicated that their greatest need is an intense source of cold neutrons, and the ANS will have the most advanced source of cold neutrons in the world.

Cold neutrons are produced by passing thermal neutrons through a region of the reactor containing a very low–temperature material, such as liquid deuterium (heavy hydrogen). In this process, the energy and velocity of the incoming neutrons are greatly reduced. Over the past 20 years, cold neutrons have been the key to new discoveries and developments in plastics, alloys, and biochemical systems made of living cells and membranes.

Cold neutrons are particularly useful for determining the structure of materials made from large molecules called polymers, long chains of smaller molecules. Such materials, including plastics, synthetic fibers, and wood, greatly influence our daily lives. Scattering techniques using cold neutrons even aid biologists in studying the building blocks of life. For example, DNA, which contains life's genetic code, is itself a polymer.

Research and Production at the ANS Facility

The ANS will be used for these major research and production areas:

• **Materials irradiation**, a technique which will be used to design and test the best candidate materials for use in fission or fusion reactors. These reactors may be a significant energy source in the future. Such tests also help determine the best materials for maintaining today's power reactors.

• **Neutron radiography**, which is similar in principle to X-ray analysis. Neutron radiography uses the penetrating power of neutron beams to examine the interior structures of materials in much the same way that X rays reveal the structures of human bones and organs. However, because neutrons are uncharged particles, they can penetrate to much greater depths in materials than X rays. Neutron radiography can be employed, for instance, to inspect the microstructure of steel girders used in the construction industry, to detect hairline cracks or early signs of corrosion in the wings of an airplane, or to analyze the flow of oil in an operating engine. The ANS can also be used to produce the isotope californium-252 for portable sources of neutrons for performing on-site radiography.

How do neutrons detect early signs of internal corrosion in aluminum and other metals? Corrosion is caused by the presence of water, and since water is made of the light elements of hydrogen and oxygen, it is detectable by neutron radiography. This is the only method that can detect the extremely small pockets of corrosion that may arise within airplane wings or other machine parts after manufacture.

• **Neutron activation analysis**, which is proving essential to environmental studies. Activation analysis can be used to determine the presence and the amount of targeted substances in soil samples. Neutron activation analysis has been used at the HFIR to detect mercury and other metallic pollutants in 100,000 soil samples. The method developed at ORNL has been refined into a technique that saved almost $3 million in analyzing 4000 samples of mercury-contaminated soil in the East Fork Poplar Creek floodplain in Oak Ridge.

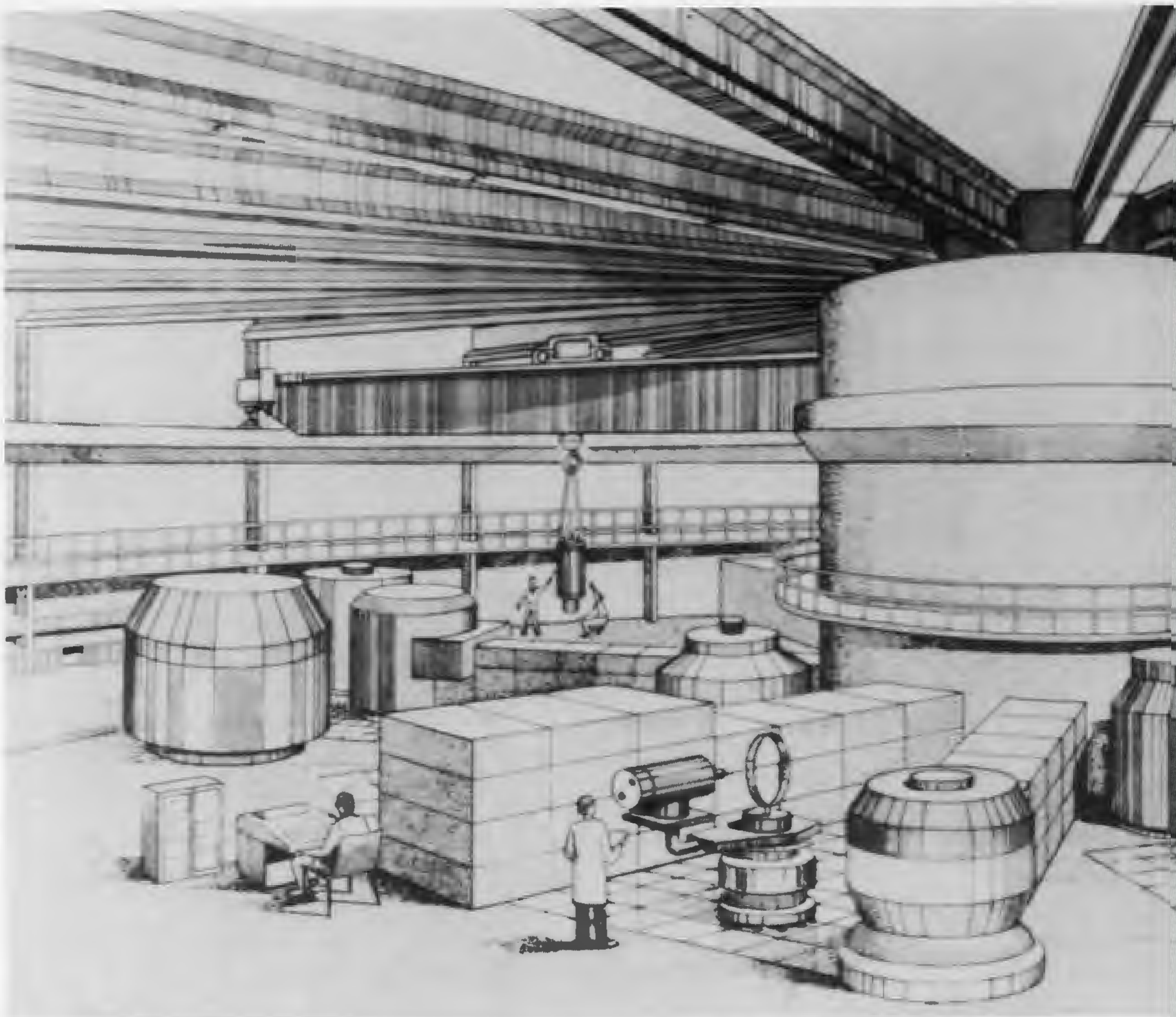
To measure mercury concentrations in soil samples by neutron activation analysis, the soil samples are irradiated with neutrons. By absorbing neutrons from the reactor, the soil mercury is transformed into the unstable isotope mercury-203, which emits gamma rays as it decays. The gamma-ray energies measured by a high-resolution gamma spectrometer indicate the presence and concentration of mercury in the sample.

At ORNL, neutron activation analysis was used in late 1963 to study fragments of the bullets that killed President John F. Kennedy. In 1991, analysis was performed at the HFIR on hair and fingernail samples from the body of President Zachary Taylor. It was determined that he did not die from arsenic poisoning as had been suggested by a historian.

In addition to being used for in-reactor neutron activation analysis, the ANS will produce californium-252 for portable sources of neutrons for on-site activation analysis to detect and

Many radioisotopes produced in the ANS in the first decade of the 21st century may be approved by the FDA to treat a wide range of cancers.

Radioisotopes from the HFIR and later the ANS also will help extend our knowledge of our domestic energy sources.



Artist's depiction of the beam room for neutron scattering experiments in the ANS facility.

measure hazardous contaminants in support of environmental remediation programs.

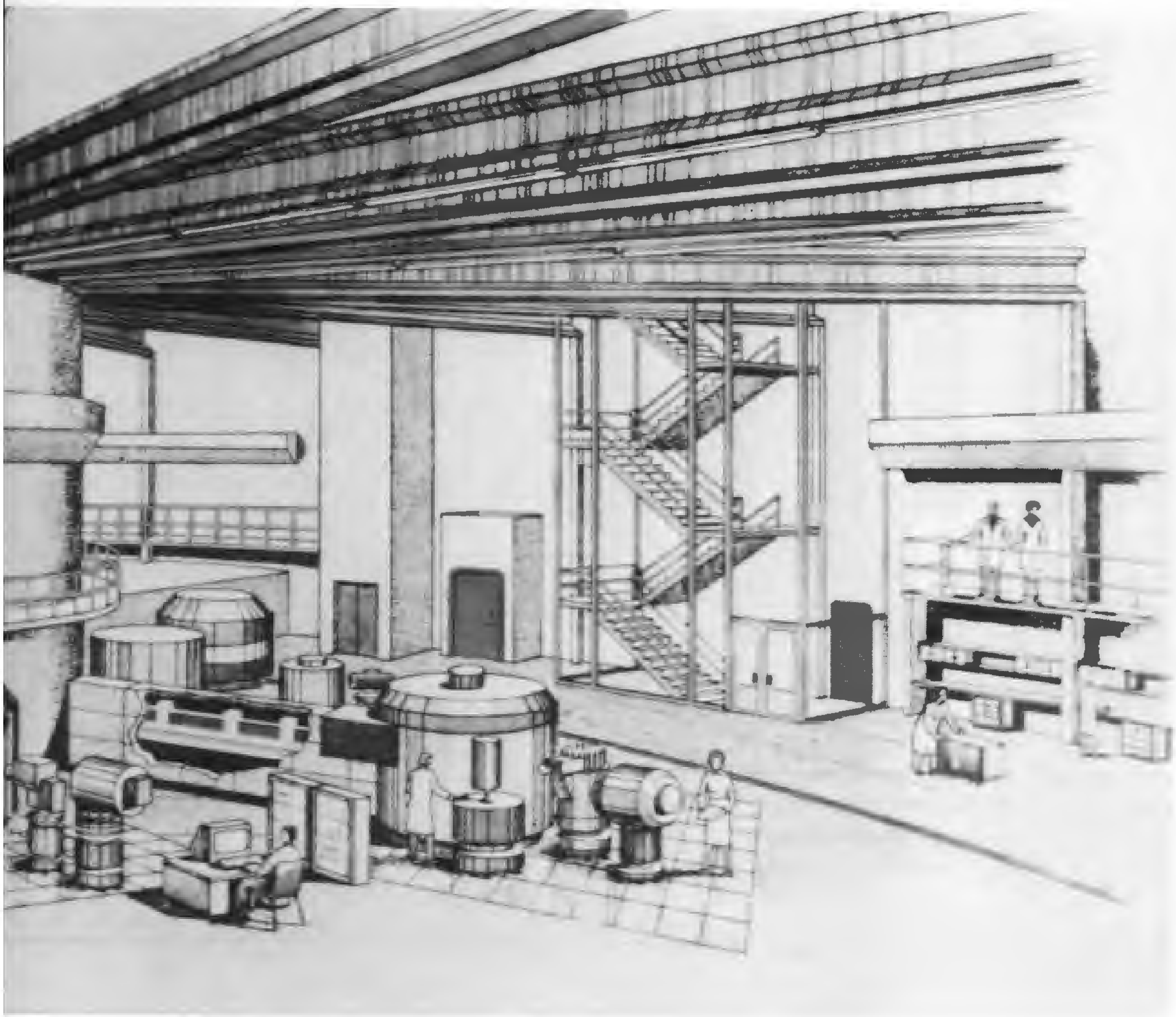
• **Isotope production**, for making radioisotopes that are used for medical, military, industrial, and scientific purposes. Many radioisotopes produced in the ANS in the first decade of the 21st century may be approved by the Food and Drug Administration (FDA) to treat a wide range of cancers, including cancer of the prostate, breast, and cervix. Two studies report that the anticipated growth of FDA-approved commercial radio-pharmaceuticals will be in the areas of therapeutical agents for cancer. Because most therapeutic radioisotopes are reactor-produced, the projected growth suggests that the ANS will play a vital role in developing new radioisotopes for cancer treatment.

An important contribution of the ANS to the medical community will be production of already approved medical radioisotopes such as californium-252, which is used to treat cancer. In the entire western world today, the only significant source for californium-252 is the HFIR.

Californium-252 is in demand because its half-life of 2.6 years gives it a useful service life and because it provides a high amount of radioactivity for a small amount of mass—2.3×10^9, or about two billion, neutrons per second per milligram. Discovered by Nobel Laureate Glenn Seaborg in 1950, this element is produced at the HFIR by neutron irradiation of curium targets.

Medical facilities in the United States, Russia, and Japan use californium-252 to treat a variety of cancers, including those in the brain and cervix. It is particularly useful against large tumors that cannot be successfully treated with other types of radiation therapy.

At the University of Kentucky Medical Center, oncologist Yosh Maruyama has reported that use of californium-252 treatments resulted in five-year



The ANS has been designed with safety at a premium.

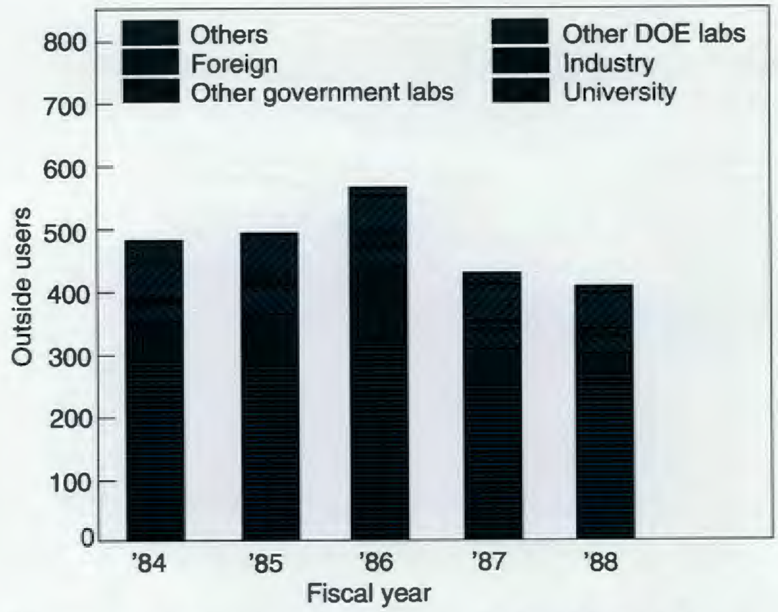
patient survival rates of 94% for victims with low-stage cervical cancer and 54% with advanced-stage cervical cancer, with some cures even for advanced severe-stage cervical cancers. For patients having malignant glioma, a type of brain tumor that was previously untreatable and invariably fatal, five-year survival has been achieved.

When treating brain cancer at the University of Kentucky center, physicians implant 30-microgram "seeds" of californium-252 into large tumors. The isotope's powerful neutron radiation destroys the cells of the tumor from within, causing less damage to the healthy tissue nearby than conventional treatments using gamma radiation or X rays. A different technique is used to treat cancerous tumors of the cervix. Stainless steel tubes containing californium-252 are implanted directly into the patient's uterus or vaginal canal; X rays guide the physicians in positioning the tubes to maximize radiation doses to the cancer cells. This method is highly effective in eradicating tumors, Maruyama says.

Interest in using californium neutrons for cancer therapy continues to increase. Recently, the Nuclear Regulatory Commission approved a license for evaluation of californium-252 for cancer therapy at Wayne State University, a comprehensive cancer center of the National Cancer Institute. ORNL will ship californium sources from the HFIR in 1994 to initiate the new clinical trials.

Radioisotopes from the HFIR and later the ANS also will help extend our knowledge of our domestic energy sources. Radioisotopes can be injected down an oil well to trace oil flow. Low-level radioactivity from the flowing oil, which decays away reasonably quickly, can be detected in the ground using a gamma-ray camera. This information helps American petroleum companies determine the direction of oil flow and, thus, the best locations for new oil wells.

The ANS is being designed to meet NRC safety specifications, although there is no legal requirement to do so.



The number of outside users at ORNL user facilities declined after 1986 because of the shutdown of ORNL reactors, including the High Flux Isotope Reactor, now back in operation. The number of outside users, especially from industry, should increase dramatically at ORNL if the ANS is built in Oak Ridge.

Other applications of radioisotopes from the ANS will be neutron radiography, medical diagnosis, power sources for space satellites, and detection of airport explosives.

Research Reactors Versus Power Reactors

Because of concerns associated with incidents such as those at Three Mile Island and Chernobyl, it is important to understand the differences between research reactors and reactors that produce electrical power.

The term nuclear reactor usually refers to a large reactor that produces electrical power. The ANS, however, does not generate electricity. It is a research reactor, not a power reactor.

The two reactor types differ in size and heat generation, for example. The core of a typical power reactor would fill a two-car garage, whereas the ANS's core will be roughly the size of a medium-capacity home water heater. The 330-MW ANS will generate only one-tenth the amount of heat produced in a typical 1200-MW power reactor.

A power reactor is similar to a giant pressure cooker. Its primary purpose is to make steam that will drive turbines for producing electricity. Tremendous amounts of heat and high pressures are required for electricity generation. Thus, the core must be big, and the facility must be complex. Equipment failures at power reactors are usually the result of damage either to valves, to pipes, or to other mechanical systems and are caused by intense pressures or the complexity of the equipment needed to ensure cooling of the plant's key systems.

By comparison, the ANS is a low-temperature, low-pressure operation because making steam is not its purpose. In fact, the ANS is designed to be a cool system because one goal is to provide cool low-energy neutrons.

The ANS has been designed with safety as the highest priority, using a principle known as defense-in-depth. There are at least two different systems capable of providing each safety-related function; critical systems have backups that are both redundant and diverse. Very simply, the idea is (1) to design the facility from the outset so that no systems will fail; (2) to ensure that if a system did somehow fail, backup systems are immediately available to bring operations back to normal; (3) to construct a containment building with double walls (2-meter- or 6-foot-thick reinforced concrete backed by a separate steel liner) to prevent the escape of any material in the reactor area to the environment and to the public; and (4) to have well-established, well-rehearsed emergency plans, regardless.

The ANS Project team incorporates the combined expertise from DOE's national laboratories and from U.S. industry to design the ANS. The design relies on proven technology and has considered compliance with more than 3000 federal, state, and local regulations. This, combined with years of experience in building and operating research reactors, is additional assurance that the ANS will be a productive facility.

Despite the fact that a commercial reactor is much more powerful and is subject to much higher pressures, the containment building of the 330-MW ANS will be bigger than that for a typical 1200-MW power reactor because ANS needs a large floor space for experiments. Furthermore, the ANS is being designed to meet the reactor licensing specifications of the Nuclear Regulatory Commission, although there is no legal requirement to do so for DOE's research reactors. It's simply a matter of putting safety first.

This way of thinking has been consistent throughout the planning of the ANS Project and will continue until the facility has run its useful course, probably sometime in the mid-21st century. It is a standard that has led to more than 50 combined years of safe, successful operation at the HFIR and ILL, which have been design models for much of the ANS. Although the HFIR began operating in 1966 when the potential of neutron beams for research was only beginning to be understood and tapped, it has laid the groundwork for the future of neutron-based studies that will be realized through the ANS.

By building and operating the Advanced Neutron Source, Oak Ridge will reaffirm its status as one of the nation's most prominent centers for scientific exploration and will lead the United States back to the rank of world leader in the field of neutron research. ornl

Biographical Sketches

Bill R. Appleton is associate director for the Advanced Neutron Source at ORNL. Previously, he was ORNL associate director for Physical Sciences and Advanced Materials. From 1986 to 1988 he was director of the Laboratory's Solid State Division. In this division, he also served as group leader, section head, and director of the Surface Modification and Characterization Collaborative Research Center. He received a B.S. degree from the University of Missouri and M.S. and Ph.D. degrees from Rutgers University in solid-state physics. He then worked two years at Bell Laboratories in Murray Hill, New Jersey, in ion implantation and ion-beam analysis before joining ORNL in 1967.

In 1987 Appleton was named Scientist of the Year by Martin Marietta Energy Systems, Inc. He is a recipient of the 1980 Department of Energy Award for Outstanding Sustained Research, an I·R 100 Award for his work in developing supersaturated substitutional semiconductor alloys, and the 1985 DOE Materials Research Award for Significant New Technologies. He has co-edited three books and is a member of editorial boards of several scientific journals. He is a past officer and councillor of the Materials Research Society and a fellow and councillor of the American Physical Society.

Colin D. West is director of the Advanced Neutron Source Project at ORNL. He received his BSc., MSc., and Ph.D. degrees in physics from the University of Liverpool in England. From 1965 to 1977, he worked for the United Kingdom Atomic Energy Research Establishment at Harwell, England. He came to ORNL in 1977 to work for the Program Planning and Analysis Office (now the Office of Planning and Management), which reports to the Laboratory director. West transferred to the Engineering Technology Division in 1981. In 1975 he was jointly awarded the Science, Education and Management Premium by the Institute of Electrical Engineers, and in 1992 he was honored at the Martin Marietta Energy Systems Annual Awards Night Ceremony for his exceptional service as ANS director. During his career at ORNL since 1977, he has been responsible for development of a novel neutron detector, materials irradiation experiments, and several reactor safety projects. He has worked extensively on development of Stirling engines at Harwell and ORNL, publishing more than 50 books, papers, reports, and patents in that field.

West helped to found the International Group on Research Reactors of which he is chairman. It provides a forum for organizations around the world to share information and research results concerning new research reactor construction and upgrade projects. Currently, groups from 21 countries participate in this organization. He is an editor of the *Journal of Neutron Research*, a new international publication. He is also president of the East Tennessee Stock Dog Association and drives a homemade car.

The authors acknowledge the contributions to this article by Jon Jefferson, Wayne Scarbrough, and Carolyn Krause.

A History of the ANS: Going Back to the Source

Dick Cheverton proposed in 1974 that ORNL build a 200-megawatt reactor with a HFIR-like core and heavy water as the core coolant and neutron reflector.

Ralph Moon made presentations to national committees on a proposed new research reactor that came to be known as the Advanced Neutron Source.

American scientists were concerned that the best neutron research was being done in France.

Ralph Moon of ORNL's Solid State Division has long believed that what this country needs is a new research reactor. Since the mid-1970s, he has urged the Laboratory to design a new reactor to better meet the scientific community's research needs and to win funding for it as a major new government facility. His persistence may pay off in the form of the Advanced Neutron Source proposed for ORNL.

Interest in building a major new source of neutrons for neutron scattering experiments in the United States was strongly expressed at a 1974 workshop at Brookhaven National Laboratory (BNL). American scientists were concerned that the best neutron research was being done at the Institut Laue-Langevin (ILL) reactor in France because it offered a variety of superior neutron scattering instruments, and they wanted a facility as good or better. Among the speakers at this Workshop on Intense Neutron Sources was Dick Cheverton of ORNL, who had been responsible for the design of the Laboratory's High Flux Isotope Reactor (HFIR). He proposed a 200-megawatt (MW) reactor with a HFIR-like core and heavy water (deuterium oxide, or D_2O) as the core coolant and neutron reflector. He estimated that this reactor would produce a thermal flux in the reflector about four times that of the ILL reactor.

As an outgrowth of this workshop, a smaller group of scientists formed an ad hoc panel to formulate recommendations on future neutron sources. In this group were ORNL scientists Mike Wilkinson, Wally Koehler, and Jack Harvey. In a 1974 letter to John Teem, head of the Atomic Energy Commission's (AEC's) Division of Physical Sciences, the ad hoc panel urged the commission "to start engineering design studies" for a high-performance, steady-state neutron source similar to but better than ILL. The scientists' goal was a reactor built by 1984 that would have a neutron flux the same as that proposed for the Advanced Neutron Source today. Also proposed for this reactor was a "cold source" to supply low-energy neutrons because of their suitability for studies leading to practical applications. [The ILL was the first large reactor to have a cold source; in the United States, smaller cold sources are available at BNL's High Flux Beam Reactor (HFBR) and at the National Institute of Standards and Technology reactor.] The AEC made no response to these recommendations.

Reactors Versus Accelerators

In May 1976, Alex Zucker, ORNL associate director for the Physical Sciences, formed the Neutron Source Committee to make recommendations on future neutron sources at ORNL, including an upgrade of the Oak Ridge Electron Linear Accelerator (ORELA) so it could be used for neutron scattering experiments. At the time, Argonne National Laboratory had proposed an accelerator-based pulsed neutron source for neutron scattering experiments (which was later built and called the Intense Pulsed Neutron Source).

The ORNL committee, chaired by Moon, recommended against the ORELA upgrade and proposed supporting the Argonne pulsed neutron source—a spallation source in which neutrons are produced by accelerating protons against a target. Most important, the committee also endorsed the Cheverton proposal to design and build a 200-MW reactor using heavy water as the moderator, coolant, and reflector. "It had been known since the 1950s that heavy water was the best coolant and reflector to use in reactors designed specifically for neutron scattering experiments," Moon says. "The ILL and HFBR both use heavy water for their reflectors."

Because of the proposals being made to build neutron sources, the U.S. Department of Energy (DOE) asked the National Academy of Sciences in 1977 to study the scientific opportunities offered by neutron research. A National Research Council committee made the assessment in its report *Neutron Research on Condensed Matter*. It recommended that a pulsed source be constructed (with a peak flux of 10^{16} neutrons per square centimeter per second) and that design efforts start for a steady-state source to replace the HFBR and HFIR.

On February 9, 1983, Zucker set up an internal competition as he challenged the staff to come up with ideas for a major new facility for ORNL. Moon proposed a 200-MW reactor with heavy water as coolant and moderator to replace the HFIR. At first, the proposal was dubbed the HFIR-II reactor.

In July 1983, the Laboratory Executive Committee announced it had decided to modify the HFIR to make it more useful as a neutron-scattering facility. Moon was asked to head the HFIR upgrade project. "My response was to argue against this decision because the HFIR building was designed for isotope production, not neutron research. I recommended that a team of ORNL researchers start design on a new 200-MW heavy-water reactor and associated research facility for three purposes—neutron scattering research, materials irradiation studies, and radioisotope production." In August 1983, Dave Bartine was placed in charge of the reactor design team, and Moon agreed to head the project provided that both a HFIR upgrade and a new facility be considered. Startup money of $650,000 was requested for fiscal year 1984 from the Laboratory Director's Research and Development (LDRD) Fund.

In November 1983, the President's Office of Science and Technology Policy asked the National Research Council to assist in establishing priorities for major facilities for materials research and related disciplines. A committee of 22 distinguished scientists and administrators, headed by Frederick Seitz of Rockefeller University and Dean Eastman of IBM, was appointed by the council; the committee began its work in January 1984. A subpanel on neutron scattering was headed by Bob Birgeneau of the Massachusetts Institute of Technology.

On January 24, 1984, a letter from Seitz to ORNL Director Herman Postma arrived on Moon's desk inviting ORNL to make a presentation to Birgeneau's subpanel February 26 at the National Academy of Sciences. On the same day, Moon learned that funds from LDRD were available to begin work on the new reactor facility.

"These events marked the real beginning of what was to become the ANS Project," Moon says. "A fast start was absolutely essential because the Seitz-Eastman committee wanted both an oral and a written report. We had only one month to develop a detailed description of the facility, a cost estimate, and an assessment of the most important recent accomplishments in neutron scattering."

Moon endorsed the Cheverton proposal to build a heavy-water reactor.

Moon and Herb Mook of ORNL's Solid State Division made presentations to the neutron scattering subpanel in February, and Moon made another presentation to the full Seitz-Eastman committee in March.

In July 1984, the Seitz-Eastman committee made recommendations for new facilities and for upgrades of existing facilities. The highest-priority new facility was an intense X-ray source, now under construction at Argonne National Laboratory and called the Advanced Photon Source. A close second, by only one vote, was an "advanced steady-state neutron source facility" designed to have a neutron flux 5 to 10 times that of ILL. Much to Moon's delight, the document stated, "Instead of upgrading an existing facility, a new reactor should be built."

Moon and representatives from three other national laboratories and the then National Bureau of Standards organized an international meeting held in October 1984 at Shelter Island, New York, on Scientific Opportunities with Advanced Facilities for Neutron Scattering. The chief issue discussed was whether a steady-state neutron source (reactor) or pulsed neutron source (spallation source) would better serve the research community. The attendees supported the conclusion of the Seitz-Eastman committee that an appropriately designed reactor should be constructed first.

More Studies and Critiques

DOE's response to the Seitz-Eastman report was to ask its Energy Research Advisory Board (ERAB) to examine the same issues. The ERAB report, published in June 1985, endorsed the conclusions of the Seitz-Eastman committee.

President Clinton agrees that the country needs a new reactor.

Meanwhile, on July 1, 1985, at ORNL, Colin West of the Engineering Technology Division was placed in charge of the newly named Center for Neutron Research (CNR) Project. The CNR Project, like the ORNL reactor design study initiated in 1984, was supported by the LDRD Fund.

On December 16, 1985, Moon helped organize an important workshop on the Advanced Steady-State Neutron Facility, held at the National Institute of Standards and Technology in Gaithersburg, Maryland. There, a national steering committee was formed to promote and guide development of a new steady-state neutron source. In addition, various reactor design concepts and technical alternatives were presented by the speakers (including West), recommendations were made, and critiques were performed. The critique group gave the best grades to the ORNL and Idaho National Engineering Laboratory concepts. Thus, the basic reactor concept continued to gather support as the preferred neutron source for meeting the needs of the U.S. scientific community.

The fiscal year 1987 congressional appropriations bill was passed, providing DOE funds for the first time for an "advanced neutron source." The money was earmarked for ORNL's Center for Neutron Research Project, which changed its name to the Advanced Neutron Source (ANS) Project to reflect the language of the appropriations bill. The ANS Project has been receiving DOE funding ever since.

In 1991, the Basic Energy Sciences Advisory Committee (BESAC) of DOE's Office of Energy Research (OER) was asked by OER Director Will Happer to form a panel to revisit the question of whether a reactor or spallation source would make the best neutron source. The panel was headed by Walter Kohn of the University of California at Santa Barbara, who had been a member of the Seitz-Eastman committee.

In June 1992, the Kohn committee issued its report. According to the report, the BESAC panel concluded that "the nation has a critical need for a complementary pair of sources: a new reactor, the Advanced Neutron Source (ANS), which will be the world's leading neutron source, and a pulsed spallation source. . . .The ANS is the Panel's highest priority for rapid construction. In the Panel's view, any plan that does not include a new, full-performance high-flux reactor is unsatisfactory because of a number of essential functions that can be best or only performed by such a reactor."

President Clinton agrees that the country needs a new reactor. In his 1993 report *A Vision of Change for America*, the president urged the U.S. Congress to build the ANS. As in fiscal year 1994, the proposed 330-MW ANS is a line item in the president's budget for fiscal 1995, suggesting that initial construction money may be available soon. "I hope it happens," Ralph Moon says with a smile.—*Carolyn Krause*

Fruits of Neutron Research

Car windshields that don't break during accidents and jets that fly longer without making a refueling stop. Compact discs, credit cards, and pocket calculators. Refrigerator magnets and automatic car window openers. Beach shoes, food packaging, and bulletproof vests made of tough plastics. The quality and range of consumer products have improved steadily since the 1970s. One of the reasons: neutron research.

The fruits of neutron research were publicly proclaimed in the mid-1980s by the Exxon Chemical Company in a two-page advertisement that appeared in science and trade magazines. The ad included an artist's impression of ORNL's George Wignall standing at a neutron beam line from the High Flux Isotope Reactor (HFIR). Exxon and other industrial firms had been invited by ORNL's Wally Koehler to use the new small-angle neutron scattering instrument at the HFIR for their research. Exxon Chemical Company recognized that the HFIR was an inexpensive source of valuable and unique information for its chemists who were developing materials from Exxon's main product—petroleum.

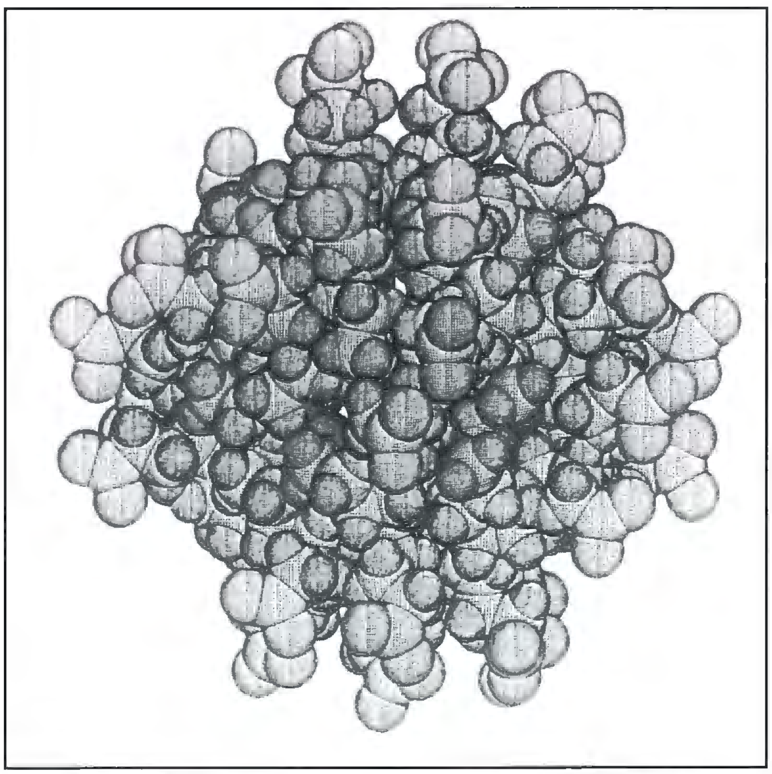
Strengthening Plastics

One focus of the Exxon chemists was to find ways of using existing polymers to make stronger plastics. A polymer is a large molecule, like molecules in rubber, made up of many smaller molecules bonded together; theoretical predictions in the 1960s suggested that polymers could be very strong if their molecules were properly aligned like the paper fibers in facial tissues. These molecules consist of such atoms as carbon, oxygen, and hydrogen.

Because neutrons, unlike X rays, are deflected by hydrogen and other light atoms, they are useful for determining the arrangements of polymer molecules. In particular, small-angle neutron scattering can reveal how long, threadlike polymer molecules pack to give plastics their diverse properties.

"Industry has been using neutrons from the HFIR and other reactors to verify that certain

The fruits of neutron research were publicly proclaimed in the mid-1980s by the Exxon Chemical Company.



Configuration of a micelle, a model for the submicroscopic structural unit of protoplasm, the important constituent of living cells that is built from polymer molecules. Almost all structural information on micelles has come from neutron scattering. Reprinted with permission from *Nature* (Ken Dill et al., *Nature* 309, 1984, p. 42), Copyright (1984) Macmillan Magazine, Limited.

processes can produce polymer molecules that line up to make some plastics very strong," says John Hayter, scientific director for the ANS Project at ORNL. "Strong plastic, for example, is used to make the familiar bags of peanuts on airlines that can be torn open only at the precut notch. Some reactors are preferable to the HFIR for these polymer studies because they produce very slow neutrons. These so-called 'cold' neutrons will be produced in the ANS."

The new polymers are much better than the breakable plastics in old toys. These synthetic polymers are tough lightweight materials used in cars and airplanes (e.g., the Boeing 757 jet), bulletproof vests for police officers, beach shoes, packaging for foods and snacks, synthetic threads for wash-and-wear clothes and textiles, and plastic sheets sandwiched between glass sheets to make nearly unbreakable windshields for cars and trucks.

Small-angle neutron scattering can also indicate if there are subtle movements of molecules between materials in a structure, suggesting that the structure is falling apart. For example, it can be used to determine if atoms are migrating between plastic sheets sandwiched together in a laminate.

Neutron scattering is in demand by industry for guiding the development of polymer composites and polymer alloys.

According to Hayter, neutron scattering is in demand by industry for guiding the development of polymer composites and polymer alloys. "The chemical industry is no longer interested in synthesizing new polymers because of the liability problems of marketing a new material that might prove harmful to human health or the environment," he says. "The emphasis today is on making polymer alloys of known and approved chemicals now being manufactured. The ANS will be needed to guide the development of these materials in the United States."

Colloidal Structures

Hayter, a native of New Zealand, is often thought of as a university-trained physicist because of his developments of neutron scattering instruments at the Institut Laue-Langevin reactor in Grenoble, France, and his considerable experience in neutron scattering experimentation. Actually, he has a Ph.D. degree in physical chemistry from the University of Sydney in Australia. He is a self-taught physicist with strong interests in neutron research and colloid chemistry.

A colloid is a collection of particles—each about the size of 100 to 1000 atoms—dispersed in a liquid or gas. Particles that size of interest today include viruses and constituents of electronic microchips.

"Twenty years ago," Hayter says, "neutron scientists were studying atoms, while industry was interested in structural detail 100,000 times larger. Today both have converged to study structures the size of 100 to 1000 atoms—the so-called colloidal size range.

"The large surface-to-volume ratio in colloids yields interesting properties," Hayter explains. "Flour, for example, becomes a powerful explosive when reduced to colloidal size in heated air. That's why we hear about occasional explosions in wheat silos."

Complex fluids, such as blood, are examples of colloidal systems. A key feature of such fluids, Hayter says, is self-assembly of molecules into higher structures, such as a micelle (see photograph). A micelle is a model for the submicroscopic structural unit of protoplasm, the important constituent of living cells that is built from polymer molecules.

Self-assembly of molecules into different structures is a phenomenon that intrigues Hayter. At his desk, he conducts a simple experiment to show that molecules have a memory. He pulls out a clear plastic, cylindrical container slightly smaller than a coffee mug. It contains a thick clear liquid called glycerin, which is held against the container wall by a cylinder in the center. Using an eye dropper, Hayter introduces a drop of glycerin colored blue into the clear liquid. He turns the cylinder around more than half way, and a blue ribbon of liquid snakes around the container wall. Then he turns the cylinder back to its original position. The ribbon disappears and a spot of blue slightly larger than the original drop remains. "The molecules remember their original positions as they reassemble themselves," Hayter notes.

Almost all structural information on micelles has come from neutron scattering," Hayter says. The information is obtained by replacing some of the hydrogen atoms in structures with deuterium atoms.

Structural details are revealed because hydrogen atoms and deuterium atoms scatter neutrons differently.

Hayter is interested in the effects of applied shear on colloids. Examples of shear are rubbing your hands together to cover them with hand lotion and pushing a roller up a wall to spread paint. He has conducted neutron scattering experiments that show that, contrary to intuition, structures in colloidal fluids may take on even more crystalline order under modest applied shear. The colorful computer-generated results of one of his experiments on a colloidal crystal made the cover of the October 18, 1985, issue of *Science* magazine. Recently, he and his associates were the first to measure shear-induced ordering in a complex fluid flowing past a surface; their results were published in a paper in the April 4, 1994, issue of *Physical Review Letters*.

Neutron scattering is useful for understanding the effect of shear on oil, Hayter says. A lubricant is effective only if it can ooze between engine parts gliding past other components, such as a piston in a cylinder. Hayter says that some oils laced with a detergentlike chemical called a surfactant act both as a liquid and solid that can be stretched when shear is applied.

"Such fluids in which molecules self-assemble into larger structures can behave in complex ways," Hayter says. He shows a photograph of a slightly tilted bottle of a thick hydrocarbon oil containing 2% aluminum dilaurate, which is a surfactant. The liquid appears to be pouring easily with normal viscous flow. But a closer examination of the bottle tilt angle reveals that the flow is induced not by gravity but by "self-siphoning."

Neutron scattering can be used to detect structural changes that may be responsible for complex behavior under various conditions. In fact, Hayter says, in 1986 at the HFIR (a few months before it was shut down for more than 3 years), he proved to biochemists at the University of Michigan that neutron scattering could show a structural change in lipopolysaccharides, helping explain why these cells containing lipids and sugars behaved strangely at a certain pH (acidity level). Such information can be useful for both basic understanding, such as relating structural changes in living cells to odd behavior, as well as for practical applications, such as the development of improved lubricants for future engines.

Authenticating Paintings

When the Smithsonian Institution in Washington, D.C., receives a painting several centuries old, officials turn to experts at a nearby neutron source to verify that the painting is authentic. Using cold neutrons at the National Institute of Standards and Technology (NIST) Reactor in Gaithersburg, Maryland, scientists subject the painting to nondestructive neutron autoradiography to determine the metallic composition of pigments and inks. In this technique, a whole painting is sprayed with slow neutrons, which activate the metals in the paint. As a result, each metal gives off gamma rays of characteristic energies. The gamma-ray energies are imaged on film laid on top of the painting immediately following neutron irradiation. The film images indicate the identities and concentrations of the different metals in the pigments. Because the composition of paints (for example, the relative amounts of cadmium in yellow pigments and lead in blue and white paints) is known for various historical times and places, neutron radiography can be used to authenticate a painting—or declare it a fake!

Neutrons are used to search for early signs of corrosion in the wings of fighter aircraft.

Detecting Corrosion in Airplane Wings

At McClellan Air Force Base in California, an underground reactor has been operating since 1990. It produces neutrons to search for early signs of corrosion in the wings of F-111 fighter aircraft positioned above the reactor. Built during the war in Vietnam and used in the Persian Gulf War in 1991, F-111 fighters are aging planes that have seen a lot of wear and, like people, need physical checkups. F-111 aircraft wings are made of honeycombed aluminum-alloy structural members, filled with air and covered with a thin metal skin to make the wings lightweight. If hairline cracks develop, moisture from the air is likely to enter the wing, possibly oxidizing the aluminum. As a result, the honeycombed structure could corrode and, if the corrosion is not detected in time, the wing could break off.

To prevent such a nightmarish scenario, the Air Force examines its fighter aircraft using reactor neutrons and neutrons from robot-held portable sources containing californium-252, which is produced in the HFIR. These neutrons fly by aluminum atoms, but they are scattered by the hydrogen atoms present in water. In this way, neutrons detect and map the locations of moisture—signs of microscopic cracking and early corrosion. These results indicate the structural parts of aircraft wings that should be replaced.

Neutrons can reveal details about the magnetic structures of certain materials that cannot be obtained any other way.

Improving Magnetic Storage Media

"Just about everything known about the atomic structures of magnetic materials has come from research at the HFIR and other reactors," Hayter says. "For example, studies at HFIR confirmed the existence of a magnetic property called antiferromagnetism, which was predicted by French Nobel Laureate Louis Neel."

Neutrons are valuable tools for this research because they behave as tiny magnets. Each one has a north pole and a south pole similar to the ends of bar magnets. Because they are magnetic, neutrons are scattered by magnetic materials just as a refrigerator magnet scoots away from another magnet pushed toward it. "It takes a thief to catch a thief," Hayter says.

Neutrons can reveal details about the magnetic structures of certain materials that cannot be obtained any other way. Such information has been vital to the creation of high-density recording media such as audiotapes, videotapes, and computer disks.

"Neutron scattering," Hayter says, "helps scientists determine the positions of atoms in material having a certain magnetism. This information helps industry develop and refine processes to manufacture materials with desired magnetic properties."

Using neutron scattering research at the University of Missouri, the Ford Motor Company has developed compact, lightweight magnets made of neodymium, iron, and boron. These small permanent magnets are used in compact motors in cars for automatically adjusting seats and opening windows.

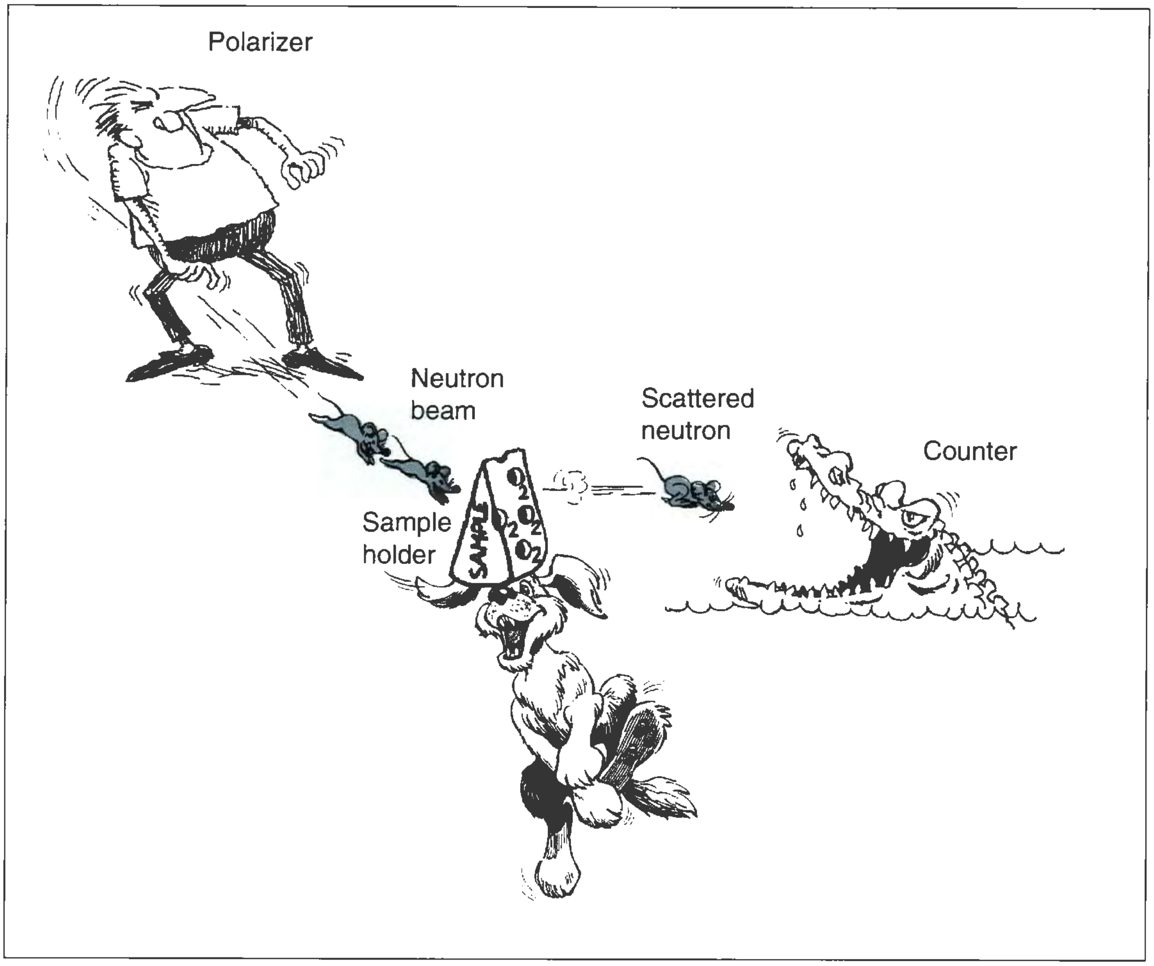
Information on magnetic materials obtained by neutron scattering has made it easier to buy consumer products. It has enabled the addition of high-tech magnetic lines to plastic sheets to make the credit card.

Neutron scattering is also being used to determine the number and positions of oxygen atoms in high-temperature superconducting ceramics, such as yttrium-barium-copper oxides (YBCO), which are also magnetic materials. The number and positions of oxygen atoms are possible keys to high-temperature superconductivity and the ability of a material to carry useful amounts of electrical current. Neutron scattering produces the type of information necessary to understand these materials, including the relationships between their structures and properties. Once they are understood, it will be possible to predict which materials will make the best superconductors.

One of the unfortunate events in American science, Hayter notes, is that two of the best neutron sources in the United States—the HFIR and DOE's High Flux Beam Reactor at Brookhaven National Laboratory—were shut down in 1987. That's the year when high-temperature superconductivity studies were being conducted at a frenetic pace worldwide. Herb Mook of ORNL's Solid State Division, for example, had to perform his neutron research on superconducting materials at the Oak Ridge Electron Linear Accelerator (ORELA) and the reactor at NIST. Other American scientists simply could not find a reactor available for superconductivity studies, while scientists in Europe and Japan forged ahead in their research in this exciting new field.

Checking for Weld Strains

Most people feel secure in vehicles and buildings, even though they are aware of famous engineering failures—the Challenger explosion and the collapses of the Tacoma Narrows Bridge and the walkways in the Kansas City Hyatt Hotel. Why do structures fail? Stresses within welded metals



Artist's view of a typical neutron scattering experiment. Neutrons striking a sample are deflected, collected, and counted. *Based on a drawing by Enrico Rastelli of Parma, Italy.*

Neutron measurements of residual stress can be used to improve manufacturing quality and uniformity.

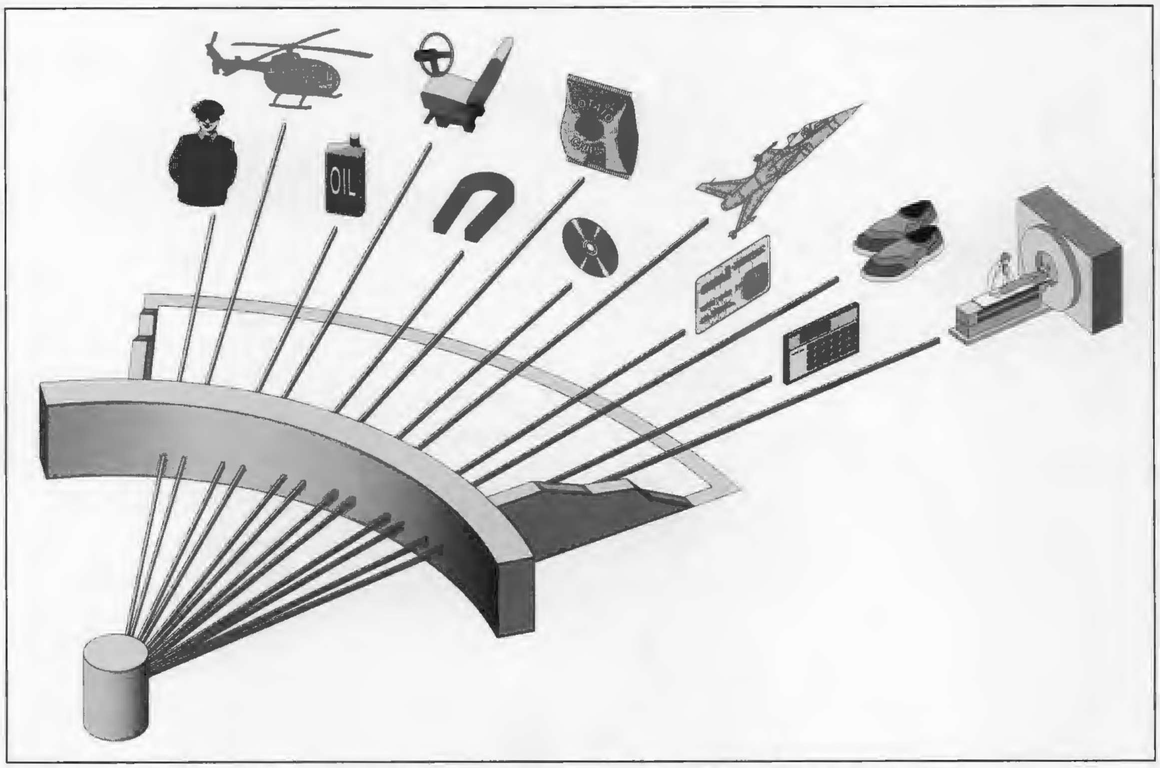
and alloys combined with stresses applied externally can lead to cracking, deformation, and failure.

Neutron scattering can measure residual stresses formed within materials during their manufacture or within welds during their formation. How? Stresses on a crystalline material cause strains in the material, or changes in the distances between the planes of atoms in a lattice. Compressive stresses cause these distances to shrink, and tensile stresses cause them to expand compared with lattice spacings in a stress-free material.

To measure these stresses, a sample is placed in a neutron beam so that the stress-free part of the material will scatter neutrons at 90°. If the separation between the atomic planes is smaller or larger than that in the stress-free part of the material, the neutrons will be scattered at slightly different angles. From these diffraction angles, the lattice spacings and, therefore, the strains are measured. This information can be used, for example, to determine if a weld will hold if operating conditions are changed or if a weld is stronger after heat treatment.

A reactor at the Chalk River Laboratory in Canada has been used to measure strain in welds in oil pipelines. A robot holds a piece of welded pipe in a neutron beam. The results of neutron scattering measurements are used to determine whether part of the pipeline should be replaced or

As a result of neutron research, a helicopter engine was redesigned to solve a lubrication problem.



Building and operating the Advanced Neutron Source research reactor, which will be accessible to researchers who have good ideas for experiments, will improve the nation's competitiveness in the world marketplace. Here's why. The quality and range of products and services available to consumers have grown in the past decade because of worldwide neutron research. This illustration features a neutron source (fissioning reactor core in can) and neutron beam lines penetrating the shielding. Benefits shown include new plastic materials, such as those in the police officer's bulletproof vest, in food packaging (e.g., for potato chips), and in shoes. Other benefits shown are improved magnets, which are used in compact motors for automatically adjusting seats in cars, compact discs, credit cards, and pocket calculators. Neutron research has also led to better lubricants and more efficient designs of helicopters and airplanes. Most important, neutrons from research reactors produce radioisotopes for treating cancer and, with the help of scanners, diagnosing it and other human diseases. *Drawing by David Cottrell.*

heat-treated to prevent oil leaks to the environment.

In France, the Institut Laue-Langevin reactor is used to measure residual stress in rails for France's high-speed trains. At the HFIR in Oak Ridge, residual stresses were recently measured in a multipass weld for the first time. These reactors could also be used to measure stresses in oil well casings and ceramic-coated turbine blades.

"Strains in various materials subjected to various stresses are predicted by finite element analysis computer programs," Hayter says. "Neutron scattering measurements of sample materials determine whether the predictions of these programs are correct. If the predictions are proven wrong, then the computer programs are altered to reflect the true situation."

Recently at the HFIR and ORNL's High Temperature Materials Laboratory, a Neutron Residual Stress User Facility has been established. ORNL researchers are working with researchers from companies such as General Motors, General Electric, Cummins Engine, and Alcoa to develop and apply neutron residual stress mapping to industrial processes. For example, maps are being made of stresses in automobile gears and silicon carbide fibers in fiber-reinforced titanium alloys. Neutron measurements of residual stress can be used to improve manufacturing quality and uniformity.

Improving Aircraft Engine Efficiency

The most efficient jet engines and helicopter engines in the world are manufactured by Rolls-Royce, Ltd. They use fuel so efficiently that jets with these engines can fly nonstop from the U.S. west coast to Australia without a refueling stop in Hawaii (as jets with other engines must do). The superior designs of these engines are based partly on the results of neutron research.

Several years ago, a newly developed Rolls-Royce Gem jet helicopter kept seizing up when operated. The lubricating oil apparently was not flowing properly through the engine. So the British company turned to the Harwell Laboratory in England to locate the source of the oil flow problem. A crane was used to position the helicopter engine for real-time neutron radiography outside the containment at Harwell's DIDO reactor. As the engine was operated, it was irradiated with neutrons. The neutrons breezed past the metal atoms of the engine and interacted with the hydrogen atoms in the flowing oil. The emitted neutrons were captured by a television camera fitted with a scintillator, and images of the flowing oil were displayed on a TV as the engine ran. Viewers could see that the oil was not flowing correctly around a particular corner of a pipe. As a result of this neutron research, Rolls-Royce redesigned the helicopter engine and solved the lubricant flow dynamic problem.

Rolls-Royce also uses an accelerator source of neutrons to help the company improve the efficiency of its aircraft engines. By operating each newly developed engine in the presence of neutrons from this source, Rolls-Royce has measured the temperature, strain, and tip clearances of its spinning turbine blades. This information helps it redesign new engines to make them even more efficient.

Hayter has proposed that neutrons from ORELA be used to measure temperature, strain, and tip clearances of spinning turbine blades of operating jet engines made by U.S. aerospace companies. Neutron resonance studies can be conducted at ORELA by painting turbine blades with tantalum, which absorbs neutrons. Because neutron absorption is related to temperature and stretching of the material, it can provide information to help improve the thermodynamic efficiency of American-made jet engines. In this way, American jet engines could become as efficient or more efficient than Rolls-Royce engines, giving the United States the competitive edge in aircraft engine efficiency. Any competitive edge that advanced neutron research could give American industry may be the best fruit of all.—*Carolyn Krause*

THE ANS: A BRIGHTER LIGHT

The $2.9 billion Advanced Neutron Source will offer at least five times greater neutron flux than current research reactors. Is a fivefold increase worth almost $3 billion?

Yes, says John Hayter, scientific director of the ANS Project at ORNL. He offers this analogy.

Compare all the scientists who want to do neutron scattering experiments to an audience in a dimly lit auditorium. Everyone in the audience has a copy of the speaker's paper. But, except for the large title words, no one can read the text.

Now imagine that the dim light in the auditorium is turned up so that it is five times brighter. The members of the audience can read the speaker's paper.

"A fivefold increase in neutron flux at the ANS will have the same effect," Hayter says. "Scientists will be able to obtain considerably more information."

Building a Better Reactor Through Research

By Carolyn Krause

Although its design uses existing reactor technology, the Advanced Neutron Source (ANS) will be better suited to neutron research than any other research reactor in the world. To ensure that this unique Department of Energy (DOE) facility will operate effectively and safely as an intense, steady-state source of neutrons for experiments, research is being conducted at ORNL and other laboratories. The best expertise and facilities throughout the nation are being called upon to work with ORNL researchers to achieve one goal: to make the ANS the best possible reactor for meeting the needs of the scientific, technological, and medical communities.

Doug Selby, head of the ANS Project's research and development program, says that 13 types of program activities address technical issues associated with the ANS, which will be used for neutron scattering research, radioisotope production, and materials irradiation. These activities and some of the issues addressed are described in this article.

Reactor Core Development

What is the best possible reactor core configuration for the ANS? This question is being addressed by the Reactor Core Development task group, which contributed significantly to the development of the conceptual design report of the ANS, published in June 1992. This group includes thermal-hydraulics task leader Grady Yoder and other researchers in ORNL's Engineering Technology Division (located at the Oak Ridge Y-12 Plant) who analyze the thermal-hydraulic behavior of the core. They study the core heat removal requirements and develop the best means of removing the heat. Reactor physics studies of the core are performed by researchers at ORNL's Engineering Physics and Mathematics Division (EPMD), led by Brian Worley, and at Idaho National Engineering Laboratory (INEL).

"This work provides input to preliminary and final safety analysis reports and support to design teams," says Selby. For the conceptual design, the task group recommended a two-element core, somewhat larger than ORNL's High Flux Isotope Reactor (HFIR) core, with 93% enriched uranium silicide (U_2Si_3) fuel—that is, fuel containing uranium atoms, 93% of which are fissionable uranium-235.

Can the ANS be operated with fuel of lower enrichment than 93%? This issue raised by DOE and various review groups has been studied by a DOE task force headed by Brookhaven National Laboratory that includes researchers from ORNL, INEL, and Argonne National Laboratory (ANL). This study that has just been completed included reactor physics and some thermal-hydraulic evaluations of various alternative enrichments.

The ANS will be better suited to neutron research than any other research reactor in the world.

"We looked at several enrichments—50%, 35%, and 20%," Selby continues. "It appears that fuel with an enrichment as low as 50% could be used without much penalty in reactor performance—that is, neutron flux and other parameters. If the enrichment level is dropped below 50%, the performance tends to degrade rapidly. Right now we get a peak thermal neutron flux of approximately 7.4×10^{19} per square meter per second. At the peak reflector flux location, we can more than likely get within 15 to 20% of that value with enrichment in the 50% range.

"However, for both 50 and 35% enrichment, we must switch from a two-element core to a three-element core. As a result, refueling outages (downtime) will be longer, the problem of what to do with spent fuel elements will be compounded, and fuel costs will be greater. Also, even with the three-element core, at 20% enrichment enough fuel cannot be put in to

Marshall McFee (left) and Dave Felde inspect the Thermal Hydraulic Test Facility, which is used to collect experimental data on the combined effects of the heat loading, water-coolant temperature, and coolant velocity expected for the proposed Advanced Neutron Source research reactor. In this facility, water runs through aluminum test specimens simulating clad fuel elements, and these specimens are heated by electrical current to simulate heating by nuclear fuel.

It appears that fuel with an enrichment as low as 50% could be used without much penalty in reactor performance.

Dick Pawel (left), Dave Felde, and Doug Selby discuss an aluminum fuel cladding test specimen at the ANS Corrosion Loop. An electrical current is run through the specimen to simulate the heat flow through the cladding from nuclear fuel under ANS conditions. The amount and rate of oxide growth from interaction of the cladding with cooling water are measured in this test facility.

maintain a reasonable core life at a reasonable power level."

Fuel Development

Is uranium silicide the best fuel for the ANS and, if so, why? The Fuel Development task group, headed by George Copeland of ORNL's Metals and Ceramics Division, has addressed this question with the help of Argonne and Babcock & Wilcox, Inc., researchers. In the 1980s DOE asked ANL to develop a low-enrichment fuel to replace high-enrichment fuel in research reactors to reduce the potential for nuclear weapons proliferation. Argonne scientists chose uranium silicide (U_3Si_2) as the low-enrichment fuel for its program because its higher uranium density allows more total uranium in the core, compensating for the lower enrichment. The ANS designers plan to use U_3Si_2 as a high-enrichment fuel rather than uranium oxide (U_3O_8) used in the HFIR and many other nuclear reactor plants.

"Our evidence to date is that under ANS conditions, uranium silicide performs even better as a fuel than uranium oxide," Selby says. "At the higher burnup levels of the ANS, the silicide fuel swells less, has better thermal conductivity, and better retains fission products."

Uranium silicide was first tested and used as a high-enrichment fuel in 1987 by Copeland and his team using the Oak Ridge Research Reactor; U_3Si_2 is now being tested in many countries, including Japan, France, Germany, Indonesia, Denmark, Sweden, and Russia. After the 1987 tests at ORNL, a team led by Colin West, ANS Project director, Copeland, and Selby proposed uranium silicide as a reference fuel for the ANS.

"We are now using the HFIR to test capsules containing uranium silicide fuel specimens," Selby says. "The fuel can be taken up to well above the average fission density we would expect to see in the ANS. Two capsules were irradiated in the reactor, each for one HFIR cycle, and a third capsule will be irradiated later this year. Argonne researchers are currently performing postirradiation examinations of the specimens from the first two capsules. Microstructural evaluation techniques, such as metallography and scanning electron microscopy, are used to judge the retention of fission products, particle swelling, and particle-matrix interactions. This information is used to validate the mechanistic fuel performance model also being developed at ANL."

Selby says that Argonne and ORNL researchers have published some results of their fuel examinations, further reinforcing the belief that uranium silicide is the best fuel choice.

"The Argonne scientists," he says, "found that the interactions between the fuel and aluminum cladding form a shell of aluminide around the fuel particles, enhancing their stability. Results to date indicate that the uranium silicide fuel will allow the ANS to reach its full planned performance."

Maintenance work being performed on the ANS Corrosion Loop.

Corrosion of aluminum alloy cladding can affect reactor operation.

Corrosion Tests and Analyses

The higher the power density (heat output divided by volume) of the reactor core, the higher the neutron flux produced. However, power density can be increased only so much because of various limiting factors. One factor is associated with the formation of an oxide film. Under ANS operating conditions, the aluminum alloy cladding for the fuel tends to grow an oxide layer from contact with the heavy-water coolant. Because the oxide layer does not conduct heat well between the fuel plates and cooling water, the fuel would overheat if this film became too thick.

Remedies proposed for this corrosion problem have included cladding surface treatment, changes in coolant chemistry, and changes in coolant flow and velocity. To test the effects of these changes on fuel plates at different simulated power densities, ORNL built the Corrosion Test Loop Facility, a high-pressure heated water loop that has been operating since January 1988. The facility is designed to measure the corrosion of aluminum and other effects under the heating levels and coolant velocity expected for the ANS fuel.

The operation of this facility at ORNL's Engineering Technology Division is conducted by the ANS Project's Corrosion Tests and Analyses task group led by Dick Pawel of the Metals and Ceramics Division. The facility is more than halfway through its planned program of 64 tests.

Selby says that the corrosion of the aluminum alloy cladding can affect reactor operation in two ways. First, film growth influences system temperatures. Second, internal reactions may limit structural and containment capability.

"The severity of internal reactions was observed to be related to the heat flux," Pawel says. "These reactions occurred only after thicker oxide films had formed and spallation had started." Spallation is a loss of portions of the oxide film as a result of buildup of mechanical stresses in the system.

The HFIR also has aluminum cladding, and experiments performed in the 1960s established oxide growth and constraints under HFIR operating conditions. "In the ANS studies we found that some assumptions made when the HFIR was designed were not applicable in the range of ANS operating conditions," Selby says. "We found that we must consider additional variables that are important to growth of the oxide film. ANS conditions not found in the HFIR, such as higher heat fluxes and coolant velocities, must be taken into consideration when determining oxide growth."

New results indicate that oxide growth on cladding can be controlled to acceptable levels if the heavy-water coolant has the right chemistry.

Marshall McFee installs a test section in a large aluminum electrical bus in the Thermal Hydraulic Test Facility.

New results from tests at the ANS Corrosion Test Loop Facility indicate that oxide growth on cladding can be controlled to acceptable levels if the heavy-water coolant has the right chemistry.

"The rate of oxide growth on aluminum alloy cladding is sensitive to the acidity level of the coolant," Pawel says. "We found that controlling the water chemistry to keep the pH at or slightly below 5.0 inhibits oxide growth.

"Under some conditions," Pawel continues, "we have linked the lower oxide growth to formation of a thin iron-rich film on the outer surface of the oxide film. In addition to creating a viable data base with our experiments, we are trying to unravel the interactions of water chemistry, film properties, and oxide growth rates."

"We developed a new correlation, or set of equations, that predicts oxide growth on aluminum cladding as a function of heat flux, coolant temperature, and flow rate," Selby says. "This correlation has been published in the literature."

Core Flow Tests

The ANS Project's Core Flow Tests task group headed by Dave Felde of the Engineering Technology Division is conducting tests to ensure that the ANS design safely accommodates the high power densities and high coolant velocity planned for the reactor. Computer codes exist to predict the conditions at which boiling of the coolant and overheating of the core would start. But these correlations, which were developed for lower heat flux conditions than the ANS, may not be valid under the advanced reactor's conditions. Experimental data are needed on the combined effects of the heat loading, coolant temperature, and coolant velocity expected for the ANS. From these data, researchers can select, extrapolate, or develop correlations that accurately predict incipient boiling, critical heat flux, heat transfer coefficients at the fuel plate wall, and flow instability (e.g., bubble formation that inhibits coolant flow). To gather such data, the Thermal Hydraulic Test Loop was constructed by the Engineering Technology Division. "With accurate experimental information," Selby says, "we will be able to predict under what conditions the reactor would get into trouble and thus be able to provide adequate margin to ensure that those conditions would not be reached."

The task group is also studying the remote possibility that the ANS might have a loose reactor part that could, unless appropriate precautions are taken, partially block coolant flow. Occasionally, a component of a pump, experiment, or refueling machine might drop into the heavy-water coolant stream. In the ANS, as in other reactors, strainers will catch loose items at various locations in the loop to reduce the probability of their entering the core. Even so, coolant flow blockage by a loose piece, although an unlikely event, is still a potential concern.

To address this concern, the Core Flow Tests task group constructed a Flow Blockage Test

Facility to determine the sizes of blockages that the ANS could take without incurring fuel plate damage. The researchers are using the facility to determine the effects on fuel plate temperature of different sizes and locations of blockages and the distances downstream of the blockages where these effects persist. Data have been obtained on fuel plates' heat transfer capability and coolant velocity with blockages of 10% and 25% on the edge of the channel and 10%, 15%, and 35% in the center of the channel.

"If a blockage occurs, there is some area behind it where the cooling capability is degraded," Selby says. "Farther downstream the coolant flow re-forms and the core is subjected to normal cooling. But between those points, the fuel plate receives less cooling than expected.

"We're trying to measure actual cooling capabilities and fuel plate temperatures downstream of a blockage," Selby says. "The measurements are obtained from a thermosensitive film placed on the plate downstream of the blockage. Different colors in a computer image of the film show the variations in film temperatures, indicating the different degrees of cooling to which the fuel plate is subjected.

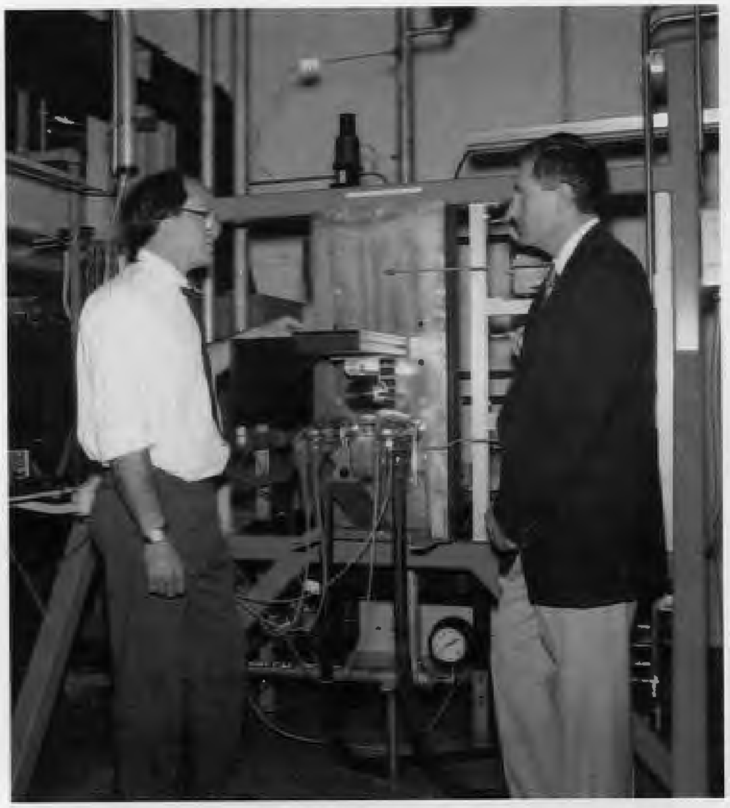
"Our goal is to determine how big a blockage we can accommodate in our design of the ANS," Selby adds. "This information will help determine

George Farguharson installs diagnostic heater connections on the Flow Blockage Test Facility. The facility provides temperature measurements using thermochromic liquid crystals and image processing in a mock fuel element. These continuous measurements are used to experimentally determine heat transfer downstream of a postulated flow blockage in an ANS-like core.

Dave Felde shows a coolant channel in which measurements are made on changes in the temperature of fuel cladding as a result of a channel blockage.

We're trying to measure actual cooling capabilities and fuel plate temperatures downstream of a blockage.

Passive safety features will be incorporated into the ANS design to make it safer during operation and shutdown.



Dave Felde explains to Doug Selby some results from recent operation of the Flow Block Test Facility (shown here). It measures changes in the temperature of the fuel cladding as a result of a blockage in the coolant channel. The variations in temperature are recorded in color on film, and a camera transmits the color information to a computer, which analyzes and displays the results in color on the screen.

how large the ANS strainer should be."

Passive safety features will be incorporated into the ANS design to make it safer during operation and shutdown. During shutdown the ANS will be designed to use the natural heat from the fuel's decay to drive the heavy-water coolant and continue to remove heat from the core. The Core Flow Tests task group will use a Natural Circulation Test Facility to be built to test this passive design feature for low-flow conditions. "In the tests," Selby says, "we will determine when natural circulation driven by heat in the fuel elements supplies sufficient cooling for the core so that forced cooling is no longer needed following shutdown."

Control Concepts Development

The ANS will be designed to control the fuel core's reactivity—release of neutrons through fission—to ensure needed heat output without overheating the fuel. The Control Concepts Development task group of the ANS Project has been examining materials—or "poisons"—that absorb neutrons to keep reactivity under control. According to Selby, "We've decided to use hafnium as the primary neutron absorber for the control rods for shutting down fission reactions in the core. We are considering the use of boron as a burnable poison—a material that gets rid of excess reactivity during reactor startup and early cycle operation but is burned up over the reactor cycle so that it is not an operational penalty. Boron would be 'burned up' by absorption of neutrons, which would transform it to a material that does not absorb neutrons."

The task group is headed by Brian Worley and consists of his colleagues in EPMD with some support from the I&C Division.

Critical Experiments

The validation of the reactor physics methods used to design the ANS is performed in three phases. The second phase of this validation effort has just been completed with the evaluation of the Institut Laue-Langevin (ILL) reactor and its critical experiments that were performed in the 1960s. Scientists at INEL and in EPMD working in the ANS Project's Critical Experiments task group have developed computer codes to analytically model the reactor physics of these heavy-water systems that have many similarities with the ANS geometry.

"We obtained measurements of reactor physics parameters for ILL and its critical experiments, built reactor physics models, and compared our predictions with their experimental results," Selby says. "A recently published report documents the work performed at INEL and shows good agreement between our calculations and ILL's experimental data."

The third and final phase of the preoperational reactor physics validation, Selby adds, is to perform a series of reactor physics experiments specific to the ANS geometry. Five sites being considered for those experiments are the Los Alamos, Oak Ridge, and Sandia national laboratories as well as Chalk River Laboratory in Canada and Winfrith Technology Centre laboratory in England.

Material Data, Structural Tests, and Analysis

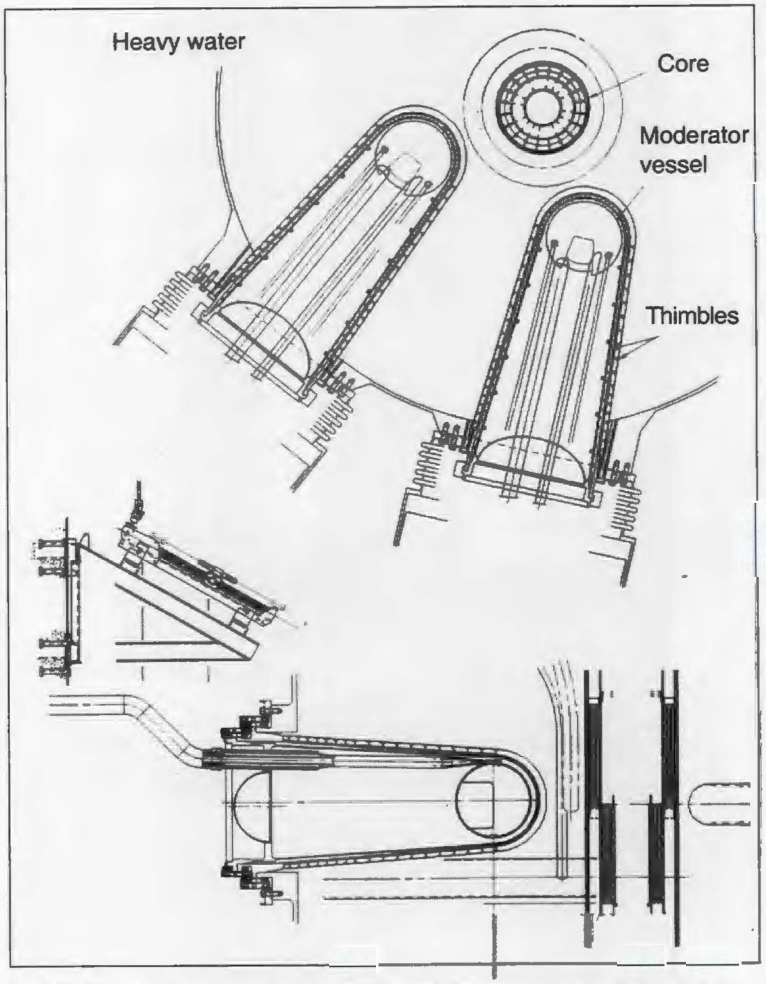
One remote possibility being considered is that the high velocity of the ANS water coolant could eventually force the closely spaced fuel plates together. The ANS Project's Material Data, Structural Tests, and Analysis task group headed by Terry Yahr of the Engineering Technology Division is studying this possibility. If such "plate deflections" were to prevent adequate cooling, fuel damage might result. To determine the conditions that might result in excessive plate deflections, the task group is operating a Plate Stability Test Facility.

"We have run four tests using epoxy plates and scaled the results to aluminum fuel plates like those that will be used in the ANS," Yahr says. "We chose epoxy plates because we can test theoretical models using lower pressures and coolant velocities than would be needed to test aluminum plates. We are now preparing to test aluminum plates to show their stability under ANS conditions."

Frank Swinson adjusts the Plate Stability Test Facility used to evaluate fuel plate stability under ANS coolant flow conditions.

"We are now preparing to test aluminum plates to show their stability under ANS conditions."

The ANS will provide the highest neutron flux ever, so efforts are being made to ensure that its structural materials will withstand damage from neutron irradiation. The same task group has irradiated two capsules (Hansal-1 and Hansal-2), which contained specimens made of aluminum 6061-T651, the reference design material for many ANS structural components. Tests on specimens from the first capsule, which was irradiated in the HFIR for three reactor cycles, showed little effect of irradiation on fracture toughness except at the highest temperature tested. Tests have not yet started on specimens from the second capsule,



In ORNL's cold neutron source for the ANS, a mechanical circulator will move liquid deuterium (for slowing down energetic neutrons) around the loop between the cold source and the heat exchanger, where the heated deuterium is recooled by the helium refrigerant.

ORNL researchers have proposed an all-liquid cold neutron source using deuterium.

which was irradiated in the HFIR for about 2 years (21 reactor cycles) for an accumulated total thermal neutron fluence of 8×10^{26} per square meter. This fluence simulates the degree of radiation damage that might be expected in some ANS components.

"Information from tests like these," Selby says, "will be used to develop a materials data base, which will be used to complete the final design of the ANS." Data are also being collected so that researchers can build computer models to predict thermal stresses in candidate reactor structural materials under various ANS conditions.

Cold Neutrons

One of the major facilities of the ANS is a source of low-energy neutrons for neutron beam experiments. These low-energy neutrons are obtained by placing a moderator at very low temperature in the reflector region of the ANS. Heating levels in the ANS cold sources, produced by high-energy neutrons and gamma rays from the reactor core, will be much higher than those in cold sources at the ILL or the High Flux Beam Reactor at DOE's Brookhaven National Laboratory. Therefore, a different approach for removing the heat is required for the ANS.

Cold sources at the ILL, for example, allow liquid deuterium to boil. The lighter boiled-off gas then rises to a heat exchanger where it is reliquefied. This heat exchanger is cooled by helium gas refrigerant from a refrigerator system.

"Because of the high heat load in the two ANS cold sources, a system that works with both a liquid and a gas leaves many complex problems to be solved," Selby says. "It would be extremely hard to assess the relative proportions of liquid and gas in the boiling vessel for all possible operating conditions."

ORNL researchers have proposed an all-liquid cold neutron source using deuterium. They say that a more efficient moderator can be produced if the liquid is cooled well below its boiling point and circulated in fully liquid form by a mechanical circulator. An external review group including representatives from BNL and the

National Institute of Standards and Technology concurs that this concept offers the lowest technical risk.

The ANS Project's Cold Source Development task group, under Trevor Lucas of the Engineering Technology Division, has developed such a system. Two prototype liquid circulators have been ordered and will be tested and developed by ORNL researchers beginning this year. Deuterium, an isotope of hydrogen, has been chosen as the neutron moderator because of its ability (unlike normal hydrogen) to slow down neutrons without absorbing them.

John Hayter (left) and Herb Mook examine a neutron supermirror of the type used in the transmission polarizer they developed that received an R&D 100 Award in 1989.

Supermirrors are being developed at ORNL to minimize the losses of cold neutrons in a beam as they are transported.

In the ORNL cold source, liquid deuterium will enter the moderator vessel at 20 K. The 30-kW heat load will raise this temperature to 25 K, which is still several degrees below its boiling point. To prevent boiling, the pressure of the liquid will be controlled. A mechanical circulator will move the liquid around the loop between the cold source and the heat exchanger, where the helium refrigerant recools the deuterium.

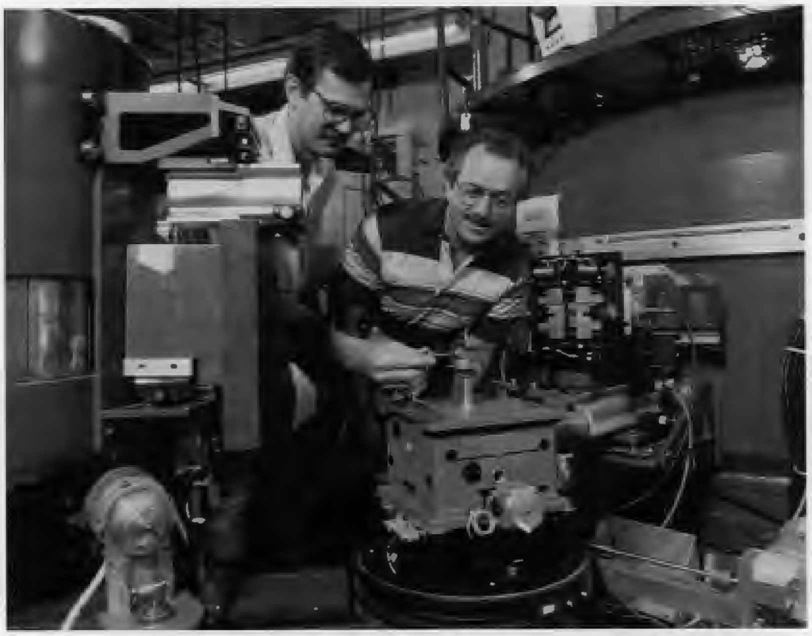
Each cold source vessel will be located close to the reactor core to take maximum advantage of the available neutron flux. The slowed, or cold, neutrons will then be guided through cold neutron guide tubes to experiments as far away as 70 to 100 meters without significant losses in the strength of the neutron beam.

Instrument and Beam Tube Development

While at ILL, John Hayter, now scientific director for the ANS Project, designed and built, in collaboration with F. Mezei, the highest-resolution neutron spectrometer in the world. Called a neutron spin echo spectrometer, it was used to test the polymer theories of Pierre-Gilles de Gennes of the College de France, Paris, who was awarded the 1991 Nobel Prize for Physics.

In the past 5 years, new devices have been developed by the ANS Project's Instrument and Beam Tube Development task group under Hayter and Ralph Moon, associate director of ORNL's Solid State Division. One device, developed by Herb Mook and Hayter, both of the Solid State Division, received an R&D 100 Award in 1989. Called a transmission polarizer, this device produces polarized beams for neutron scattering research while minimizing the loss of neutron intensity in the polarization process. In other words, it deflects neutrons of one spin state without affecting neutrons of the other spin state. The device was used by researchers to study the magnetic properties of materials such as high-temperature superconductors.

The ORNL polarizer allows efficient use of short-wavelength neutrons (2.5 angstroms) that



Jerel Zarestky (left), a user from DOE's Ames Laboratory, and Bob Nicklow, manager of ORNL's Neutron Scattering Research Facility, adjust the orientation of a cobalt manganese alloy using a triple-axis spectrometer. The machine measures the energy of neutrons scattered from the sample. *Photograph by Bill Norris.*

Bob Nicklow adjusts the beam aperture at the HB-3 triple-axis spectrometer, the type of instrument that will be available at the experimental workstations in the neutron beam room of the ANS.

will be abundantly available in the ANS. It uses a stack of 80 magnetic supermirrors—excellent reflective surfaces for neutrons.

Supermirrors are being developed at ORNL in conjunction with NIST to minimize the losses of cold neutrons in a beam as they are transported from the reactor to the experimental sample in the guide hall. "We are developing new surfaces and new ways to transmit neutrons from the source to the experiment and reduce the neutron losses between both points," Selby says. "If improvements can be made in neutron beam transmission, additional experiments may be moved out of the space-constrained containment area to a larger neutron guide hall area that has lower radiation background."

The key to designing an effective supermirror for a cold neutron-beam guide is to make a surface that continuously reflects back those low-energy neutrons that leak out of the beam.

"Once neutrons enter a beam guide, if the surface has the right shape and composition, they keep reflecting off surfaces with only small losses until they reach the experiment," Selby says.

"For any given neutron energy, we try to improve the angle of the guide tube's acceptance—the neutron angle that will allow the neutrons to be reflected down the guide tube rather than transmitted through the tube wall. For a given neutron energy, there is some angle that will reflect a neutron perfectly while neutrons of higher energies pass through the surface. We're trying to improve surfaces to increase the angle so more neutrons can be delivered to experiments."

Neutrons from the reactor can also be used to produce positrons (positively charged electrons) for research. A new conceptual design study for an ANS positron source has been completed. In this concept, a copper-64 target would be irradiated in the intense neutron flux near the reactor core, producing copper-65. During decay, copper-65 emits positrons. Copper-64 was chosen over other metals because it does not transmute to materials that decay into long-lived radioactive wastes. It was selected instead of krypton gas as a positron source to eliminate concerns about the consequences of an accidental release of a radioactive gas. Examples of applications for positrons are measurement of electron momentum densities in metals and alloys and three-dimensional mapping of material defects.

Hot Neutrons

The ANS Project has a Hot Source Development task group, which is exploring ways to raise neutron energies from room temperature to higher equilibrium temperatures. One approach is to use the energies of gamma radiation from the reactor core to heat a graphite block to 2000 K and above. Carbon-bonded carbon fiber insulation would be wrapped around the graphite block to retard the outward flow of heat.

"The energy of neutrons entering the block from all directions would be raised by transfer of energy from the graphite block," Selby explains. "The neutron energy spectrum shifts into the desired range—say, from 0.04 electron volts to the 0.2 to 0.4 electron volt range—and are then transported to experiments via beam tubes."

Neutron-Gamma Transport and Shielding Analyses

The large number of penetrations of beam tubes and guide tubes through the biological shielding presents special problems to the shielding designers. These issues are being studied by the ANS Project's Neutron-Gamma Transport and Shielding Analyses task group led by Brian Worley of EPMD. Researchers in EPMD have set up complex models to evaluate identified shielding problems and provided possible solutions.

"We also evaluate high-energy neutron and gamma radiation that is unfortunately transmitted through the biological shield via the beam tube path," Selby says. "We try to determine beam tube orientations that minimize this gamma and high-energy neutron radiation that is considered noise to the experimenters. We found that neutron and gamma contamination of beam tubes is high if they are oriented so that they are 'looking' at the core. If we change the beam tube orientation to look away from the core, fast neutron and gamma flux is reduced. Because the thermal neutron source is nearly isotropic at the beam tube mouth, any beam orientation will work for neutrons in the energy range desired by researchers."

Neutrons from the reactor can also be used to produce positrons for research.

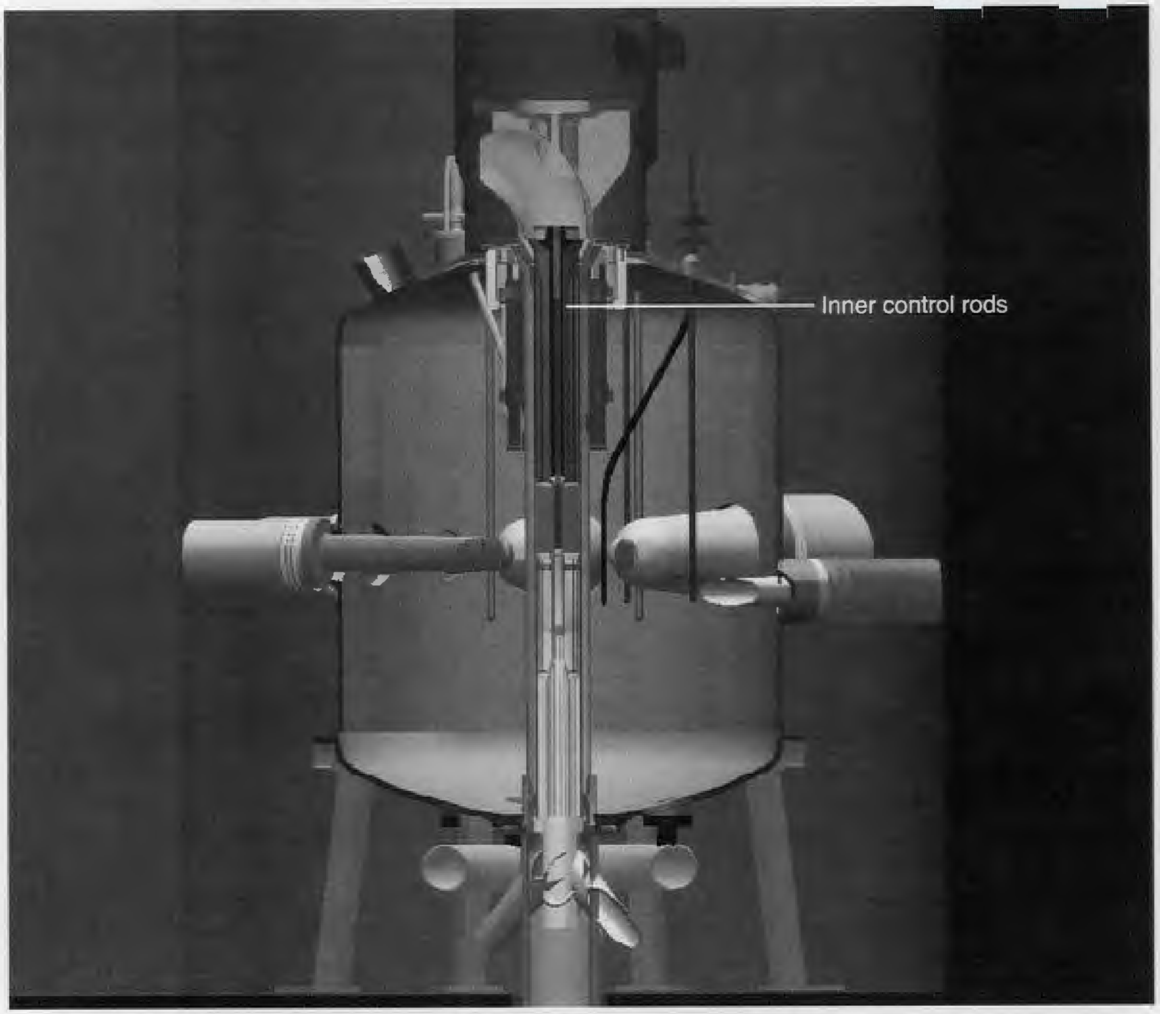
Selby says the "primary biological shield" planned for the ANS is reinforced heavy-duty concrete. Other materials are being looked at to provide shielding for areas where radioactive fuel elements are moved for storage.

The task group is also using computer modeling to predict the neutron and gamma heating of various reactor components under ANS conditions. By determining how much energy is deposited, the researchers can learn how much heat must be removed to keep the components cool. This information will affect the design of many components in the reflector region.

Instrumentation and Controls

The Instrumentation and Controls task group under John Anderson of the Instrumentation and

Throughout the design, the ANS Project has taken advantage of the availability of new computer-based modeling tools.



Cutaway of the ANS reactor core showing control rods and neutron beam tubes. ORNL has been conducting research to aid selection of the best neutron absorber for ANS control rods and to improve the reactor design to obtain desired control rod performance. *Drawing by Barbara Smith.*

Controls (I&C) Division is determining the requirements of a fully integrated ANS control and plant protection system. Instrumentation is an integral part of almost every major ANS system, and, for this reason, the I&C team is involved with many other ANS research and development groups.

Selby says that one of the main challenges of the design is to obtain the desired control system response time, which requires fast actuation of control components. Through use of computer simulations, the I&C team has developed a series of rod performance requirements and is continually interacting with the engineering design team to evaluate design options.

The control rods are just an example of how modern design techniques are influencing the final outcome. Throughout the design, the ANS Project has taken advantage of the availability of new computer-based modeling tools. One example is the ANS Dynamic Model, which allows designers to simulate with a personal computer the dynamic response of the ANS core and its cooling circuits. This model has been used extensively to test different design options, and it has also been used to set initial requirements for the control and plant protection systems.

The I&C research team in cooperation with the Electric Power Research Institute is developing a reactor protection system using application-specific integrated circuits (ASICs). These circuits are being investigated for potential use in commercial power plants and in the ANS. Selby says that ASICs can be designed to perform as well as computers, and the task team is working to show that they are simpler, cheaper, and more reliable than software-based systems.

Reactor Facility Concepts

The testing of various reactor components is being performed by the ANS Project's Reactor Facility Concepts task force led by Steve Litherland of Martin Marietta Energy Systems Engineering Division. "For example," Selby says, "the group has tested the holding power of prototype control-rod magnets. They obtained magnets like the ones we propose to use in the ANS, put them in a clamp, and applied force until the magnets pulled apart."

A proposed test would examine the seal that separates the primary loop from the neutron reflector area. "We hope to design a device to increase pressure on one side of a prototypic seal to test how much pressure the seal can take before weakening," Selby explains. "We also want to test latching devices for control rods and measure the time it takes to release them."

Many ANS operations will be performed remotely, so ORNL is testing certain remote operations. "Key features of certain components will be modeled with high fidelity and the interfaces with remote operation devices will be examined," Selby says. These tests will provide indications of potential remote handling interface problems as early in the design as possible.

In conclusion, Selby notes that almost half of the research and development on the ANS Project is scheduled to be performed at ORNL because of the wide-ranging reactor expertise and facilities here. However, he adds, "We work very hard to determine the best place to do different pieces of ANS research. We are building a team of experts and using the best facilities from all over the nation to solve problems to ensure safe, reliable operation of the ANS." ornl

"We are building a team of experts and using the best facilities from all over the nation to solve problems to ensure safe, reliable operation of the ANS."

Laser Ablation: Opening Doors to New Materials for Industry

By Carolyn Krause

For ORNL's Douglas Mashburn, 1987 was a particularly exciting year. The world had become aware of the promise of new ceramics that conduct electricity without resistance at the temperature of liquid nitrogen. He and many other scientists at ORNL and elsewhere worked frantically in their laboratories to make and test these new ceramics. The news media proclaimed that high-temperature superconducting materials would improve the efficiency and lower the cost of underground power transmission lines for cities. Because the electricity they carry isn't partially wasted as heat, superconducting wires are believed to be potentially more economical than conventional copper cables. The appeal of these new materials is that they are superconductive when chilled only by liquid nitrogen, a much less expensive refrigerant than the even colder liquid helium needed to cool low-temperature superconductors such as niobium-titanium alloys. The new materials have also been considered promising for making smaller and more efficient motors, microelectronic circuits that would speed up computers, and compact magnets powerful enough to levitate and propel high-speed trains. Although the timetable for these wonders may have been very optimistic, the possibilities are still very real.

In May 1987, Mashburn, a laser expert then in the Solid State Division, learned that the high-temperature superconducting material yttrium-barium-copper oxide (YBCO) had been made as a thin film using an excimer laser. By September, he and his ORNL associates had demonstrated that indeed thin films of these materials could be made using a process called laser ablation. By establishing a presence in the field of superconducting thin films, ORNL in 1988 became one of three national laboratories designated by the Department of Energy to have a High-Temperature Superconductivity Pilot Center (now called a Technology Center). As a result, under pilot center cooperative agreements, ORNL scientists began collaborating with researchers from industrial firms to develop processes and products of commercial value.

In 1993, the ORNL High-Temperature Superconductivity Technology Center managed by Bob Hawsey boasted its first commercial product—a software-driven, pulsed-laser system for depositing films of a specified composition and thickness. Called the Automated Multilayer Deposition Accessory (AMDA), the system was developed in collaboration with the private firm Neocera, Inc., of College Park, Maryland, in a cooperative research and development agreement (CRADA). ORNL's technical contribution was provided by Mashburn, a researcher now in ORNL's Engineering Technology Division. He helped Neocera researchers incorporate features from two of his inventions into their laser deposition system, resulting in the AMDA device. One invention was a rapid target-switching scheme that he conceived in 1987, and the second was a dual-beam laser arrangement conceived in 1990. (For details, see "Technology Transfer" in the *Review*, Vol. 26, No. 2, 1993, p. 68.)

Mashburn's system offers significant advances in the deposition of crystalline films by laser.

Mashburn has continued to develop his own laser deposition system, similar to AMDA but offering more capabilities. It may solve problems impeding commercial production of high-quality superconducting films, including films thick enough to be made into conductors for magnets and motors. His system offers significant new advances in the deposition of crystalline films by laser. It shows promise for creating defect-free films and improved materials by constructing them an atomic layer at a time. "Perhaps even more exciting," Mashburn says, "the new system could be developed into a 'materials workstation' that would open the door to exploring dozens of new materials" (see sidebar on p. 51).

Doug Mashburn demonstrates the "laser ablation from rapidly exchanged sources" setup. Note the rotating target drum in the triangular laser ablation chamber at center. The LARES computer at left controls the energy and timing of the pulses fired from the laser at the targets to evaporate material for making thin films. *Photograph by Bill Norris*

Among the many film samples Mashburn and his associates produced were the first super-conducting YBCO films at ORNL.

This laser ablation chamber was built in 1987 by Doug Mashburn and Dave Geohagan. With it, they produced ORNL's first thin films of high-temperature superconducting material. The bright light in the center is emitted by the plasma generated when an excimer laser beam vaporizes a pellet of superconducting material for deposition as a film on a substrate.

Early Superconducting Films Made at ORNL

In laser ablation, pulsed light from an excimer laser is focused onto a solid target inside a vacuum chamber to "boil off" a plume of energetic atoms of the target material. A substrate positioned to intercept the plume will receive a thin film deposit of the target material. This phenomenon was first observed with a ruby laser in the mid-1960s. Because the films made then by this process were contaminated with particles, little use was found for such "dirty" samples.

In the mid-1980s, a Rutgers University–Bellcore group led by T. Venkatesan explored excimer laser ablation as a means of depositing materials in the manufacture of integrated circuits. In early 1987, shortly after the discovery of YBCO, Venkatesan's group tried the process on a YBCO pellet and produced a superconducting film. This result came to Mashburn's attention, and he pressed his management to let him proceed with a similar experiment. As luck would have it, Mashburn had brought with him to the Solid State Division an excimer laser and other critical equipment needed to construct the apparatus, and his colleague Lynn Boatner had the special materials needed. Mashburn had salvaged the equipment from the Molecular Laser Isotope Separation (MLIS) Program at the Oak Ridge Gaseous Diffusion Plant, where he had worked on the process from almost its inception until its cancellation in 1982. MLIS was an advanced method for producing enriched uranium for nuclear power stations.

During the MLIS work, Mashburn was on assignment for several months at a time at Los Alamos National Laboratory. The excimer laser, a high-power ultraviolet pulsed laser, had just been invented at Los Alamos in 1976, when Mashburn joined the team that developed it and adapted it to the MLIS process. During this work he first encountered laser ablation when he unintentionally vaporized optical components for handling high-energy laser beams, damaging expensive parts. Also during this period, he developed his first laser ablation device, a "laser pulse detector" patented in 1981. After cancellation of the MLIS project, Mashburn joined the Atomic Vapor Laser Isotope Separation (AVLIS) team at Lawrence Livermore National Laboratory, where he helped design and install the copper vapor laser system for the AVLIS demonstration facility completed there in 1985. His first big task in ORNL's Solid State Division had been to design and install an excimer laser–assisted chemical vapor deposition system. By 1987, he had accumulated considerable experience on laser applications and insights into the internal workings of lasers.

Boatner, a crystallographer in the Solid State Division who was trying to grow single crystals of YBCO, was excited by Mashburn's proposal to produce superconducting films with laser ablation. Shortly after he heard about it, Boatner saw Venkatesan at a physics meeting and confirmed Mashburn's speculations. Convinced by new information brought back by Boatner, the Solid State Division management finally agreed to limited support of laser ablation experiments. That was all Mashburn needed.

In only 13 days in the summer of 1987, Mashburn and Dave Geohegan, a newly arrived postdoctoral fellow, built a laser ablation chamber as they rushed to compete in the superconductivity sweepstakes. Then they donned their laser goggles, fired up the excimer laser, and watched as the glass chamber lit up with the ablation phenomenon. On one side of the chamber was a heater holding a strontium titanate substrate supplied by Boatner on which they hoped to form a thin-film YBCO superconductor. In the center of the chamber was the YBCO pellet made by Boatner's group. Coming in from below was the focused excimer laser beam.

In their experiments, pulses of ultraviolet light from the excimer laser entered the chamber from below and within 30 billionths of a second (nanoseconds) heated a spot on the target to over 12,000°C (as they later determined). Atoms on the target surface became so superheated by the laser light that they literally exploded off the surface. As the ejected material traveled from the target to the substrate to make a film, its trail was visible as a glowing plume.

"These atoms are ionized, forming a dense plasma just above the surface of the solid," Mashburn says. "Laser ablation is a unique phenomenon in which a plasma at near-solid density explodes with energy greater than is present in any chemical explosion. The vaporized material deposits on the nearby substrate, which we heated to 500°C to assist our film growth."

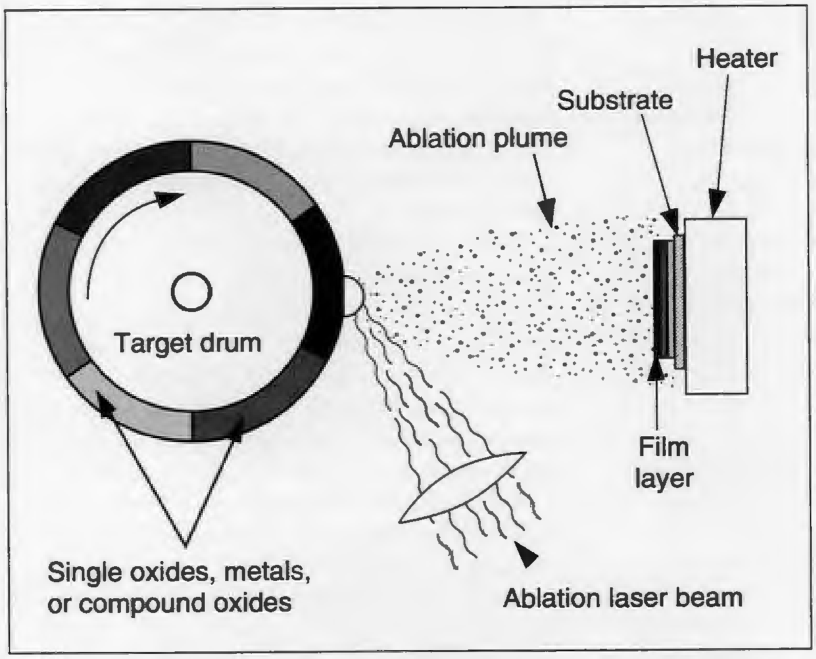
The scientists used a single-crystal wafer of strontium titanate as the substrate for the thin films because they suspected it would serve as a good template, forcing the atoms of the YBCO to line up in a neat, orderly pattern—that is, as an oriented crystal. After the film deposit was annealed in high-temperature, high-pressure oxygen, this atomic alignment did, in fact, occur. Their measurements verified that the substrate atoms imposed an order on the film layer just as a waffle iron impresses a grid pattern on waffle batter as it bakes. The results suggested that this technique might be superior to conventional deposition methods such as sputtering or thermal co-evaporation.

A major use of thin films is expected to be in tiny electronic components.

Among the many film samples Mashburn and his associates produced were the first superconducting YBCO films at ORNL. He reported his results in a scientific paper and at a meeting of the Materials Research Society. Color photographs of the glowing blue chamber made the covers of the *ORNL Review*, *Mechanical Engineering*, and the *MRS Bulletin* of the Materials Research Society.

Promise and Problems Of Thin Films

Thin films of high-temperature superconducting (HTS) material showed more early promise for applications than the bulk HTS materials. A major use of thin films is expected to be in tiny electronic components not exposed to high magnetic fields.



Schematic of Mashburn's laser ablation from rapidly exchanged sources (LARES) setup. Six different targets are mounted on the rotating target drum. The pulsed laser beam at right repeatedly strikes the rotor at the same point, but because the drum is spinning, the beam vaporizes, or ablates, different targets at appropriate energies controlled by a computer. When a target is ablated by the laser beam, a small amount of material shoots in a visible plume toward the substrate attached to a heater. Repeated ablations of different target material results in a thin film on the substrate.

"With the proper setup such a laser could tattoo a bullet in flight!"

By growing thin films on templates of other crystalline materials, the films' crystal grains can be lined up to form a continuous path for current, thereby avoiding the "weak link," or misaligned grains, problem that limits the amount of electrical current bulk materials can carry.

According to Mashburn, routine thin films several years ago could carry 5 million amperes per square centimeter and the best films could hold 50 million amperes if cooled to 4 Kelvins. By comparison, the best bulk material could carry only 50,000 amperes per square centimeter. The ability of thin films to carry current was at least 1000 times better than that of the bulk materials.

Now thin HTS films are being used in a commercial product introduced in 1992 by Conductus, Inc., of Sunnyvale, California, to detect weak magnetic fields.

The technology for making thin films has not yet been perfected, however. Hurdles remain to be overcome to make possible mass production of films of uniform composition and a range of thicknesses for various uses, including superconducting wires. Mashburn says that his and other advances in laser ablation may solve the problems currently blocking achievement of these goals.

In recalling those heady days of 1987, Mashburn says, "When we started ablating these materials, we were exhilarated by the success of our first try. But we soon realized that the films weren't perfect. For better understanding, we took each film to ORNL's Surface Modification and Characterization Collaborative Research Laboratory to determine the composition. In searching for ways to get the best ratios of elements, we changed the laser power, the gas pressure in the vessel, the substrate temperature, and the composition of the target.

"We had to wait a couple of days to get information back on each sample film. After a dozen or so films, we could project that in a brute force approach, it might take 10,000 samples to pin down the optimum conditions for YBCO deposition. At a rate of days per sample, it could take years to figure out how to make perfect films."

Bothered by this situation, Mashburn kept saying to himself, "There has to be a better and faster way to do this exploration." Then he saw the light. The approach, later named LARES, was conceived in the fall of 1987. It drew not only on his HTS film experience but also on his previously gained insights about the internal operation of lasers. However, he had to wait several years for funding to implement his innovative approach.

Meanwhile, numerous groups of American scientists took up the trial-and-error approach to making superconducting films. "Every team in the field," Mashburn says, "was depositing oxygen-deficient films by evaporation, ablation, sputtering, or other methods. Then, films had to be oxidized before they could be characterized. Because there was no reasonable way to monitor the incomplete precursor film in situ, it took days to obtain results for each sample. Over the next few years, the federal government ultimately paid for thousands of samples at a cost of several work days each. It was a long, laborious, expensive way to perfect the process of making superconducting films."

LARES: On-Line Variation and Control of Film-Element Ratios

Mashburn knew that experimenters elsewhere had shown that HTS films could be made by sequential evaporation of the metals yttrium, barium, and copper followed by oxidation. Oxides of these metals were preferred as targets, but the potential of oxygen to interfere with their vacuum systems kept scientists from using oxides. Mashburn knew that laser ablation did not have this difficulty, but it offered no guarantee that the delivered ratio and position of elements in a film (stoichiometry), when using a mixed compound target, would be desirable. Existing film thickness monitors could help only if the stoichiometry was already known. Such information was available only for pure elements or single stable compounds. Because metal oxides are stable or at least predictable, he thought about ablating them separately so they could be monitored and then combining them at the film.

Mashburn envisioned a device that combined a laser, a rotating target drum on which separate oxide targets would be mounted, and a computer-controller that would select (or skip) each target and adjust the laser energy needed to ablate it as it spun by several times each second. Such an automated device would switch targets for pulsed laser ablation much faster than manually operated mechanical shutters. It could not only control stoichiometry but also add buffer layers and contact layers or construct complex multilayered structures with ease. Mashburn began making the drawings and later built his invention, which he called LARES—laser ablation by rapidly exchanged sources.

"LARES gives you control of film composition," says Mashburn, "and you can quickly switch the composition from one type of atom to another within a film." This "atomically abrupt" switch can be made by automatically changing the power of the laser pulse and timing it so that it precisely ablates a material different from the previous target just zapped on the rotating drum.

"This is easy," Mashburn says, "because the time uncertainty between the triggering of the excimer laser pulse and its predicted arrival at the target is just a few nanoseconds—so short that with the proper setup such a laser could tattoo a bullet in flight!"

How could he use LARES to set the composition of a superconducting film?

"First, we must obtain high-purity targets of each element or oxide to be incorporated in the film, mount them on the target drum, and enter their position into the controller. Now, we calibrate the device by temporarily replacing the substrate with a crystal rate monitor," he says. "Then, after chamber evacuation, the laser is programmed to fire several times, at a fixed power level, at only one of the targets. A film of the target material is deposited on the crystal rate monitor. The monitor gives an electrical readout of the mass deposited, which is converted into atomic units or thickness using the composition data. That's why we must use single-element or stable compound targets of predetermined composition. The laser energy and resulting deposition rate are recorded in the computer. The procedure is repeated for a range of energy levels. Then another target is selected and the entire procedure is repeated for it. When all the targets have been calibrated and the information has been stored as a table in the computer, the rate monitor

"The speed and flexibility of this system will allow researchers to do material composition explorations at least 10 times faster."

is removed and the substrate is reinserted into the chamber.

"Now we have a system that can simply be programmed for the desired composition, and the controller will select the proper targets and fire the laser with the correct energy to deliver the needed amount of each target material. With newer lasers, this controller can make the laser power dance up and down in a precise manner hundreds of times per second. This action happens too fast for the eye to follow. Such thorough control of the laser firing, including skipping a target, enables precise regulation of the film composition. The speed and flexibility of this system will allow researchers to do material composition explorations at least 10 times faster than previously."

In 1990 Mashburn conceived a dual-beam optical arrangement to solve the problem of target erosion in LARES.

Dual-Beam Scheme: Smooth Targets

As he conducted laser ablation experiments in the Solid State Division, Mashburn began thinking about a problem affecting film deposition in some laser systems. ORNL scientists there noticed that, over time, the plume of evaporated material was no longer heading just for the substrate. The plume was steering in the direction of the laser beam and dirtying up the window through which the beam entered. Worse, the film composition changed with target use. They soon determined that as the target surface wore away, its texture changed.

"We found that as the target wears down, its surface develops microscopic fingers, also called texturing," Mashburn says. "These fingers shift the direction of the plume toward the beam. The first solution to this problem was to slowly scan the laser beam up and down the diameter of a rotating disk target so that the top half of the scan negated the texturing effect created by the bottom half scan. It works well for a single target setup. Unfortunately, this solution does not work for LARES, for here the beam-target drum intersection point must stay fixed."

In 1990 Mashburn conceived a dual-beam optical arrangement to solve the problem of target erosion in LARES. The laser beam coming straight at the target is split into two halves, one going up and one going down. A mirror in each half-beam directs it back toward the target so that the beams intersect at the target after coming from opposite sides of the target. Thus, the texturing tendency of one is simultaneously counteracted by the other, keeping the target smooth.

"The main advantage of such a balanced optical arrangement," says Mashburn, "is that the microscopic fingers do not form in the target. Instead, the target is actually polished. The smoother the pellet, the more likely it is that the desired film composition can be maintained. Additionally, for laser beams that do not have a flat intensity profile, the overlap also improves the beam uniformity."

Because the color and intensity of the laser ablation plumes are intricately related to the type, amount, and condition of material in transit, optical spectroscopy can be employed for precise noninvasive monitoring of the deposition process—a strong potential advantage of the laser ablation technique. "It can determine if the target surface has altered or the delivered laser energy has fallen," says Mashburn, "suggesting that the film composition will not be as expected." However, the spectroscope must always see the same area of the plume to make good comparisons. Because a fixed plume greatly simplifies this task, the dual-beam system makes such monitoring practical in LARES, which can even use the spectroscopy information in a feedback mode. Mashburn notes that he plans to add this capability to his advanced laser ablation system because "it tells you if your process has unintentionally changed and needs correction."

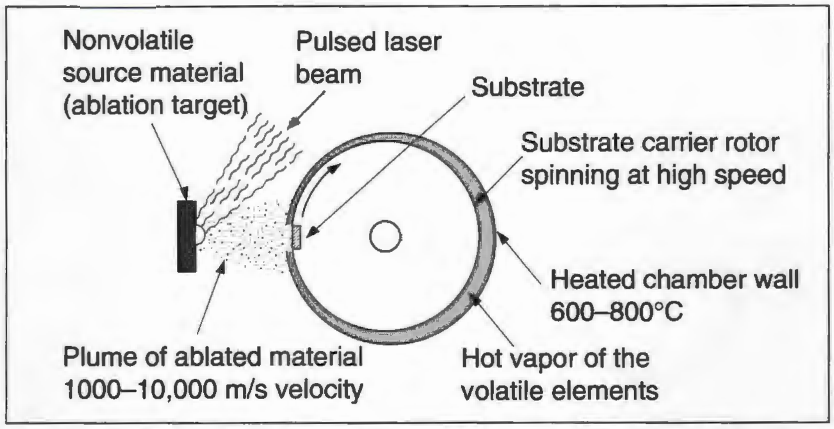
ICEPAC: Controlling Volatile Elements

A major problem with superconducting films is the volatility of their components. "When you heat YBCO in vacuum to a temperature above 450°C, the oxygen boils out, and the material degrades," Mashburn says. "Good growth of crystalline films requires a temperature over 700°C, which really exacerbates this effect." So far, in all high-quality YBCO film preparations, the oxygen has been diffused back into the film to reconstitute it after deposition. Unfortunately, diffusion of gases into films is done at much higher pressure (200–400 torr) than any physical deposition process can tolerate. The energy of deposition of ablated target material drops as gas pressure in the chamber rises.

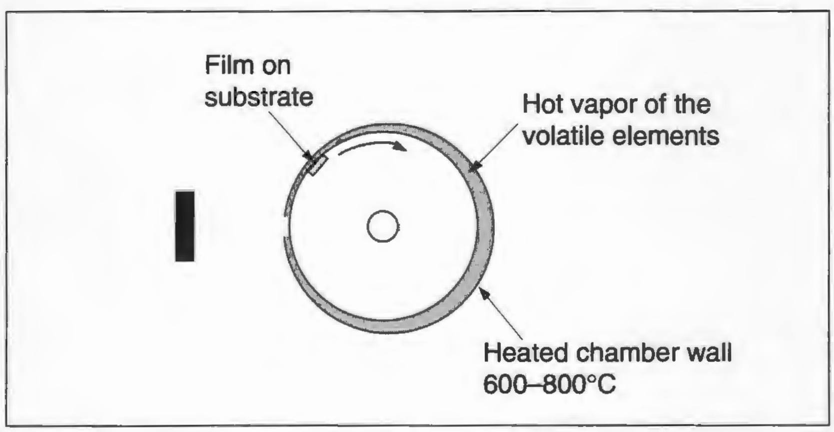
A similar but worse phenomenon affects the fabrication of films of thallium-based superconducting material. It has two volatile components—oxygen and thallium. Mashburn knew about this problem by 1988. It seemed impossible to solve.

"We needed low pressure for good film deposition," he says. "We needed high pressure for good crystal formation in the film. One condition seemed to exclude the other."

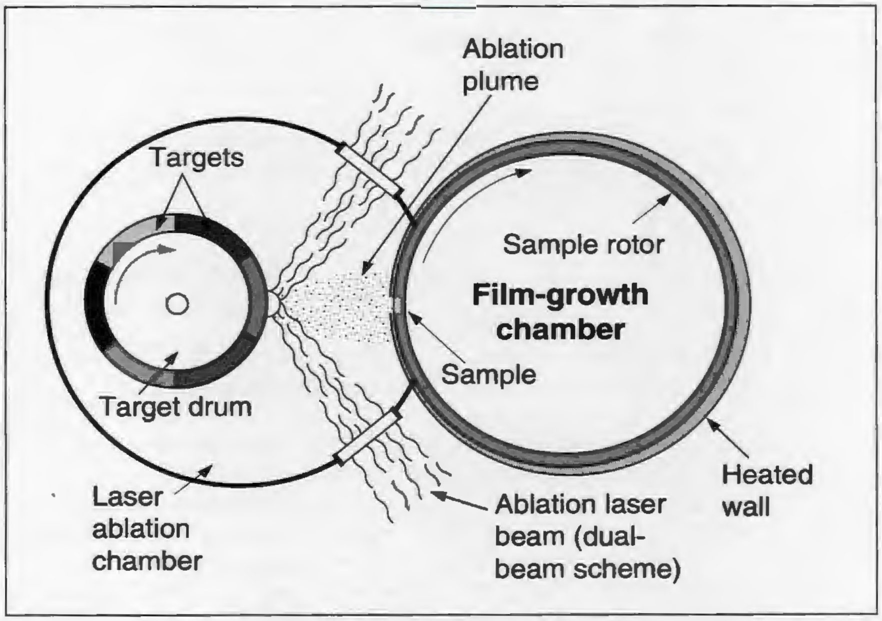
It took Mashburn three years to come up with a scheme that allows both low-pressure deposition and high-pressure growth of thin crystalline films to prevent their degradation. He called his invention "individually controlled environments for pulsed addition and crystallization" (ICEPAC). It accomplishes the impossible by taking advantage of the extremely quick nature of pulsed laser ablation. In their 1989 measurements he and Geohegan showed that the



Nonvolatile elements deposition phase: In ICEPAC, the substrate for growing the film is mounted facing outward on a rotor that spins inside a hot pressurized chamber whose wall has a small opening. Outside the opening is a laser ablation target of the desired film material. When the rotor turns and brings the film by the opening, the laser is fired, sending a high-velocity plume of ablated material through the opening to build up the film. The plume reaches the substrate in 10–30 microseconds, and the substrate takes 100 microseconds to cross the opening.



Volatile element condensation and film-ordering phase: In ICEPAC, the film has picked up a new layer of material from the ablation plume as shown in the above figure. Now it passes back into the hot vapor of the volatile element(s). It will spend much longer (0.01 to >1000 seconds) in this environment as it makes one or several revolutions of the chamber before receiving another ablation layer. Independently adjusting this time, the temperature, the vapor pressure of the volatile element(s), and the thickness of each ablated layer could greatly improve flexibility in the growth of compound materials.



Schematic of LARES, dual-beam chamber, and ICEPAC (individually controlled environments for pulsed addition and crystallization). In this scheme, dual laser beams in the LARES laser ablation chamber vaporize atoms from targets on the rotating LARES drum. The adjacent film-growth chamber is filled with volatile material, such as oxygen or arsenic gas, that is kept at a desired uniform temperature and pressure to facilitate film growth. The substrate on the furnace rotor revolves around the inside circumference of the chamber, passing a small opening each time. Nonvolatile material from the laser ablation chamber is deposited on the substrate just as it passes by the opening. The layer of atoms lining up on the substrate then reacts with gas in the film-growth chamber as it spins toward the opening again. The procedure is repeated many times.

intense material pulse in laser ablation lasted only about 20–30 microseconds but deposited as much material as an evaporator could in 1 second. Thus, laser ablation is at least 10,000 times faster than evaporation.

"By connecting a laser deposition chamber with a chamber for controlling film growth to prevent the escape of volatile elements, a film can do time sharing of two environments in a very unequal way," Mashburn says. "The film spends 99% of its formative life in the growth environment, visiting the deposition environment only 1% of the time. The heart of this concept is the maintenance of two widely different environments dynamically connected to rapidly and repeatedly exchange the film between them."

In this scheme, Mashburn combines an ICEPAC film-growth chamber with a LARES laser ablation chamber in which dual beams vaporize material from targets on a rotating drum for deposition on a revolving substrate (see figure). The chambers are physically distinct but dynamically connected. The ICEPAC film growth chamber is filled with the volatile material, such as oxygen gas, kept at a desired uniform temperature, pressure, and composition that facilitate film growth. The substrate, on which a film is to be deposited, is placed on a cylindrical rotor so that the surface of the film faces outward and is exposed to the inner wall of the ICEPAC chamber containing the rotor. The revolving substrate passes a small opening between both chambers every revolution.

At the instant when the film is in front of the opening, the laser is fired and a plume of nonvolatile material shoots through the opening to add a layer of atoms to the film. By adjustment of the ablation conditions, each additional layer can be varied in thickness from one atom to many atoms. The laser-deposited layers on the substrate react with gas in the ICEPAC chamber as the sample is carried around. The film sample is at the opening long enough for deposition of nonvolatile material; however, its presence there is too brief

(1% of the time) for a significant amount of the film's volatile elements to escape. The film sample is repeatedly and sequentially exposed at predetermined times to the material from both LARES and ICEPAC.

The dual-beam system is essential to operation of ICEPAC, Mashburn says, because it helps keep the plume aimed at the opening. Because the opening represents 1% of the ICEPAC chamber circumference, a fixed plume position is needed to ensure that the ablated material is deposited on the substrate.

"Current laser ablation practice uses thousands of pulses to grow typical films of a few hundred nanometers in thickness," Mashburn says. "Thus, there is ample opportunity to add evenly to the film volatile elements such as thallium or oxygen from their vapors in the film-growth chamber. A longer time for layer crystallization can be allowed by skipping the laser firing on the next revolution, or series of revolutions, of the rotor. This technique would permit the growth time for a 300-nanometer film to be varied from 10 seconds to many hours for research studies on film growth mechanisms. The ratio of volatile elements in the film can be changed by adjusting the partial pressures of those elements in the film-growth chamber."

Applications of New Laser Technology

Mashburn envisions using ICEPAC to make high-quality films of YBCO superconducting material of indefinite thicknesses. The maximum thickness of current films is about 5000 angstroms, or about 1000 atoms, thick (an atom is roughly 3 angstroms). He thinks he can make films 20 times thicker, forming a superconducting tape 1 centimeter wide that can carry 100 amperes and run a superconducting motor. He also believes he can make a 35-gram, 5-tesla superconducting "permanent" magnet the size of a flashlight battery for a superconducting motor. "Of course," he says, "you would have to keep it cold continuously or it would lose its magnetic field."

Manufacturers of advanced flat-panel displays for notebook computers, high-definition television, and other uses have begun exploring ways to employ Mashburn's laser ablation technology. OSRAM Sylvania and Planar Systems have asked him to conduct laser ablation experiments on phosphors to make them more suitable for application to flat-panel displays. "In one case," he says, "we plan to use LARES to construct a brand new phosphor material—an artificial material made by multilayering. If this fabrication method is successful, it could revolutionize the lighting industry as well as the display industry." Two CRADA proposals in this area have been submitted and more are in process.

If this fabrication method is successful, it could revolutionize the lighting industry as well as the display industry.

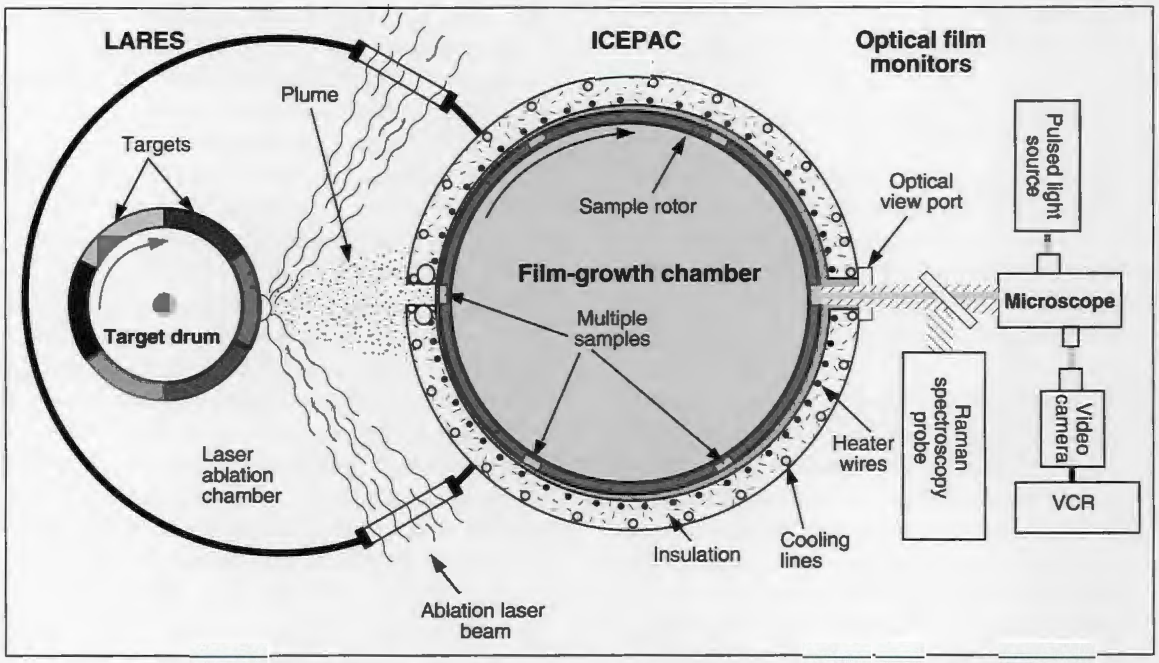
A small startup company, which makes super-sensitive charge-coupled device (CCD) sensors for astronomical telescopes, is considering using LARES to fabricate its CCD sensors. Finally, an established semiconductor fabrication equipment supplier is also considering the potential of LARES to meet its needs.

Materials Workstation: 21st-Century Tool?

Energy Systems has applied for patents on the three Mashburn laser technologies because they show promise for industrial applications. In addition to their potential for making materials for flat-panel displays, compact rechargeable batteries, special semiconducting devices, and superconducting wires, these technologies may be a source of brand new materials.

Some 4000 known inorganic materials exist in the world. Most of these are made by wet chemistry or some variation of mixing elements together and heating them up. The problem with the latter approach is that some materials that might be possible are never recovered because certain elements are segregated out during the heating process.

Mashburn has conceived of a "materials workstation" that would combine LARES, the dual-beam scheme, and ICEPAC. "Such a setup" he claims, "will open the doors for the exploration and discovery of many new materials, perhaps as many as 100,000." These materials could be made one layer of atoms at a time. Such artificially layered materials could include new multilayered



This artificial materials synthesizer, or "materials workstation," combines LARES, the dual-beam scheme, and ICEPAC. This concept enables the exploration and discovery of many new materials, perhaps as many as 100,000, fabricated one layer of atoms at a time. It incorporates noninvasive technology, such as a miocroscope, video camera, videocassette recorder, and Raman spectroscopy system, to directly monitor a crystalline film of new material as it grows. From the spectroscopic results, an artificial intelligence program would "learn" the compositional and structural features that make a good film . The program could guide researchers in producing new stable materials that possess desired properties.

structures called superlattices, which have special properties for electronic and photonic applications.

One of the goals of ORNL in carrying out DOE's high-performance computing and communications initiative is to make the massive number of complex calculations required to design new alloys and other materials. "If the researchers at the Laboratory's Center for Computer Sciences calculate that a new, presumably complex, material would be stable once formed and might have desirable properties, such as superconductivity," Mashburn says, "we could use such a materials workstation to rather quickly construct the material as a thin film."

For such a sophisticated materials workstation, Mashburn would incorporate noninvasive technology (such as Raman spectroscopy) to directly monitor the film as it grows (see figure on this page). He might also add an artificial intelligence program that would "learn" the compositional and structural features that make a good film from the spectroscopic results. The program could guide the researchers in producing new stable materials that possess the desired properties.

Already, Mashburn has met the challenge of turning his concepts into actual working devices, refined versions of which may be designed and built. If sufficient funding is available, the world may someday learn of promising new materials that exceed our dreams and are made in Mashburn's laser machine.

From Fire to Laser Ablation: Routes to New Compounds

Lightning strikes a tree on a cold night in Indonesia almost 2 million years ago. Several branches burst into flames. A few fall burning to the ground. A shivering ape-man (*Homo erectus*) bravely picks up a branch burning at one end. He basks in its heat until he burns himself and screams in pain. Man has discovered fire.

Thousands of years later, women cook meat in clay pots suspended over fire. Humans have learned to use fire not only to cook but also to harden clay into pots, giving rise to the pottery industry. Thousands more years pass. A new use for fire has been found: extracting copper from rocks. The age of metals is born.

What do these examples from prehistory and early recorded history show? According to ORNL's Doug Mashburn, "The combination of a materials processing technique, such as fire, and accessible materials, such as clay and rock, spawns new industries, such as potterymaking and metalworking. Such technological advances proceed in a cyclical synergistic fashion."

"New industries arise from the use of newly discovered or invented processing methods and newly discovered accessible materials. As each industry grows, it hones the process, makes the new materials widely available, and eventually enables the next cycle. Each cycle significantly expands the range of materials accessible."

Fast forward to the inventions of mechanical power and precision rotating machinery in the 19th century. These innovations, Mashburn says, were enabled by the existence of a well-developed metals-processing industry. The harnessing of electricity was made possible by the existence of industries to produce and shape copper and iron into wires, magnets, and other components. The inventions of the dynamo for generating electricity and the electric motor for using it depended upon the precision rotating machinery industry, which was made possible by the availability of affordable and appropriate metals.

A significant jump in materials access came with the combination of electricity and vacuum. "Practical use of vacuum depended on both precision machinery and mechanical power," Mashburn says. "Invention of the hot filament electric light was enabled by the harnessing of vacuum and electricity. The combination of vacuum and electricity in the form of an electron beam opened up possibilities of discovering and accessing many new materials, such as refractory metals, superalloys, refractory ceramics, and large pure crystals."

Electricity and vacuum together have also made possible the evaporation and deposition of material as optical films for high-performance mirrors, lenses, and windows. These new optical components enabled the invention and development of the laser. A unique materials-processing tool, quite different from fire or electricity, the laser is still being perfected and folded into industry.

The invention of the pulsed laser has enabled laser ablation deposition, an extremely versatile processing technique. "Because of its ability to 'boil off' atoms and rapidly assemble them into thin films," Mashburn says, "laser ablation opens the door for a quantum leap in materials access."

According to the *Handbook of Chemistry and Physics*, 4000 inorganic compounds are available in more than microscopic quantities today. These materials can be made by using traditional processing technologies, mainly heating, which segregates out some elements rather than incorporating them into the structure of materials.

"Because laser ablation removes so many processing limitations, we can now contemplate the synthesis of previously impossible compounds," Mashburn says. "By combining oxides of the 60 different metallic elements in groups of three, simple math shows that the possibilities exceed 100,000 compounds. If we consider more complex combinations of more than three elements, such as the high-temperature superconducting yttrium-barium-copper oxide, the possibilities are far greater. And then if we consider such combinations of metals with fluorine, sulfur, chlorine, and so on, it is clear that the 4000 existing compounds make up only a tiny corner of the huge continent of possibilities. How many more complex materials as exciting as the new superconductors are still awaiting discovery?"

The laser ablation technique, already showing distinct promise for such an exploration, is in its infancy. Mashburn expects that new advances—including his own innovations—will improve lasers, ablation chamber designs, the physics and control of the ablation process, and monitoring of both the ablation process and the deposited material.

Just as a lightning strike may have sparked the discovery of fire, a laser beam striking a target could launch the discovery of astounding new materials—and the creation of whole new industries.—*Carolyn Krause* ornl

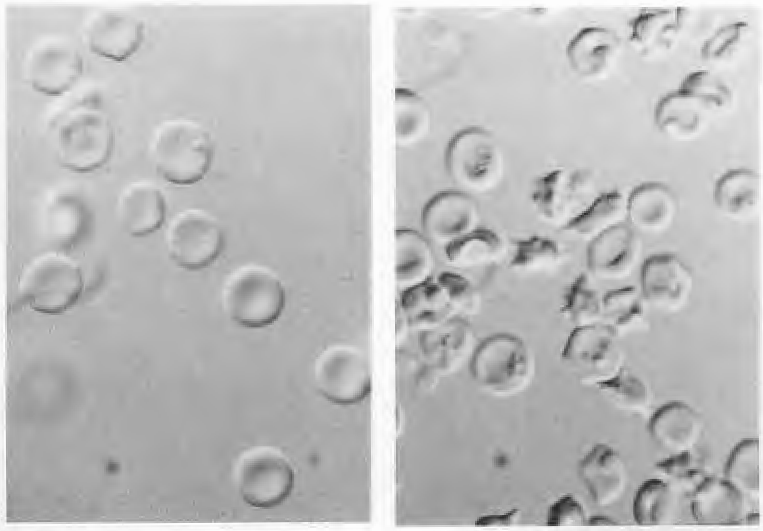
Mice and Men: Making the Most of Our Similarities

By Jim Pearce

Because a big chunk of the genetic information that goes into building a mouse is also needed to put together a human, mice are often employed in the laboratory as our genetic stunt doubles. In fact, the similarities between sections of human and mouse DNA enable researchers working with mouse genes to make surprisingly accurate predictions about the location and function of their human counterparts.

For over 40 years, ORNL researchers have been studying the nuances of the genetic relationship between mice and humans, sometimes with considerable fanfare, other times in relative obscurity, but always with the goals of increasing our understanding of the subtle language of genetics and improving human lives.

Some of the Laboratory's latest research in this area is described in this article.



Unlike normal red blood cells (left), cells having sickle-cell hemoglobin (right) become stiff and distorted, blocking blood vessels and limiting oxygen to muscles and other tissues.

Building a Better Mouse Model for Sickle-Cell Disease

"Often, things don't turn out as beautifully as you expect," says ORNL biologist Ray Popp describing the trials of research in the emerging field of genetic engineering. It also explains his excitement over the success his group has had in "building" a breed of mouse to serve as a proving ground for the treatment of sickle-cell disease in humans.

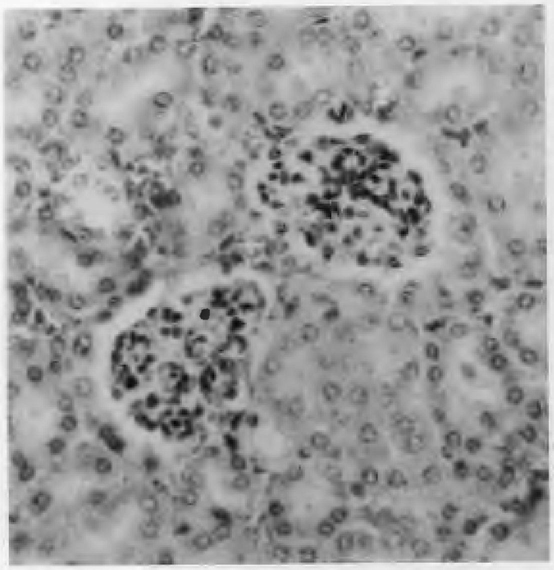
Affecting about 100,000 Americans with roots in Africa, India, and the Middle East, the sickle-cell gene is thought to have prevailed over the normal form of the gene because it provides a defense against another scourge—malaria, a mosquito-borne disease common to equatorial regions. Inheriting the gene from one parent provides an individual with some resistance to malaria, while inheriting the gene from both parents results in sickle-cell disease.

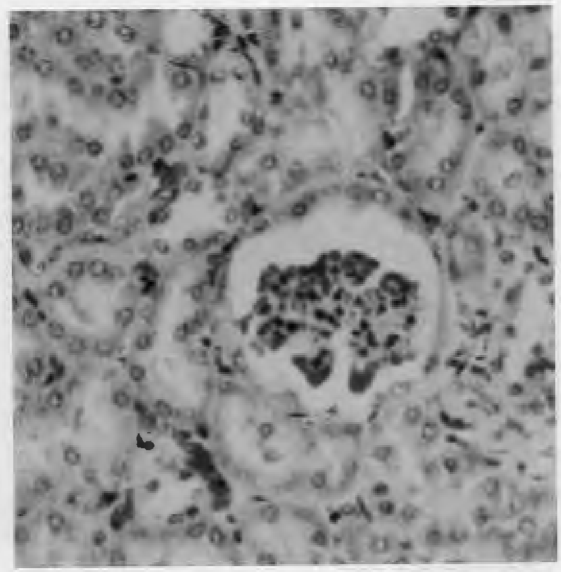
The sickle-cell disease affects the body's hemoglobin—the substance red blood cells use to absorb oxygen from the air breathed into the lungs and distribute it to the rest of the body. When hemoglobin gives up its oxygen, it becomes deoxyhemoglobin. In the blood of sickle-cell patients, deoxyhemoglobin is less soluble than its normal counterpart and causes the red blood cells to twist into stiff, sickle-like shapes.

"This condition has the effect of pouring irregular rocks, instead of marbles, through a small pipe," says Popp. "The distorted cells tend to block up the blood vessels." When this happens, muscles and other tissues around the blockage don't get enough oxygen, and outward signs of a condition called sickle-cell crisis occur. These signs include ulcers on the skin in the area of the blocked vessels and deterioration of the

Popp and his group set out to build a model of human sickle-cell disease in the mouse.

ORNL scientist Ray Popp and his research team have genetically engineered mice to produce a mixture of human and mouse sickle-cell hemoglobin.





In normal kidney tissue (left), tufts of capillaries in the kidneys, called glomeruli, allow waste products like urea and ammonia to be filtered out of the blood. In mice with sickle-cell disease, malformed cells clog these capillaries, causing them to rupture and decreasing kidney function by 25 to 50%.

The mutation created a mouse hemoglobin that could be used to approximate human sickle cell disease.

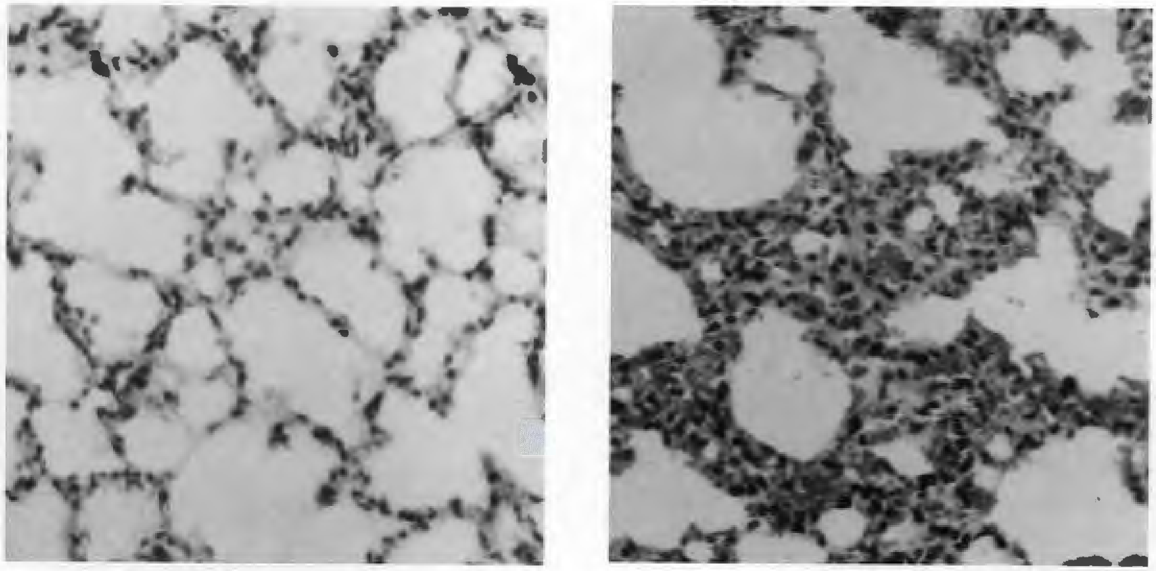
kidneys, lungs, liver, and the retina of the eye. In fact, older sickle-cell patients often go blind.

Over time these blockages cause small blood vessels of the kidneys to rupture, decreasing kidney function by 25 to 50%, and slowly poisoning the body with accumulated waste products. Similarly, sickle cells accumulate in the small capillaries of the lungs' air sacs, causing them to repeatedly break and heal. This process can build up scar tissue through as much as two-thirds of the lung, interfering with the efficient exchange of oxygen between the lungs and the blood. The leakage of blood into the lungs and back into the blood vessels can also lead to infections like pneumonia from contaminants being passed from air in the lung into the blood.

Hoping to help alleviate some of the hardships brought about by this debilitating disease, Popp and his group set out to build a mouse model of human sickle-cell disease to use for testing drugs that interfere with the sickling process. These compounds can't be thoroughly evaluated on blood samples because samples don't allow researchers to look at side effects on other parts of the body. "That's why we need to have a whole animal to test," notes Popp, "not just blood in a test tube."

The first step toward the goal of producing a mouse model for this disease was taken about 10 years ago when researchers found they could transfer a human sickle-cell gene known as *beta S* into a line of mice and have the mice produce human hemoglobin. Unfortunately, these mice exhibit the sickling trait only when their oxygen intake is reduced, as it occasionally is when the mice are tested in a special chamber with a controlled, low-oxygen atmosphere. The mice can be kept in this environment for a couple of weeks, but they can't be maintained or bred under these conditions.

The next step was taken when Popp's group was doing research for DOE on the mutagenic effects of chemicals and radiation on genes that control the production of mouse proteins, including mouse hemoglobin. One of the changes they created caused the resulting mouse hemoglobin to have a high affinity for oxygen, a characteristic of normal human hemoglobin. "We suspected," says Popp, "that the changes that had occurred as a result of the mutation had created a



Capillaries in the air sacs of the lungs can be blocked and ruptured by sickle cells, building up scar tissue through as much as two-thirds of the lungs, interfering with oxygen exchange between the lungs and the blood, and creating an ideal environment for infections like pneumonia.

"Exactly what we predicted occurred—it's rewarding that it worked out that way."

mouse hemoglobin that could be used to develop a mouse model for human sickle cell disease."

As these animals were developed, Popp and his colleagues found that if they crossed the *beta S* mice with normal mice, the red blood cells of their offspring were normal. However, as Popp suspected, if they were crossed with mice having altered hemoglobin, the next generation would have elongated cells or cells with spurs, a less-pronounced form of sickling. This sickling isn't as extensive as it is in human red cells because the mouse produces a mixture of mouse and human sickle-cell hemoglobin, and usually, only the human portion of the hemoglobin sickles. Also, like humans with sickle-cell disease, these mice suffer from anemia—an abnormally low number of red blood cells—although the mouse anemia is not as severe as that noted in humans.

"It's not perfect," says Popp, "but it's a model in which there is expression of the sickling phenomenon under normal conditions. We don't have to place these mice in a reduced-oxygen environment to induce the effect."

Despite these successes, Popp is clearly not laboring under the illusion that this model of sickle-cell disease in humans cannot be improved. "It would be ideal if one could produce 100% human hemoglobin inside the red blood cell of the mouse," he says. "In this mouse, we have combined mutations that favor sickling and production of a relatively large amount of sickle-cell hemoglobin. Unless someone can replace essentially all of the mouse hemoglobin with human sickle-cell hemoglobin, all animal models of sickle-cell disease still have the problem of the mixture of hemoglobins, which interferes with the sickling phenomenon."

Popp's current research is funded by a grant from the National Institutes of Health, and he is hoping to get further funding to test the effectiveness of compounds designed to combat sickle-cell disease in humans on these genetically engineered mice.

Meanwhile, work on improving the model continues. It's been three years since researchers began crossbreeding these mice, but only in this past year has the sickling begun to be expressed with regularity. Some mice express the sickling problem more severely than others because the sickle-cell trait shows up better on some genetic backgrounds than others.

"It takes about 20 generations, or about 6 or 7 years, for the sickle-cell trait to be bred into a new strain of mice and the population to become genetically inbred," says Popp. A new strain of sickle-cell mice could be used to test preventive drug therapies, which may eventually prove useful for treating sickle-cell disease in humans.

"It's true genetic engineering when you design an experiment based on what you know about human genes and put them in mice having the right genetic characteristics to maximize their expression," says Popp. "Our contribution to the field was to put human *beta S* hemoglobin on a background which favored expression of the sickle-cell trait.

"Exactly what we predicted occurred—it's rewarding that it worked out that way."

Closing in on Mouse Diabetes and Obesity at the Molecular Level

Can a bunch of fat, yellow mice help uncover the genetic roots of diabetes?

Can a bunch of fat, yellow mice help uncover the genetic roots of diabetes, tumor development, and obesity? Rick Woychik of ORNL's Biology Division thinks it's an intriguing possibility.

The straw-colored rodents in Woychik's laboratory possess a mutant form of the "agouti" gene, whose location was recently pinpointed by a team of researchers from ORNL and the University of Tennessee. The agouti gene, named after a large, South American rodent, is normally responsible for the grizzled coat color of wild mice, which results from the combination of black (or brown) and yellow areas on each hair. But mutant forms of the gene can cause animals to have not only yellow coats, but also diabetes, obesity, and tumors. The genetic variations that cause these effects are referred to as "obese yellow" mutations.

Researchers are most interested in the inability of obese yellow mice to effectively use insulin—a hormone produced by the pancreas to process sugar and other carbohydrates. This biochemical shortcoming is also characteristic of Type II, or non-insulin–dependent, diabetes in humans. This form of diabetes affects one of every 20 Americans, producing symptoms ranging from blurred vision to chronic infections and fatigue. Unlike Type I diabetes, which is potentially deadly and far less common, the non-insulin–dependent form of the disease does not result from a lack of insulin. Instead, it stems from the body's inability to use insulin efficiently.

"There are many instances where people have produced diabetic mice by genetically knocking out the insulin-producing cells of the pancreas," says ORNL researcher Rick Woychik. "The reason for this type of diabetes is quite straightforward—the mice are unable to produce insulin—period. Those animals are valuable for certain things, but they don't tell you much about the mechanisms of the Type II form of the disease."

The obese, yellow mice, on the other hand, start developing a diabetes-like condition and obesity when they are just out of adolescence—at about 4 to 5 weeks old. These animals still produce insulin. In fact, to maintain normal blood sugar, they produce a lot more than normal mice—but they can't use it as efficiently."

The ORNL-UT team was successful in both isolating the agouti gene from the rest of the mouse's DNA and in cloning it. Cloning the gene involves inserting it into a bacterium where it is copied over and over as the bacterium reproduces. This process provides a relatively large quantity of the gene, enabling researchers to study them in minute detail.

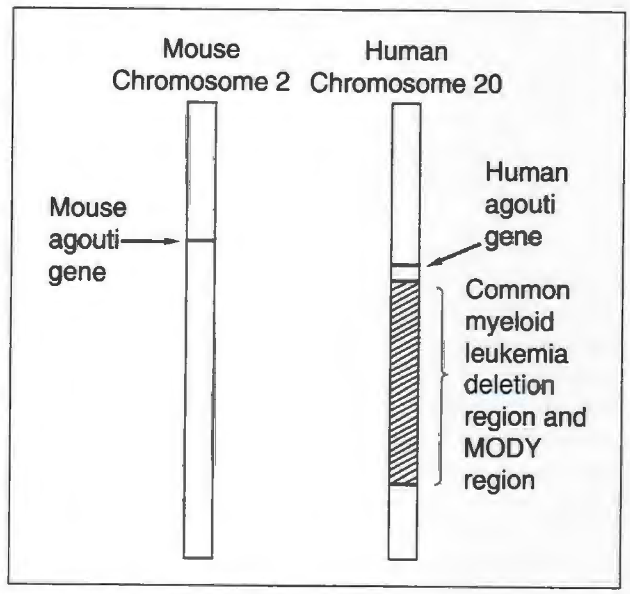
Although this latest work breaks new ground, the Laboratory is no stranger to the agouti gene. For years, ORNL genetics pioneers Bill and Liane Russell have studied the effects of radiation and chemicals on the gene. "Based on their work," says Woychik, "we know quite a bit about how damaging or deleting the agouti gene affects the animal."

It appeared that the agouti gene was unusually complex, accounting, in part, for the 16 different classes of mutations it produces. For example, inactivating the gene or deleting it entirely results in a totally black mouse because the protein that is supposed to be produced by the gene in the mouse's skin is missing. This deficiency causes a breakdown of the normal molecular communication of the gene with the melanocytes, or pigment-producing cells, and, in the absence of other instructions, they produce only black pigment. Another mutation produces two-tone mice, black on their backs because the agouti gene is not activated in this area and tan on their bellies because the gene is overactivated in this region. Obese, yellow mice are entirely yellow because, in this mutation, the agouti gene has been changed in a way that causes it to be overabundant when attached to part of another gene, causing the protein produced by the gene to be drastically overproduced in their skin and also in other tissues and organs where it normally doesn't occur.

Because there are so many different mutations of the agouti gene, it was thought for years that these differences were the result of interactions among a complex family of genes, or one gene that behaved in a variety of different ways under different circumstances. "So, for example," says Woychik, "it was thought that black-and-tan mice resulted, perhaps, from one agouti gene that regulated coat color on the back and another that controlled coat color on the belly. We have now discovered that agouti is a relatively simple gene, although it does have different regulatory regions that normally function in different areas of the skin."

Of the 16 varieties of the agouti gene, the mutation linked most closely to these health effects is known as "Lethal Yellow." This mutation, which was described by the French geneticist Cuenot in 1905, is a recessive embryonic lethal mutation—meaning that, if a mouse inherits the Lethal Yellow gene from both parents, it will die before it is born. On the other hand, if a mouse inherits the mutant gene from only one parent and a normal

Four variations on the agouti theme: (top) a brown mouse with no agouti mutation, (right) a black mouse showing the effects of deleting the agouti gene entirely, (bottom) a two-tone agouti variation known as black and tan, and (left) a mouse with the "Lethal Yellow" mutation.



ORNL researchers have determined that human and mouse agouti genes are 85% identical. Deletions in the region of the mouse agouti gene can cause a non-insulin-dependent diabetes-like condition, as well as obesity and tumor development. The human agouti gene is contained on a portion of chromosome 20 that is closely linked to the development of mature onset diabetes of the young (MODY), a suspected cause of non-insulin-development diabetes. The region is also linked to the development of myeloid leukemia.

Researchers are interested in the inability of these mice to effectively use insulin.

Understanding the agouti gene may provide keys to understanding diabetes, obesity, and the growth of tumors.

gene from the other, it will develop the yellow hair and health problems described previously.

"The other reason this is so exciting," Woychik continues, "is that, although the Lethal Yellow mutation was the first lethal mutation ever characterized in the mouse, no one had any idea of the biochemical nature of the mutation or which gene was responsible." Now that Woychik and his team have uncovered the structure of the gene, they are beginning to understand, at the molecular level, why it can have such a devastating effect."

Woychik believes that the real story behind the lethal yellow mutation unfolds something like this: In normal mice, there are two genes sitting next to each other—one that appears to regulate how genetic information is copied during the early stages of embryonic development, and the agouti gene, which controls hair color. These genes normally don't interact, but, in Lethal Yellow mice, a large deletion causes the regulatory portion of the development gene to be moved closer to the agouti gene. This arrangement puts the agouti gene under the control of the development gene's regulating signals, which are normally activated throughout the body. As a result, the protein produced by the agouti gene also appears throughout the body.

Just as the absence of the gene's protein is thought to interrupt communication with pigment-producing cells in the skin of black mice, its presence in places where it should not be may also interfere with normal intercellular molecular communication in the liver, pancreas, skin, and breast of these animals, triggering the development of tumors. "The same thing may be true in adipose, or fatty, tissue," says Woychik. "Normally, after adolescence, the production of fat tapers off, but not in mice having one of the Obese Yellow mutations. We think the presence of the agouti protein interferes with the normal signaling mechanisms that tell adipose tissues to stop producing fat molecules."

Similarly, Woychik speculates that the mutant expression of agouti in muscle tissue in these mice is responsible for their resistance to absorbing insulin. "In fact," he says, "it is known that obese people with a lot of body fat somehow become insulin-resistant in their muscle—and, if they lose weight, their insulin resistance improves."

Agouti isn't your standard coat-color gene. This characteristic is primarily regulated by several other genes acting in the color-producing cells called melanocytes. Agouti, on the other hand, is not expressed in the pigment-producing cells, but in the neighborhood of the hair follicles, and it is somehow communicating with the melanocytes to tell them to produce black or yellow pigments. "So, at the level of cell biology," Woychik says, "agouti is not just a pigmentation gene. It also provides an insight into how cells communicate with each other."

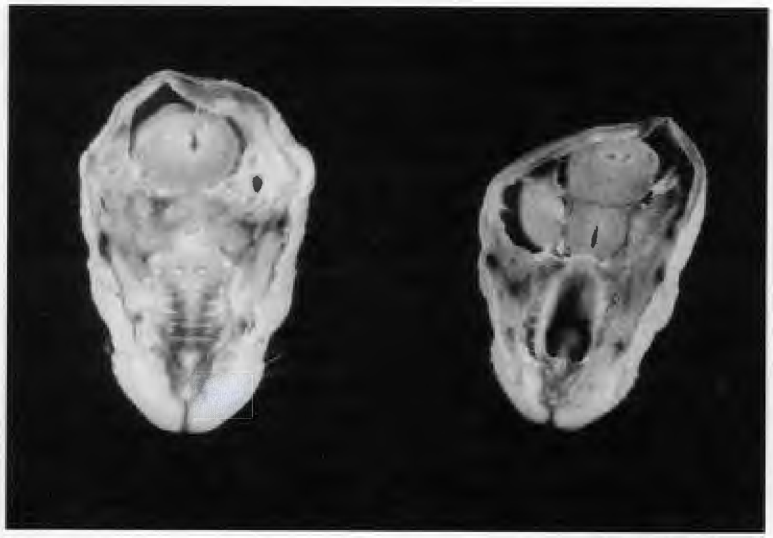
So, given all of these intriguing findings, is the research team ready to pack up and move on to other projects? Hardly.

Woychik still has plenty of questions he wants answered: "Can we express the agouti gene specifically within muscle and induce the type II diabetes without the obesity?" he wonders. "And can we induce the obesity without the diabetes by only expressing agouti in adipose tissue? Moreover, can we express the gene in liver specifically and induce the liver tumors without the obesity and without the diabetes?" Affirmative answers to these questions would enable researchers to begin to understand cellular signaling mechanisms in these tissues and how they cause some cells to form tumors.

To accomplish this goal, Woychik and his team will build DNA constructs—variations on the agouti gene with specific instructions for where the gene should be expressed. These constructs will then be introduced into fertilized mouse eggs, producing genetically engineered, or "transgenic," offspring.

"If we make a transgenic mouse with the normal agouti gene," says Woychik, "the gene would be expressed only in the skin because there are regulatory elements associated with the gene that tell it to behave that way. What we are going to do is trick the gene into being expressed in the liver, for example, by building a construct that connects the DNA sequences that control expression of genes in the liver to the agouti gene. Then we'll use that construct to make transgenic mice in which the agouti gene product is expressed only in their livers."

The problems created when the agouti gene shows up in too great a quantity or in places where it shouldn't be at all continue to drive this research effort. "This is an important research area," says Woychik. "Understanding the agouti gene and the consequences of its overexpression may provide keys to understanding human health problems like diabetes, obesity, and the growth of tumors, as well as giving us insights into how communication among cells occurs."



The results of having or not having the *cp1* gene: The palate on the left is normal and the palate on the right is only partially formed because of a missing *cp1* gene.

Researchers have demonstrated that the protein the gene produces prevents cleft palates in mice.

Tracking Down the Cleft Palate Gene

One of the areas of DNA that mice and humans have in common is located on chromosome 7 in the mouse and chromosome 15 in humans. This region first came to the attention of researchers because it contains one of the genes responsible for determining the color of a mouse's coat, making genetic alterations in the area easy to track.

Over the years, researchers have employed chemicals and radiation to remove dozens of different pieces of DNA from this region in an effort to isolate and study the coat-color gene, as well as other genes located nearby. An unexpected effect of these deletions was that some of the genetically altered offspring developed cleft palates in addition to their coat-color changes, suggesting that a gene involved with forming palates was also in the neighborhood.

By reviewing the results of previous research on this area of mouse chromosome 7 and selectively causing and studying other mutations in the area, members of the Mammalian Genetics and Development Section, including group leader Dabney Johnson, have isolated a gene that is at least partly responsible for the development of normal palates. They have demonstrated that the protein it produces prevents cleft palates—a birth defect in which the roof of the mouth fails to develop completely.

This gene, known as *cp1*, produces a protein previously thought to function only in the brain, where it acts as part of a neurological inhibitor—moderating brain activity by keeping neurons from constantly firing. However, during palate devlopment, the protein steps outside this role to contribute to the process of making normal palates. "We checked the pharmacology literature," says Johnson, "and we found that people had known for years that exposing pregnant rats, and their developing embryos, to valium and related neurodepressors could result in offspring having cleft palates. To prove that they had indeed isolated a gene that played a crucial role in the production of normal palates, Johnson and her staff used a technique known as "phenotype rescue" to inject normal copies of the gene into fertilized eggs of mice that carry the defective palate gene. Some of these normal genes succeed in taking over the function of the

The situation may be more complex in humans, but the genetic similarity is very strong.

defective genes, resulting in offspring that have normal palates. As a result, the newborn mice, which would otherwise die within a day presumably because they suck milk up into their lungs and drown, are "rescued" from the lethal effects of the cleft palate.

Phenotype rescue experiments are by no means foolproof. Sometimes the inserted gene doesn't make any of the product it's supposed to—or it may make too much, too little, at the wrong time, or in the wrong place. In the case of this cleft palate gene, however, results of these experiments support the contention that the *cp1* gene is critical to palate formation.

"This gene is just a small part of the complex developmental process involved in forming a palate," says Johnson. One in 100 of the mice that have the faulty palate gene still manages to form a normal palate, but these mice exhibit neuromuscular nervousness, they are small, and they usually survive for a only few weeks. Even mice that develop from fertilized eggs that have been fixed by adding a normal gene are still small, although they don't show the same nervousness.

Johnson believes that these mice have more problems than just a damaged *cp1* gene. "We think there may be another missing or damaged gene that only shows up when the mice survive the palate problem, she says."

Johnson and her group are looking forward to using the knowledge they've gained from isolating the *cp1* gene to find other genes involved in the palate formation process by studying groups of mice that are genetically very similar except for the *cp1* gene.

"It is almost never just one gene that does a complex job, like palate formation," Johnson says. "It always seems to be a cascade of genes, so when one gene is missing, the cascade is interrupted and the end product is abnormal."

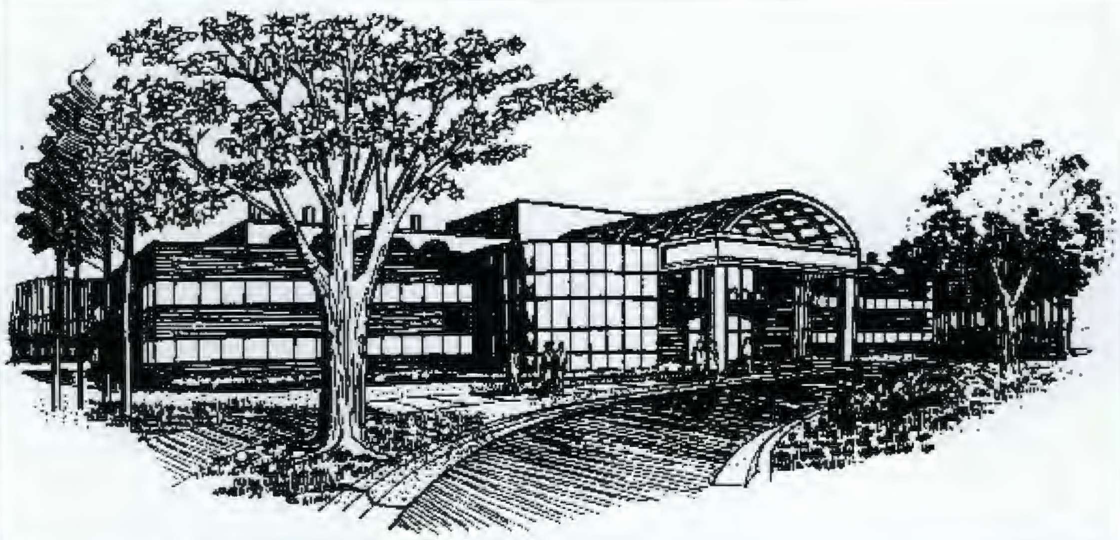
Johnson and her group will have ample opportunity to explore the nuances of the *cp1* gene thanks to a three-year grant from the National Institutes of Health supporting their research. This bodes well for determining the cause of cleft palates in humans. "Mouse mutations that resemble classic human birth defects get people's attention," Johnson says. "People have looked at cleft palates for years and never found evidence that a single gene was responsible for the condition. The situation may be more complex in humans, but the genetic similarity between the regions of mouse and human chromosomes is very strong.

"This is a recessive gene that works in classic Mendelian fashion," she continues. "It must be missing in both parents to cause a cleft palate, and when you replace the gene, the cleft palate goes away. This finding suggests that the *cp1* gene alone can correct the defect—there is no other gene missing from the deleted region of mouse chromosome 7 that is involved in palate formation. If we can prove this result experimentally, it will be very exciting."

Conclusion

At the genetic level, mice and men share much more than a passing resemblance, as these efforts to unearth the genetic roots of sickle-cell disease, diabetes, and cleft palate demonstrate. For almost half a century, ORNL scientists have cultivated this similarity to provide a living model for the structure, the rhythm, and the functioning and malfunctioning of the genetic engine that powers the human species.

More and more frequently, these efforts are yielding insights into the genetic causes of human disease and holding out the promise of treatments or even cures for these ailments in the not-to-distant future.



The Center for Biological Sciences

The Biology Division looks forward to moving into a 250,000-square-foot building that will have modern laboratories specifically designed for biological research. It will accommodate working arrangements for the single researcher or for large groups. The center will house the very extensive mouse colony, and, in separate, isolated quarters, a facility for sensitive transgenic or immune-deficient mice. X-ray crystallography, flow cytometry, electron microscopy, computer workstations, and other facilities will be accommodated with easy access to the laboratories. The biology library and conference rooms will be in the same building, as will the offices and classrooms of the ORNL–University of Tennessee Graduate School of Biomedical Sciences.

In the immediate neighborhood of the building will be the current Environmental Sciences Division buildings, and, not far away, the anticipated Advanced Neutron Source, with facilities specifically dedicated to analyzing biological materials. Within easy walking distance will be other basic science divisions like Health Sciences Research (including Nuclear Medicine), Chemical and Analytical Sciences, Physics, Solid State Physics, Engineering Physics and Mathematics, Instrumentation and Controls, and the new Center for Computational Sciences.

The Center for Biological Sciences will be readily accessible to visitors and guest users—and ready to move into the 21st century.

Altered Growth Factors: Tools in Cancer Research

A stylized view of the structure of EGF. The arrows point in the direction in which the molecule is synthesized. The joined spheres are sulfur-sulfur bonds that help give the molecule its shape.

Researchers are looking at modifying proteins called growth factors to slow or stop cancer's progress.

One of the hallmarks of cancer cells is their uncontrolled growth. So, hoping to find a way to rein in this behavior, researchers are looking at modifying proteins called growth factors—molecules that trigger the process of cellular reproduction—to slow or stop cancer's progress.

One of these molecules is epidermal growth factor, or EGF. As its name suggests, EGF was first found in skin cells, but it works in a variety of tissues throughout the body. Because it promotes cell growth, EGF has been used to speed the healing of severe burns, stomach ulcers, and the lens of the eye after cataract surgery.

In 1986 ORNL researcher Salil Niyogi and his colleagues in the Biology Division cloned the gene for human EGF. Their aim was, and still is, to better understand the structure and function of EGF by studying the effects of minor variations in the sequence of amino acids that make up the EGF protein. Some of these altered, or mutant, forms of EGF could be useful in preventing normal EGF from fulfilling its role as the "on" switch for cellular reproduction—serving instead as "off" switches for cancer growth.

To determine which amino acids to change, Niyogi and his team look at several different aspects. Because EGF is shared, with some variations, among many species, researchers studying the similarities and differences in the structure of these molecules can begin to identify points along human EGF's amino acid sequence at which changes could make a critical difference.

Another way of locating promising sites for changes is to examine the structure of the molecule as revealed by nuclear magnetic resonance (NMR) studies—the same type of technique used for medical imaging in many hospitals. In fact, a diagram of the structure of EGF based on collaborative studies between ORNL and Rutgers University recently appeared on the cover of the British journal *Protein Engineering*.

Drawing on this information and experience with other proteins, researchers can determine the steps the cell goes through in building an EGF molecule and many of the critical junctures in that process. "Look at the antiparallel beta sheet structure," Niyogi says, tracing one of the

Human EGF	NSDSECPLSHDGYCLHDGVCMYIEALDKYACNCVVGYIGERCQYRDLKWWELR
Mouse EGF	NSYPGCPSSYDGYCLNGGVCMHIESLDSYTCNCVIGYSGDRCQTRDLRWWELR
Rat EGF	NSNTGCPPSYDGYCLNGGVCMYVESVDRYVCNCVIGYIGERCQHRDLR
Guinea Pig EGF	QDAPGCPPSHDGYCLHGGVCMHIESLNTYACNCVIGYVGERCEHQDLDLWE

Shared Amino Acids

Aligned amino acid sequences of EGF in different species. Each letter represents one of the amino acids that make up proteins. The shaded areas of the EGF protein are quite similar across several species and are of particular interest to researchers.

crooked horseshoe shapes on a diagram of the EGF molecule. "These structures at either end of the linear molecule are quite close together in the EGF-like molecules of many species, suggesting that both the shape of the molecule and the composition of these structures are important enough to be conserved."

Once they have altered the composition of the EGF gene, Niyogi and his team measure the performance of the protein it produces. "We measure function by first measuring how well EGF binds to its protein receptor on the cell membrane," Niyogi says. "Once the molecule binds to the receptor, it transmits a biochemical signal to the inside of the cell. This signal, known as the protein-tyrosine kinase reaction, begins a series of biochemical reactions—a cascade turns on—leading to the synthesis of DNA, RNA, and protein and, finally, to cell division." Niyogi stresses that this entire process is started by the binding of EGF to the receptor on the cell membrane, telling the cell it's time to grow and divide. If the EGF molecule fails to bind to the receptor, or if it fails to send the necessary signal to the cell, the cell will not reproduce.

Six major sites are involved in binding EGF to its receptor. When Niyogi's team makes a change in the protein, they look at the effects of the change on both EGF's structure and its ability to bind to its receptor. The structural work has been done in collaboration with Guy Montelione of Rutgers University. "He's a protein structure person and one of the first to determine the structure of EGF," says Niyogi. Using NMR, this group has determined that, when substitutions are made for each of the amino acids at these six sites, the structure of the molecule is mostly unchanged. "Therefore," Niyogi says, "we believe that these sites are mostly functional, rather than structural."

To determine how these sites bind EGF to its receptors, Niyogi and his team created a series of double-site mutations by simultaneously replacing both amino acids at any two of the sites. They found that each site binds to the receptor independently. "Previous investigators thought that a particular site was the key," Niyogi says, "but the protein binds like a hand in a glove—all the fingers are important.

"Most of the time," he continues, "when you change an amino acid in a protein, nothing improves. You make it worse because you are tampering with Mother Nature." Despite this admonition, Niyogi and his colleagues have discovered a double-site mutation that results in an altered EGF protein that binds to its receptor twice as strongly as normal EGF.

Other intriguing EGF mutants produced at ORNL include molecules that, even when they occupy all of the EGF receptors, still do a poor job of stimulating the tyrosine kinase reaction that spurs cell growth. "It's like the car is running," says Niyogi, "but it can't get into high gear." Mutations like these competetively inhibit normal EGFs stimulation of the receptor's tyrosive kinase reaction and, therefore, could act as antigrowth substances by preventing normal EGF molecules from initiating cell growth. "These agents may be effective as growth inhibitors with a little more engineering to make them bind more strongly to cell receptors," Niyogi adds. "But we still have some basic research to do with normal and cancer cells before we can tell whether an EGF mutant might be able to control cancer."

Niyogi and his team think they have a good understanding of how EGF interacts with its

"We still have some basic research to do with normal and cancer cells before we can tell whether an EGF mutant might be able to control cancer."

receptor and how to make EGF mutants that inhibit the chemical cascade that leads to cell growth. Their next goal is to produce cells with mutant receptors to learn how receptors work. "This would help us understand both how normal cell growth takes place,"says Niyogi, "and how things get out of control, resulting in a cancer."

Niyogi is also quick to point out the invaluable contributions of his co-workers: the cloning of human EGF and its mutagenesis by Dave Engler and Risë Matsunami; elegant mutagenesis studies by Steve Campion, Doug Tadaki, and Krishnadas Nandagopal; fruitful collaborations with researchers in John Cook's laboratory, including cell culture studies by Melinda Hauser; and the scientific contribution of senior staff scientist Audrey Stevens, who mentored Matsunami, suggested EGF as the protein for study, and provided advice and inspiration for the project's success.—*Jim Pearce*

When Good Cells Go Bad: Alpha Radiation and Cancer

What makes a normal cell turn cancerous? An answer to this question could guide development of cancer therapies.

What makes a good cell go bad? Or, more precisely, what makes a normal cell turn cancerous? That's the question that drives Biology Division scientist Margaret Terzaghi-Howe's studies of radiation-induced cancer in mice. An answer to this question could lead to a better understanding of the mechanisms that control the cellular changes foreshadowing cancer and precancerous conditions. It could also guide the development of cancer therapies.

Terzaghi-Howe's research in this area focuses on determining the effects of alpha particle radiation on both intact rat tracheas and cultures of cells removed from rat tracheas. "The reason we are working with rat tracheal cells," she says, "is that their diameter and cell structure are very similar to those of cells in the area of the human lung that is most affected by radon."

Radon and its close relatives emit primarily alpha radiation and are blamed for an estimated 7000 to 30,000 lung cancer deaths in the United States each year. Studies like Terzaghi-Howe's improve researchers' ability to gauge the environmental and occupational risks posed by radon and other radionuclides.

Her latest work involves exposing tracheal cells and tissue to three different radiation sources: plutonium-238, polonium-210, and americium-241. Although all of these radionuclides emit alpha radiation, their differences are probably more important than their similarities.

As they decay, americium and plutonium isotopes produce not only alpha particles but also low-energy gamma particles; these radionuclides are also relatively long-lived, with half-lives measured in years. On the other hand, polonium, one of the products of radon decay, is a nearly pure alpha emitter, and its half-life is measured in days.

These contrasting qualities come into play in Terzaghi-Howe's research for several reasons. First, it is not entirely clear that alpha particles alone can induce cancer. "It is very difficult to transform cells with alpha radiation," says Terzaghi-Howe. "My suspicion is that other things interacting with alpha particles, like the chemicals in cigarette smoke or gamma radiation, might make the difference."

One of the problems Terzaghi-Howe faced in setting up this experiment was that polonium emits alpha particles at a slower rate than the other two sources, making it likely that cell and tissue samples would dry out before being completely irradiated. Terzaghi and her colleagues chose to irradiate samples on the surface of the polonium source, rather than at a distance, as is usually done. The greater alpha particle fluence—the number of particles passing through a given area—closer to the source ensured that the polonium-exposed samples would encounter the same number of alpha particles as the other samples.

To test the hypothesis that some attribute of intact tissue or the environment of a live animal is responsible for inhibiting tumor development, the intact tracheas were irradiated and then implanted under the skin of mice to approximate an in vivo environment. The cultured tracheal cells were suspended in a liquid and then irradiated.

Inspection of the irradiated samples revealed precancerous changes in cell structure in some of the samples but not in others. "We did the same experiments with plutonium-238, polonium-210, and americium-241 at the same alpha particle fluences," says Terzaghi-Howe, "and we got no neoplastic transformation from the polonium isotope, but we did get transformations in both the cell suspensions and the tracheal implants that had been exposed to the plutonium and americium.

"We don't know what the explanation for this is," says Terzaghi-Howe. "All of these experiments are aimed at determining whether we can detect an alpha-gamma interaction effect that causes cellular changes to take place—or an effect based on the position of the sample relative to the source."

After rat tracheas are irradiated, Margeret Terzaghi-Howe transplants them under the skin of mice to test the hypothesis that some attribute of intact tissue or the environment of a live animal is responsible for inhibiting tumor development.

"It's hard to improve on three billion years of evolution."

The distance a cell is from the radiation source can make a big difference. When an alpha particle is emitted, the farther along its track it is, the more energy it dumps. So it's conceivable that the sources were located at distances from the samples where, by chance, they either did or did not cause cell transformations to take place."

Jim Turner, a physicist in ORNL's Health Sciences Research Division, is developing a computer model that takes the energy transfer characteristics of alpha particles into consideration to optimize the differences among the three sources. His model also predicts the chances that a cell will be hit by both an alpha and a gamma particle. "The chances of that happening are ridiculously low," says Terzaghi-Howe. "So, if gamma radiation is important in causing changes in cells, then it's not because a cell needs to be hit by both alpha and gamma particles. It could be that something else happens to the unhit cells."

Another dilemma that Terzaghi-Howe points out is that, if an alpha particle passes through a cell nucleus, the cell is killed before it can become a tumor cell. "If that's true," she asks, "what's transforming cells? Either the near-miss cells are affected, or it's another effect altogether."

Despite the lack of an obvious explanation for why good cells go bad, Terzaghi-Howe maintains her enthusiasm for the research. "These experiments are intriguing," she says. "There's clearly something happening here that we don't quite understand, but there are more puzzles than answers at this point."—*Jim Pearce*

Reengineering Photosynthesis

"It's hard to improve on three billion years of evolution," says Fred Hartman, director of ORNL's Biology Division, but that hasn't stopped him from trying—and he's not thinking small either. Hartman and his colleagues are tinkering

Improving the efficiency of this enzyme could increase plant growth, crop yields, and biomass energy production.

Richard Mural examines a computer model of the Rubisco molecule as Fred Hartman looks on. Understanding the structure of this protein may enable researchers to enhance its efficiency.

with the most abundant enzyme on earth—a protein that is directly or indirectly critical to the survival of almost every organism on the planet.

The enzyme, known as Rubisco, is a key component of the process of photosynthesis, used by all plants and some bacteria to convert carbon dioxide in the air into food. Rubisco provides the critical chemical link that enables plants to combine carbon dioxide molecules absorbed from the air, each containing a single carbon atom, with five-carbon sugar molecules. This reaction produces two three-carbon sugars—a net gain of a carbon atom. Then, using energy drawn from sunlight, these simple sugars are transformed into complex carbohydrates, like starch. These carbohydrates nourish the plant, and plants, directly or indirectly, nourish us.

"So," you might ask, "if something has worked for three billion years, why mess with it?"

"It's a question of efficiency," says Hartman. "Photosynthesis is a very inefficient process, and improving the efficiency of this enzyme could increase plant growth, crop yields, and biomass energy production."

Rubisco's main problem is that it doesn't do a very good job of distinguishing between oxygen and carbon dioxide. As a result, it's about as likely to react with one as the other, even though the oxygen reaction apparently serves no biological purpose. This laissez faire approach to chemical reactions on the part of the enzyme cuts some plants' capacity for processing carbon dioxide in half.

It also has several chemical inefficiencies that render it only about 1% as effective as other enzymes at promoting its assigned reaction—the transformation of carbon dioxide to sugar. Hartman points to the fact that the human body contains 50,000 enzymes, most of which are much more efficient than Rubisco. "It seems reasonable," he says, "that we should be able to improve the efficiency of this enzyme."

He is realistic, however, about the difficulty of the task facing him. "When a scientist projects improvement on Mother Nature, you should be skeptical," he says. Part of the reason Hartman counsels caution is that Rubisco has a much bigger job than most other enzymes.

A typical enzyme's job is to make or break a single chemical bond. For example, pepsin, an enzyme that works primarily in the stomach, is devoted to breaking proteins apart into amino acids so they can be absorbed by the body. "On the other hand," says Hartman, "Rubisco is responsible for catalyzing six distinct partial reactions in a single stage of photosynthesis. Its inefficiency may be a reflection of the difficulties of designing a single enzyme to execute all of this chemistry."

To unravel the mysteries surrounding how Rubisco works, Hartman and his research team use recombinant DNA technology to alter the enzyme's 475-amino-acid-long structure (see sidebar). By changing one acid at a time they can monitor the effect of each change on the enzyme's performance. Because there are 20 amino acids, there are about 9000 different ways to replace a single amino acid along the length of the Rubisco molecule. Rather than creating 9000 variations of the enzyme, Hartman's group has relied heavily on information about Rubisco's three-dimensional structure provided by X-ray crystallography and functional information drawn from earlier chemical studies. This information, particularly a knowledge of which areas of the enzyme are binding sites for substrates, has enabled Hartman and his group to make educated guesses about which amino acids to substitute to effect the desired changes in Rubisco.

Of the dozens of altered versions of Rubisco produced by the group, several can distinguish between carbon dioxide and oxygen somewhat better than the normal form of the enzyme—which is half the battle. But, so far, none of the group's creations can match the rate at which unaltered Rubisco promotes the carbon dioxide reaction.

In the long run, determining how to increase the efficiency of Rubisco could have profound implications for agriculture and biomass energy production. It has also been suggested that increasing Rubisco's use of carbon dioxide could decrease levels of the gas in the atmosphere, reducing the likelihood of global warming while promoting plant growth if the improved version of the enzyme were incorporated into crops and other plants on a large scale.

"That would be nice," Hartman adds, "but nothing like that is going to happen today, this week, or even this year," In the short run, his team is focusing on understanding how enzymes tell

Designer Genes

So how do you change just one of Rubisco's 475 amino acids without fouling everything else up? Very carefully.

To begin with, all of the instructions for producing Rubisco are written, in a chemical code, on a gene—one of the thousands that it takes to build a plant. All of these genes are included on the handful of chromosomes that appear in almost every cell in the plant. If you think of the information included in these chromosomes as a set of encyclopedias, then somewhere in one of the volumes, there is a chapter on making Rubisco. This chapter is 475 paragraphs long, and each paragraph explains how to use a single amino acid. If you want to replace a specific amino acid with another, you have to replace its paragraph with one containing instructions for using the new amino acid.

To make this swap, researchers employ the services of a bacterium called *E. coli* and a host of enzymes used to cut and paste pieces of DNA. Outside the laboratory, *E. coli* usually makes itself at home in the digestive tracts of mammals, but it has become a favorite tool of genetics researchers for the manipulation of genetic materials. Borrowing a ring-shaped piece of double-stranded DNA known as a plasmid from an *E. coli* bacterium, researchers use one enzyme to cut the ring and another to paste a Rubisco gene (or chapter) into the resulting gap.

A single strand of this new plasmid may be copied in the laboratory, including the desired change of instructions (the new paragraph). Enzymes are used to reassemble the plasmid, which is then reinserted into an *E. coli* bacterium and rapidly reproduced.

This new strain of bacteria will use its updated instructions to produce an altered form of Rubisco, which can then be tested to determine how well it can distinguish between carbon dioxide and oxygen and how quickly it works.

the difference between potential reactants, such as carbon dioxide and oxygen, and what factors control how quickly or slowly they work—a reasonable goal, particularly since the enzymes have a three-billion-year head start.—*Jim Pearce*

Tracking Antique Waste

A major question has been whether PAHs absorbed by plants could come into contact with humans or even enter the food chain.

Most people think of hazardous wastes as by-products of modern technology; however, since the early 1800s, many American cities and towns across the country were unknowingly creating their very own toxic waste dumps through the production of "town gas." At the industry's peak, over 1500 gas plants were operating in the United States, first providing fuel for street lighting and, later, for heating, cooking, and industry. However, as natural gas delivered by transcontinental pipeline became more available in the 1950s and 1960s, production all but ceased.

Town gas was the vaporous result of the slow heating and cooling of coal or oil—a process that left a lot of incompletely burned material in the form of tar. Because tar wasn't good for much, utility companies usually dumped it somewhere—often on the outskirts of town. Over the years, these dumps were often buried, forgotten, or overrun by expanding cities and their suburbs.

Recently, however, interest in coal tar has been renewed as researchers have found that it is rich in polycyclic aromatic hydrocarbons (PAHs), many of which are mutagens or carcinogens. These findings have made tar dumps a major liability for some utility companies, spurring studies of the effects of these sites on the environment. A major question has been whether PAHs absorbed by plants could come into contact with humans or even enter the food chain.

PAH molecules come in a variety of sizes. Initial studies of larger, heavier PAHs, particularly benzo[*a*] pyrene, showed that they were not absorbed from the soil by vegetation. However, few of these studies clearly addressed the behavior of lighter-weight PAH molecules. To help determine whether lightweight PAHs could be absorbed by plants, the Electric Power Research Institute funded a study by ORNL scientists Barbara Walton and Anne Hoylman on the subject.

"Coal tars break down over time when oxygen is present," says Walton. "However, lighter PAHs are most likely to remain at older sites, particularly if they are buried and don't have any contact with oxygen. This isolation prevents them from being broken down further through oxidation."

Hoylman, then a University of Tennessee doctoral student working at ORNL, designed an experiment to measure plant uptake, or absorption through roots, of PAHs. The key to this study was an experimental design that isolated the aboveground foliage from the roots and soil, thereby providing a clear route for the uptake of PAHs tagged with radioactive carbon-14.

"We wanted to determine where the PAHs were going in the plant and soil systems," Hoylman says. "If we established that they were being absorbed by the plants, then there would be a reason to be concerned, and further research might be required."

To create a worst-case scenario for the uptake of PAHs by the plants in their study, Hoylman and Walton tailored their experimental setup to favor the absorption of PAHs. First, because PAHs are likely to attach themselves to organic material, the researchers reduced the amount of organic carbon in the soil, increasing the likelihood that the plants would take up the radiolabeled PAHs. Also, they chose to grow white sweetclover plants, a plant found at the site, which has a large root mass and, as a result, a high likelihood of absorbing PAHs.

Under these optimized conditions, the plants were grown in airtight flasks that isolated the stems and leaves from the soil and any PAHs released from the soil into the air. This approach ensured that the presence of PAHs in the stems and leaves of the plant would be a result of absorption through the plant's roots. The specially designed flasks also ensured that any carbon-14 released into the air was trapped and measured.

At the end of the study, the soil and the plants were analyzed. Hoylman and Walton found that the bulk (86%) of the PAHs remained in the soil. Of the PAHs that were absorbed by the plants, the lightest and most water-soluble, naphthalene, had the highest concentration (0.5%), remaining primarily in the roots, with progressively lower concentrations in the stems and leaves. Three times more naphthalene was absorbed, on the average, than any of the other three hydrocarbons: pyrene, phenanthene, and fluoranthene.

So although a small quantity of lightweight PAHs was absorbed by the plants' root systems, only a fraction was transported to the plant's stem and leaves. "We established conditions to enhance the uptake of PAHs," says Hoylman, "and we saw that the root tissue of plants could be a potential 'sink' for PAHs. But, overall, it was a very limited mechanism, given that we established conditions to enhance uptake." This finding has led to the hypothesis that roots, in conjunction with microbes that inhabit the area around them, act as a defense mechanism for plants against absorption of toxic chemicals, such as PAHs.

The results of this study also provide some encouragement for power utilities and others who ask, "Is it okay for people to use these areas?" The answer may be "yes."—*Jim Pearce*

New Air Conditioner Beats the Heat for 20% Less

Researchers at ORNL have designed an air-conditioning system that increases the efficiency of automobile air conditioners by 20%, cuts fuel consumption and greenhouse-warming gas emissions, and could possibly lengthen the life of the cooling unit.

"For every ten dollars normally spent running the air conditioner, two dollars will be saved," says Fang Chen, leader of ORNL's Thermal and Environmental Technology Group in the Laboratory's Energy Division.

The patented new design, created by Chen and division colleague Vince Mei, is compatible with coolants that do not contain chlorofluorocarbons (CFCs), which are believed to contribute to ozone depletion in the upper atmosphere and which are being phased out.

If the design is fully implemented in the U.S. auto industry, Chen says, the increased energy efficiency could save about 1.29 billion liters (340 million gallons) of fuel a year nationwide and could cut annual carbon dioxide emissions by more than 2.9 billion kilograms (6.5 billion pounds). Annual fuel cost savings to the consumer would exceed $400 million a year at a fuel price of $1.20 per gallon. Chen said he and his ORNL group are now talking with two U.S. automakers and with air-conditioner manufacturers about licensing the technology.

The improvement involves adding a simple, inexpensive heat-exchange device to existing air-conditioner designs. The device allows the coils in an air conditioner's evaporator to be "overfed" with liquid coolant, increasing cooling capacity. Any excess liquid coolant exiting the evaporator is rerouted back into the same heat exchanger for vaporization, protecting the unit's compressor and decreasing its work load, thus lowering energy consumption and CO_2 emissions.

The 20% efficiency boost and the associated savings may be applicable to home air-conditioning units. If the ORNL device were added to each home air conditioner, American consumers would save $5 billion and the carbon dioxide output would be cut by 12.2 billion kilograms (27 billion pounds). Further studies to apply the technology to stationary air conditioners, home heat pumps, and refrigerators are pending. Development of the new heat-exchange device has been funded by DOE's Office of Transportation Technologies.—*Wayne Scarbrough*

If the ORNL device were added to each home air conditioner, American consumers would save $5 billion.

Ozone's Effect on Trees Studied

ORNL researchers have joined environmental scientists from the Tennessee Valley Authority (TVA) in a project to learn more about the effects of ground-level ozone on the environment.

Team members working in conjunction with ORNL's Cooperative Forest Studies Program have erected 18 open-top chambers made of clear plastic and aluminum near TVA's Norris Dam Reservation. The purpose of these chambers is to help scientists learn how tropospheric ozone—caused by emissions from motor vehicles, petroleum refineries, coal-burning power plants, and many other industries — interacts with mature northern red oak trees and seedlings.

"The chambers allow us to monitor and regulate the exposure of trees and seedlings to ground-level ozone, while comparing responses," says Paul Hanson of ORNL's Environmental Sciences Division. "Although we have learned that the leaves of mature trees are somewhat more sensitive to ozone, the key goal of our study is to determine whether seedling studies can be used to extrapolate data for mature tree responses."

"The chambers allow us to monitor and regulate the exposure of trees and seedlings to ground-level ozone, while comparing responses."

Currently, it is not known how accurately seedling responses will reflect responses of mature trees and forest ecosystems to air pollution. The information derived from the ORNL-TVA study, however, will be developed into plant response models that will help researchers better understand tree and forest ecosystem responses to air pollution.

When exposing trees to elevated ozone levels, researchers use computer software to compare the average ozone concentration of ambient air with that in the chamber to calculate amounts required for maintaining the desired elevated ozone concentration in the chamber.

"After harvesting the seedlings," says Jim Kelly, TVA project manager for the study, "we'll then use another nearby chamber site to also study red oak, yellow poplar, and shortleaf pine trees that were planted 3 years ago to simulate a forest."

Some 24 model forest ecosystems then will be exposed to various levels of ozone, as well as soil temperature and moisture treatments. The chambers, which are 9 meters (28 feet) high by 4 meters (12 feet) in diameter, will accommodate measurements over several growing seasons to show researchers how tree responses vary over the years.

"We believe this project will eventually help utility industries and federal agencies because the electric power industry and the biological science community have long had the goal of being able to predict the responses of ecosystems to a changing atmosphere," Kelly says.

The ORNL-TVA project is sponsored by TVA and the Electric Power Research Institute.—*Brian Daly*

Fiber Optics for Safer Buildings

ORNL researchers have developed a new type of flexible fiber-optic system that can be used to measure concrete's state of cure, to sense crack formations, and, over time, to monitor strains within the building's structure.

Currently, the fiber-optic sensors are being used in the construction of a new science and engineering research facility at the University of Tennessee at Knoxville.

ORNL researchers have embedded optical fibers in the concrete support beams of the UT building to measure the strain on the concrete before and after the post-tensioning process and throughout the life of the building. If a crack forms in a concrete slab, the silicone rubber fiber deforms as the crack shifts. The changes in the amount of light going through the fiber then can be monitored to gather information about the characteristics of the crack and the building's superstructure. The flexible fiber-optic sensors also have many other uses, including measuring the strain and pressure on bridges and in airplanes.

The post-tensioning of a beam involves putting more than 50,000 pounds of tension on the concrete to reinforce the post-tensioning strands (braided wire within a plastic jacket). The goals of the project are to better understand the dynamics of the post-tensioning process and to monitor the integrity of a building's superstructure over time.

By observing changes inside the beams as tension increases and as the building ages, civil engineers will gain new information that will enable them to design better and safer buildings, highways, bridges, dams, and other concrete structures. Embedded optical fibers also are sensitive to vibration and may be used to

ORNL scientists have developed a method to help ensure that pesticides and other agricultural sprays will land where intended rather than drift to an off-target area. Here chemical engineer Osman Basaran (pointing) and postdoctoral research associate Xiaoguang Zhang study a screen image of a tiny droplet of liquid suspended from the needle-like capillary in the small clear box at lower left. The research will help determine proper droplet size for specific mixtures as they are blasted from a spray nozzle.

ORNL scientists are lending their expertise to scrutinize the phenomenon of "spray drift."

improve the accuracy of early warning systems for earthquakes.—*Angela C. Swatzell*

Probing Spray Drift on Farms

Exactly what happens when a pesticide, fungicide, or fertilizer is sprayed on a crop from above? How does an agricultural company ensure that what they are spraying ends up where they want it, and not on a neighboring piece of land?

ORNL scientists are lending their expertise to a consortium of 27 companies that have formed a task force to scrutinize the phenomenon of "spray drift."

The ORNL team has developed a unique means to measure critical qualities of droplets during the milliseconds of their formation. Their discoveries will be used to help determine proper droplet size for specific mixtures as they are blasted from a spray nozzle. The knowledge gained from the measurements will help ensure that what is sprayed from above will land where it is intended.

"This is good for the health of the people in the area, good for protecting the groundwater, and good from the standpoint of saving money through less waste," said Osman Basaran, a chemical engineer and group leader in ORNL's Chemical Technology Division.

The nature of how droplets of a sprayed solution will drift through the air obviously has something to do with the prevailing winds. But there are other factors, including evaporation, droplet composition, viscosity, flow rate through the spray nozzle, and a property called dynamic

ORNL drift data may also be applicable to spray-painting aircraft and buildings.

surface tension, which is the quality that relates to the ability of a droplet to maintain a uniform shape instead of breaking up.

Through years of research focused on the chemical and petroleum industries, ORNL has become a leader in measuring these subtle surface forces when chemicals are manufactured by separation processes, such as when kerosene or gasoline are derived from crude oil. "This expertise made ORNL a natural choice for the spray-drift studies," Basaran said.

"Just as the petroleum industry wants to ensure the best separation processes, agricultural companies and regulatory agencies want a sound scientific basis for predicting the drift of chemical sprays," he said. "Each of the 27 companies in these studies has its area of expertise in providing this basis."

But existing means of measuring dynamic surface tension, for example, of gas bubbles during their relatively slow formation and ascent through a more dense surrounding liquid, proved useless for studying droplets sprayed at high pressure.

To make their assessments, the ORNL team uses a system of precision pumps and flow regulators, and electronics to digitize information from the growing droplets. A powerful video camera, capable of recording 12,000 partial images per second, is focused on a tiny, needle-like capillary from which the droplets emerge.

On a video monitor in the laboratory, the droplets appear as large, shimmering globes of fluid. They are actually not much bigger than the period that ends this sentence.

As droplets form at the end of the capillary, the scientists determine surface tension by measuring simultaneously the curvature of the droplet and the pressure difference between the inside and outside of the droplet. Capillaries having small enough diameters cause the droplets to maintain the shape of a partial sphere throughout their formation, which aids in measurements. (A vibration table is used throughout the experiment to minimize or eliminate unwanted movement of the droplets.)

Dynamic surface tension of droplets depends in large part on the surfactant, or additive such as a pesticide, in the liquid. As droplets form, the movement of surfactants within the droplet may lag behind the expansion of the droplet's surface. This effect changes the surface tension and, thus, will affect spray drift.

Basaran and his colleagues Michael Harris and Xiaoguang Zhang, also of the Chemical Technology Division, will use the new measurement techniques on several solutions to determine dynamic surface tension and other parameters.

"It's important to get baseline measurements for various solutions that are representative of what the agricultural industry might be spraying," Basaran said, explaining that in the future, agricultural companies will be required to tell regulatory agencies before spraying begins what droplet size will result for a particular spray.

"With the data being produced at ORNL and by others in this project," Basaran said, "sprayers will be able to predict spray drift with more confidence because they will be able to better control the factors that determine drift. That's good not only for the companies involved but for everyone who lives near the area being sprayed."

Basaran said that the ORNL drift data may also be applicable to other work involving sprayed solutions, such as spray-painting aircraft and buildings.—*Wayne Scarbrough*

RE: Awards & Appointments

Bill Appleton

John Sheffield

Steven Hildebrand

Chet Richmond

Bill R. Appleton has been named ORNL associate director for the Advanced Neutron Source.

Steven G. Hildebrand has been appointed director of ORNL's Environmental Sciences Division.

Chester Richmond has accepted an appointment to the National Research Council's Mathematical Sciences Education Board.

John D. Galambos has been presented a 1993 Excellence in Fusion Engineering Award by the Fusion Power Associates of Gaithersburg, Maryland.

Susana Navarro-Valenti has been presented the 1993 American Nuclear Society Mark Mills Award.

John Sheffield has been presented a 1993 Leadership Award by the Fusion Power Associates Board of Directors.

Vance K. Wilkinson has been designated a fellow by the Institute of Industrial Engineers.

Murray W. Rosenthal has received the Distinguished Career Award by the Fusion Power Associates Board of Directors.

C. Y. Ma and **Charles K. Bayne** have received the 1993 Statistics in Chemistry Award from the American Statistical Association.

Emily D. Copenhaver has been chosen 1993 Woman of the Year by the Oak Ridge Chapter of the American Business Women's Association.

Charles C. Baker has received a Distinguished Service Award from the University of Wisconsin-Madison's College of Engineering.

Vinod K. Sikka and **G. (Gil) Gilliland** have been named fellows of the American Society of Metals (ASM) International.

Peter Mazur has been named winner of the American Association of Tissue Banks' 1993 Distinguished Service Award.

Robert H. Gardner has been appointed chairman of the Scientific Review Committee of the Ecological Society of America.

Lee Shugart has been appointed a member of the organizing committee for the Conference on Genetic and Molecular Ecotoxicology.

Robert L. Siegrist has been named a contributing editor to the *Journal of Environmental Engineering*, published by the American Society of Civil Engineers, and he has been appointed a member of the Groundwater Committee of the Water Environment Federation.

Carolyn Hunsaker has been elected chair of the applied ecology section of the Ecological Society of America. She also has been appointed to the Board of Control of the Water Environment Federation.

Steven E. Lindberg was in Sweden for a sabbatical stay with three Swedish institutes. He will be a guest researcher at the Meteorological Institute of Stockholm University, the Department of Energy and Environmental Studies at Lund University, and the Swedish Environmental Research Institute in Göteborg.

Peter T. Cummings, a chemical engineering professor from the University of Virginia, has been named a Distinguished Scientist by the University of Tennessee and ORNL.

Fay M. Martin has been appointed to two board positions by the Oak Ridge City Council. Martin will serve as a member of the Elder Citizens Advisory Board and as secretary of the Community Television Board.

Robert B. Honea has been appointed director of Energy Systems' Oak Ridge Transportation Technology Center.

Frank C. Kornegay has been appointed deputy associate director for Operations, Environment, Safety, and Health at ORNL.

Murray Rosenthal

Vinod Sikka

Robert Honea

Frank Kornegay

Becky J. Verastegui has received an award from the journal *Government Computing News* for her leadership in DOE's long-range strategic planning and acquisition management processes.

Jeffrey C. Seitz and **Bruce A. Pint** have been named winners in DOE's Distinguished Postdoctoral Research Program competition.

Ralph M. Moon, Jr., has been elected a fellow of the American Association for the Advancement of Science.

Richard Hicks has received a certificate from the journal *Government Computing News* for his leadership in implementing a supercomputing program at 49 high schools in the United States.

Robert Burlage has been selected to organize a special issue of the *Journal of Microbiological Methods* presenting research accomplishments of scientists from the former Soviet Union.

Harold C. Thornton, Jr., has been selected by *Industry Week* magazine as one of its "50 R&D Stars to Watch."

Stan A. David has been presented the 1994 Champion H. Mathewson Award by the Minerals, Metals, and Materials Society.

Tuan Vo-Dinh has received the 1993 Advanced Technology Award from the International Hall of Fame.

Stephen H. Stow has been appointed a member of the Geology and Public Policy Committee of the Geology Society of America.

ORNL '93: Chips to Hips, a publication by **Sybil Wyatt, Jann Alexander** (design subcontractor), and **Jon Jefferson,** received an award of excellence in informational brochures in the International Technical Publications Competition sponsored by the Society for Technical Communication.

Numerous ORNL employees were recognized for their achievements during the 1994 Martin Marietta Energy Systems Awards Night ceremonies. **Don Box** was named Scientist of the Year for developing the "PNEU-WORM," a novel robotics technology that inspects pipelines and ductwork. **Don Spong** was named Author of the Year for a paper published by the American Institute of Physics that represents a great leap forward in understanding toroidal magnetic fusion devices. **Jim Corley** was named Engineer of the Year for the Small Projects Design organization, which was formed to use creative and innovative solutions and to eliminate paperwork on small projects.

Operations and Support Awards for providing exceptional support to the missions and programs at ORNL by office, clerical, or administrative support staff went to **James L. Baxter** for exemplary support of utilities operations by effective utilization of the resources available, both inside and outside the organization and Energy Systems.

Deborah B. Buchanan for successfully guiding the financial management of the Waste Management and Remedial Action Division and contributing substantially to freeing $1 million for priority work.

S. M. Dawn, David Barncord, John B. Czachowski, Donnie Finks, Jeff Hill, Doug Loflin, Dan Russell, Ann M. Shirley, and **Justin Woody** for outstanding and innovative craft support in providing immediate, effective response to safety and health concerns in the 4500 complex.

Shirley G. Frykman for continued and extraordinary effort in the successful administration of the Metals and Ceramics Division's Work for Others programs.

Michael D. Galloway for excellence and distinction in developing an effective environmental, safety, and health program for the Solid State Division.

Mark S. Hawley, Terry Brown, Kenneth P. Curtis,

Robert Burlage

Stan David

Tuan Vo-Dinh

Stephen Stow

Al DeVaney, John E. Dixon, Eric L. Fogel, Philip Guertin, Gregory J. Hirtz, G. L. Kickendahl, Nicholas Matiash, John L. Overly, John E. Polinsky, Sr., Ronald J. Reagan, and **Christopher Redmon** for excellence in the cleanup of the HRLEL carrier iridium release at the High Flux Isotope Reactor.

Marjorie C. Matthews for creating an outstanding administrative services organization within the Metals and Ceramics Division and for championing the Energy Systems Value of Concern for People.

Sylvia D. McGhee, Susan Beightol, J. C. Copeland, C. W. Cross Jr., Mark B. Hawk and **Greg L. Livengood** for contributions toward improving formality and rigor in the conduct of the radioactive materials packaging and shipping program at ORNL.

Bill Miller for superior leadership in establishing and implementing a comprehensive and workable environmental, safety and health program in the Metals and Ceramics Division.

Richard Montgomery for superior operational support in constructing and renovating six major facilities in the Engineering Technology Division for the Centers for Manufacturing Technology.

Charles C. Phillips, Marwan Bader, Bradley E. Copeland, Nancy S. Dailey, Shar Hollis, Ed Long, Doug Miller, Theodore R. Mueller, Denise Reynolds, Tony Reynolds, L. E. Stokes, Clark L. Surrett, Jr., and **Wayne Underwood** for outstanding operational support toward abating unsafe working conditions associated with perchloric acid salts-contaminated hoods at ORNL.

Christina M. Poole for extraordinary sustained performance in office management, organization, and communication and for exceptional skills in facilitating an off-site relocation.

Victoria A. Schultz for contributions in implementing the DOE-EM Office of Technology Development's mixed-waste integrated program.

Management Achievement Awards for exemplary management contributions in the areas of functional, project, or technical/scientific management went to **Richard K. Genung** for distinguished management service to Energy Systems, ORNL and the Chemical Technology Division and for providing leadership in professional societies and the community.

Anthony C. Schaffhauser for successfully developing the energy-efficiency program through teambuilding and motivating people within and external to ORNL.

Technical Achievement Awards for employee contributions of a technical nature in the areas of research, development, engineering, publication, or invention went to **Osman A. Basaran** for major contributions to the understanding of droplets in electric fields and their application to the significant improvement of separation processes.

Stephen L. Blankinship for the development of an important technique in renewable fuels production.

W. Don Box for inventing, patenting, and licensing an ingeniously propelled robot for pipeline and ductwork inspections.

Charles L. Britton, Jr., and **Alan L. Wintenberg** for superior contributions to the experimental physics community by developing the world's first radiation-hardened analog memory unit.

Virgil R. Bullington for technical support in publicizing and transferring ORNL technologies to the public and private sectors.

Fang C. Chen and **V. C. Mei** for developing an air conditioner system modification with significant energy efficiency.

Kenneth W. Cole for technical input, careful observation, and diligence in developing cryopreservation methods for the biologically important fruit fly *Drosophila.*

J. H. DeVan for major contributions to the field of high-temperature materials science, especially related to understanding corrosion behavior and solving corrosion problems.

Lawrence Dresner for calculating, in convincing fashion, that high-temperature superconducting magnets can be adequately protected.

Robert L. Hettich for extraordinary achievements in developing powerful new structural techniques in organic mass spectrometry.

F. F. "Russ" Knapp, Jr., Arnold L. Beets, Saed Mirzadeh, and **Dennis E. Rice** for developing a new system that provides a simple and readily available source of the rhenium-188 radioisotope, which has shown significant promise in the treatment of some types of cancer.

Russell Lee, Clay E. Easterly, Carolyn T. Hunsaker, and **Gordon E. Michaels** for completing the Joint DOE/European Community Study on Fuel Cycle Externalities.

Peter Mazur, Kenneth W. Cole, and **Jerry W. Hall** for contributions to a paper developing cryopreservation methods for the biologically important fruit fly *Drosophila.*

Gayle S. Painter for writing a publication that advances knowledge of the basic properties of atomic clusters and their relation to properties of solids.

Donald A. Spong, Benjamin A. Carreras and **Clyde L. Hedrick, Jr.,** for developing a new fluid, analytical, and numerical approach for studying the stability of reactor-grade plasmas to energetic particles such as fusion-produced alphas.

Glenn W. Suter II and **Lawrence W. Barnthouse** for publication of the first comprehensive textbook on ecological risk assessment.

Edward C. Uberbacher and **Richard J. Mural** for successfully extending the multisensor/neural network approach and integrated optimization methods based on genetic algorithms toward solving the problem of predicting the three-dimensional structure of a protein from the amino acid sequence.

Claudia A. H. Walls for sustained contribution to the rapid development of gelcasting advanced ceramics, a technology now receiving industrial support for early commercialization.

William B. Whitten and **J. Michael Ramsey** for writing the *Journal of Chemical Physics* publication "Homogeneous Linewidths of Rhodamine 6G at Room Temperature from Cavity-Enhanced Spontaneous Emission Rates."

Rick Woychik for cloning and sequencing a mouse gene that uncovered a model for human genetic obesity, non-insulin dependent diabetes, and certain cancers.

A Community Service Award for outstanding and noteworthy performance in voluntary activities that provide significant benefit to the community went to:

Larry Robinson for outstanding leadership in enhancing minority involvement in science and engineering and for promoting cultural diversity throughout the Oak Ridge–Knoxville area.

Eighty-two Energy Systems employees were honored for having received patents at this year's Inventors' Forum. They are **Alan L. Wintenberg, Alfred J. Mattus, Alvin P. Callahan, Brian H. Davison, Carl A. Burtis, Charles D. Scott** (2), **Charles H. Byers, Charles L. Britton, Jr., Chung-Hsuan Chen, Claudette G. McKamey, Clyde Hamby, Jr., Cressie Holcombe** (2), **Cyril V. Thompson, Daniel J. Hoffman, David M. Eissenberg, Donald A. Casada** (2), **Donald F. Simandl** (2), **Douglas E. Goeringer, Edward C. Lisic, Edward J. Klages, Edwin F. Babelay, Jr., Fang Chen** (2), **Frederick J. Walker** (2), **Frederick Schultz, Furn F. Knapp, Jr., Gary L. Glish, H. Alan Fine, Harold D. Kimrey, Jr., Henry D. Cochran, Jr., Howard D. Haynes** (2), **I. Lauren Larsen, Ivan L. Morgan, James H. Wilson, Jeffrey D. Muhs, John D. Brown** (2), **John K. Jordan, John M. Googin, John T. Mihaiczol, John V. LaForge, Kenneth C. Liu, Kenneth W. Tobin, Jr., L. Curtis Maxey, Lisa M. Thompson, Louis H. Thacker, Lynn A. Boatner, M. Alfred Akerman, Marcus B. Wise, Marion M. Chiles, Marvin S. Morrow, Matthew B. Scudierei, Michael J. Roberts, Michael Sepaniak, Michael T. Harris, Norman L. Dykes, Richard L. Heestand, Robert A. Hawsey, Robert DeVault, Robert I. Shepard, Robert J. Lauf** (5), **Robert Wichnerl, Rodney A. McKee, Roeland Fennstra, Roger D. Spence, Roland D. Seals, Ronald F. Simandl** (3), **Saed Mirzadeh, Scott McLuckey, Steve L. Allman, Terrence L. Donaldson, Terry N. Tiegs, Theodore J. Huxford, Theron V. Blalock, Thomas Kollie, Timothy C. Scott** (2), **Tuan Vo-Dinh** (2), **V. Clint Miller, Vinod K. Sikka, Viung C. Mei, Walter D. Bond** (2), **Wayne Johnson, Wendell J. Biermann, Wesley D. Arnold, Jr.** (2), **William A. Walker,** and **William E. Barkman.**

Training Teachers for a High-Tech Future

High-school student Brandy Justice, accompanied by John Wooten (left) and Chet Richmond, learned to cruise the information highway through ORNL's Saturday Academy for Computing and Mathematics.

"There are thousands of buildings in this country, with millions of people in them who have no telephones, no cable television, and no reasonable prospect of broadband services. They're called schools," said Reed E. Hundt, chairman of the Federal Communications Commission in a *New York Times* interview on December 6, 1993.

Many students today are not getting the technological information in the classroom that they need to meet the demands of the future. To combat this problem, DOE's Office of Science Education and External Relations at ORNL has created the Oak Ridge Regional Education Center. The center offers year-round, hands-on learning and research opportunities for students and teachers from elementary school through college using the most up-to-date computer equipment.

Several years ago, DOE named several national laboratories, including ORNL, as science education centers. The Oak Ridge Regional Education Center was built in January 1993. The center interacts with numerous regional groups, including the Tennessee Valley Authority, the Appalachian Regional Commission, and the Appalachia Education Laboratory.

DOE is committed to using its highly trained technical staff and advanced facilities to strengthen science and mathematics education nationally. New partnerships are strengthening the center's focus on national education goals and on education reform within the Southeast. Support for these partnerships includes a major new focus on computing and communications technology for educational applications.

The center is equipped with a computer classroom, where students and teachers learn through a series of exercises how to collect data, how to apply data to certain problems, and how to use a computer to visualize the complete package. The wave of the future in computer technology is networking, a phenomenon that allows amateur computer users to access information from computers around the world using Internet, an international network of computer users.

For example, if a person needed a document in Spanish for a research project, chances are he or she would have no idea where to look. But students and teachers are learning that, at the touch of a button, and with some simple computer knowledge, it is possible through Internet to retrieve a document electronically from the University of Buenos Aires, Argentina, for example, to use on their computer in Oak Ridge or elsewhere.

The center is the "umbrella" organization for ORNL's Saturday Academy for Computing and

"There are thousands of buildings in this country, with millions of people in them who have no telephones, no cable television, and no reasonable prospect of broadband services. They're called schools."

Mathematics (SACAM), which offers promising, college-bound students the opportunity for practical experience in science, mathematics, and computing. The eight-week course presents a different topic each Saturday morning during the sessions, held twice a year.

As part of SACAM, scientists from ORNL teach students and teachers how to use computers and present information on science and technology through activities the students can understand. Some of the topics that have been discussed in the sessions include "Cryptology and Cryptography," "Finding Lost People: An Application of Probabilities," "Modeling Controlled Fusion," and "DNA and the Human Genome Project."

"When you're dealing with educating youngsters, you're seeing what you've done for years at ORNL applied and you start seeing the benefits very quickly."

"We try to guide teachers and students into a system that will meet their present needs and be compatible with future technological changes," says John Wooten, program administrator for Education Technology and Outreach Programs.

The goal of SACAM is to give students a general knowledge of different topics to increase their interest and comprehension of scientific subjects. Because it is sometimes difficult to interest students in science and computing, SACAM classes make difficult theories easier to understand through activities that show students they have the ability to grasp complex scientific concepts.

"Science is the process of finding answers, not knowing answers," said Chester R. Richmond, director of ORNL's Science Education and External Relations Office. "You don't have to inherently know the answers to excel in science. This attitude makes kids less uptight about science."

Once teachers and students learn about computer networking at the center, they can take their knowledge back to their schools. Several schools are investing in their students' futures by purchasing computers and telephone lines that will allow them to have networking capabilities. Currently, Oliver Springs High School; Webb School of Knoxville; the Oak Ridge, Lenoir City, and Roane County school systems; and Ingleside School in Athens, Tennessee, have computer networking capabilities or are in the process of getting connected to the system.

"I think the use of the computer classroom and the training we provide has set an example and a strategy for schools in the region," Wooten says. "Now they know the path to follow when it comes to staying abreast of the latest technology in and out of the classroom." He adds that ORNL is serving its role as a national laboratory by taking the technology that has been at the laboratory for years and teaching people how to apply it in the private sector.

Terry Hacker, a teacher at Oliver Springs High School, was invited to the program after taking part in SACAM's early planning sessions. Hacker says the program "creates a lot of interest in kids who want to be on the cutting edge of new technology."

One of the success stories of SACAM is Brandy Justice of Oliver Springs High School. Brandy was identified by one of her teachers as a candidate for computer classes, which she took as a high-school sophomore and senior. Because Brandy became so proficient at using computer networks, she was asked to attend a national meeting in Washington, D. C., where she demonstrated her computer knowledge and discussed the role of technology in schools.

When Brandy graduated from Oliver Springs High School, she went on to Furman University in Greenville, South Carolina. There she attempted to obtain an Internet account to continue her networking activities. To her dismay, she was informed that it was Furman's policy to give Internet accounts only to graduate students and computer science majors. When Brandy explained that she had had an Internet account since her high school sophomore year, Furman administrators decided to reevaluate the school's policy on computer accounts. Now, all Furman students may have access to Internet accounts. And because no Furman faculty members were qualified to teach the students how to use their Internet accounts, Brandy has been hired to teach Internet classes.

"When you're dealing with educating youngsters, you're seeing what you've done for years at ORNL applied and you start seeing the benefits very quickly," Wooten says.

Once schools decide to install networked computers, ORNL's Science Education and

External Relations Office assists in planning the networks, wiring them, and establishing the Internet connections. These services are free to the schools, as are the computer classes for students and teachers.

The Office of Science Education also offers programs for students and teachers. Precollege programs allow students and teachers to experience "hands-on" learning opportunities into the frontiers of science. These programs include "Science Bowl" competitions, high-school science-student honors workshops, and the Ecological and Physical Sciences Study Center.

Undergraduate programs reach students at a time in their academic development that is important in influencing career choices and decisions on advanced study in energy-related fields. These programs include the DOE Science and Engineering Research Semester (SERS), summer and academic-year professional or technical internships, and customized technical internships.

Graduate-level advanced study and research opportunities, which make further use of ORNL's unique facilities and staff, help prepare emerging scientists and engineers for their roles in national energy-related missions. These programs provide close association with ongoing energy research and development at ORNL. Graduate-level programs include the DOE Fellowship Practicums, Research Participation/ Research Visits, and Graduate Education for Minorities Consortium Appointments. —*Angela C. Swatzell*

Conference Motivates Girls in Math and Science

The fifth Sharing Adventures in Engineering and Science (SHADES) colloquium for middle-school girls was held in March 1994 at Pellissippi State Technical Community College in Knoxville. The goal of the one-day conference was to show sixth-, seventh- and eighth-grade students that mathematics, physical sciences, life sciences, and engineering disciplines are fun and interesting. The program was highly interactive, with demonstration-oriented exhibits and presentations. Speakers included engineers and scientists from ORNL interested in motivating young girls to pursue careers in science and engineering. ORNL researchers who helped organize the colloquium were Julie Watts, Katie Vandergriff, Bernadette Kirk, Deanna Barnett, and Linda Horton.

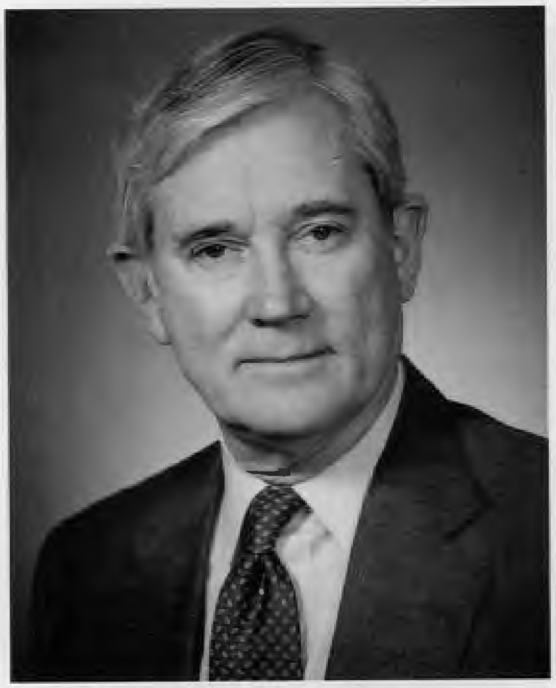
"We reached a variety of girls, especially those who have shown an interest in and an aptitude for science and math. We served a broad spectrum of young girls—not just the best students—who may need some motivation to take the high-school math and science courses that will allow them to major in technical fields in college," says Peggy Emmett, chairperson of the Greater Knoxville Math/Science Coalition, a sponsor of the event.

"We reached a variety of girls, especially those who have shown an interest in and an aptitude for science and math."

Various topics in life sciences, physical sciences, social sciences, math and computers, everyday engineering, and high-tech engineering were explored. Students attending the conference were from Knox, Anderson, Roane, Loudon, Morgan, Blount, Jefferson, Sevier, and Grainger counties. A teacher's program featured the Jasper Woodbury Video Series on critical thinking skills and problem solving. Teachers used techniques learned from the series in the classroom to make math and science more interesting.

SHADES was partially funded by grants from the Thompson Charitable Fund of the East Tennessee Foundation, the American Association of University Women Education Foundation, the American Nuclear Society, and Martin Marietta Energy Systems, Inc., as well as by the member organizations of the coalition.—*Yvonne Loveday*

State of the Laboratory Described by Trivelpiece



Alvin Trivelpiece delivered the State of the Laboratory address on March 9, 1994, at ORNL.

Trivelpiece said he is optimistic about ORNL's future projects.

During his annual State of the Laboratory address on March 9, 1994, ORNL Director Alvin Trivelpiece said that he has come to realize there is "no such thing as a normal year."

Trivelpiece, who is also vice president of Martin Marietta Energy Systems, Inc., told an audience of ORNL employees and guests that the inauguration of President Clinton, and his subsequent appointment of Secretary of Energy O'Leary, had greatly affected ORNL. He noted that O'Leary's strategic plan, released in 1994, is based on input from DOE staff, laboratories, and other stakeholders.

Still, Trivelpiece said, things "can't be too gloomy," because President Clinton has shown support for the Advanced Neutron Source (ANS) by including it as a line item in his proposed budget this year.

In discussing highlights for 1993, Trivelpiece mentioned the celebration of ORNL's 50th anniversary and recognized the creators of the special *ORNL Review* issue, saying "the publication makes one realize that ORNL has a proud history and has been involved in many matters that have shaped world affairs."

Trivelpiece recognized the ORNL winners of the three R&D 100 Awards presented by *R&D* magazine in 1993. This achievement brings the Laboratory's total of these awards to 72. He also commended former Metals and Ceramics Division staff member Bill Manly for receiving the National Medal of Technology and Larry Hawk of the Engineering Technology Division for receiving the Rolex Award.

Trivelpiece said he is optimistic about ORNL's future projects, explaining that some form of the Center for Biological Sciences may eventually be funded. " He also is confident that the ANS, a research facility that will accommodate up to 1000 users, will be constructed at ORNL.

Other construction projects he discussed included a new Guest and User Building at the main portal and a new Measurement and Controls Center near Building 2000. Trivelpiece commended the Engineering Organization of Energy Systems for devising a "master building plan" for ten new office buildings to be constructed at ORNL over the next few years.

Trivelpiece reminded the staff of an important DOE mission for the national laboratories: to provide science education to help inspire students to enter fields of science, technology, and mathematics. "The Laboratory has done a good job in this area," he said. "We recently welcomed our 100,000th student at the Ecological and Physical Sciences Center."

Because of the importance of educating and inspiring students as well as attracting highly qualified scientists and engineers to ORNL, Trivelpiece said the new vision statement for the Laboratory is the following: "ORNL should strive to be a place that is so well recognized for its excellence that students in certain fields of science and engineering regard working at the Laboratory as an essential element in their education."

Noting that greater than one-third of the 4400 guest scientists at ORNL are from private industry, Trivelpiece said that increased external attention has posed many questions for ORNL. "The Laboratory must show the public the value of science. We must now explain what we do and why we do it." *—Sharon Boudreaux*

Radio-Controlled Car Sweeps Up Tank Trash

Cleaning up waste is not child's play, but Don Box of ORNL's Chemical Technology Division has done it with a toy—a $50 radio-controlled car.

Box, inventor of the pressure-driven PNEU-WORM robot for inspecting pipes and the 1994 Scientist of the Year for Martin Marietta Energy Systems, Inc., thought of a way to clean up the trash left by the manufacturer in a diesel fuel tank it sent to ORNL. He lowered a camera and lights into the tank through a 15-centimeter (6-inch) hole and observed slag, pellets, wire, and styrofoam. He decided he needed a vehicle to pull a vacuum hose around the bottom of the tank to suck up the trash.

Don Box operates the remote-controlled vacuum cleaner used to remove trash from a tank at ORNL. *Photo by Steve Eberhardt.*

Box remotely steered the radio-controlled car around the bottom of the tank to the scattered piles of trash.

So Box bought a $50 radio-controlled car and attached a camera, lights, and vacuum hose to the chassis. Then he removed the wheels so he could fit the chassis and its attachments through the hole. Finally, he lowered the wheels into the tank by hand and reattached them to the car.

Guided by the camera images, Box remotely steered the radio-controlled car around the bottom of the tank to the scattered piles of trash. All together, Box vacuumed up a half cup of trash.

Box says he chose the radio-controlled car over other devices for the job because of the cross braces that connect the sides of the rectangular 3.6 meter (12 foot) by 1.5 meter (5 foot) by 1.2 meter (4 foot) tank to hold its shape under pressure. The car could be more easily placed in the tank and manuevered around it.

"The radio-controlled car," he notes, "was best able to do the job at hand."
—Carolyn Krause

ORNL Document Aids Midwest Flood Victims

In early summer of 1993, the rain-swollen Mississippi River and its tributaries overflowed their banks in the Flood of the Century, causing major damage in thousands of homes in the Midwest. By late summer and fall, many of the victims were following the advice of an ORNL-developed report entitled *Flood Damage: Guidelines for Restoring Your Home.*

The document, published by the Department of Energy, tells flood victims how to return to their damaged homes safely, clean and dry out their homes, deal with the effects of flood water, rebuild their homes, and upgrade insulation and replace appliances for increased energy efficiency.

"We were asked to do this report because of the opportunity for improving energy efficiency in homes that needed to replace wet insulation and damaged appliances such as water heaters, air conditioners, heat pumps, and refrigerators," says George Courville, head of the Efficiency and Renewables Research Section in ORNL's Energy Division.

ORNL researchers have made mercury, barium, and copper oxide super-conductors.

Here's a sample paragraph: "A considerable effort will be expended to dry, repair, and restore most electrical equipment in the home. It may be much more cost effective to replace these appliances outright. By so doing, you will (1) gain a new system with manufacturer warranty, (2) have fewer maintenance problems, (3) be more confident in the reliability of the system, and (4) lower your utility bill by replacing appliances that are inefficient."

In late August 1993, DOE asked ORNL to produce a report to guide flood victims in restoring their homes. The need for such a document was recognized at a meeting of relief agencies dealing with the Midwest flood disaster.

ORNL drafted a report in a month and sent it to DOE. The department published the report and mailed copies quickly to a long list of state and local energy offices throughout the United States.

"This document," Courville says, "had a fast turnaround, thanks to a good team effort." As a result of this work, the ORNL team was recognized for exceptional support to recent "emergency" requests by the director of the DOE's Office of Building Energy Research.

ORNL's Energy Division also provided display materials on buildings for Secretary of Energy Hazel O'Leary's kickoff of Energy Awareness Month and President Clinton's announcement of the Climate Change Action Plan.

Flood Damage: Guidelines for Restoring Your Home was researched and written by John Tomlinson, Jan Kosny, and Melissa Voss, with help from Pat Love and Jeff Christian; all are with ORNL's Energy Division. Editing and assembly of the document were done by Deborah Counce and Leroy Gilliam, both of Information Management Services of Martin Marietta Energy Systems, Inc. Information was also provided by Brookhaven National Laboratory and Joseph Lstiburek, a consultant from Building Science Corporation.

A DOE-hired support contractor has prepared a new version of the ORNL document complete with figures.

Mercury Promising for High-Temperature Superconductor

Mercury in the form of an oxide may be a promising ingredient for high-temperature superconducting material based on experiments performed in Russia, France, Switzerland, Texas, and Oak Ridge. A high-temperature superconductor offers zero resistance to the flow of electricity at a critical temperature called T_c.

In March 1993, Russian and French researchers reported in the journal *Nature* that a new material composed of mercury, barium, and copper oxides becomes a superconductor at 94 K. In May 1993, researchers at ETH in Zurich reported in *Nature* that a mixture of mercury, barium, calcium, and copper oxides remained superconducting at 133 K.

Then Paul C. W. Chu, the University of Houston scientist who discovered in 1987 that yttrium-barium-copper oxide could be a superconductor at 91 K, published a paper on mercury compounds in *Nature*. He announced that these mercury compounds show a drop in electrical resistance at around 153 K under high pressures of about 150,000 atmospheres. Chu also told *Time* magazine in October 1993 that he had pushed the temperature for the onset of superconductivity up to 164 K (–109°C) for the same compound. However, the sample resistance becomes zero only at 134 K.

View of the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory.

At ORNL Mariappan Paranthaman and Jorulf Brynestad, both of the Chemical and Analytical Sciences Division, have made mercury, barium, and copper oxide superconductors with a T_c of 95 K. Recently, they have also reproduced the T_c of 134 K with a mercury-based material.

"The studies using high pressures can predict only the upper limits of the T_c's of these materials," Paranthaman says. "The race is still on to stabilize these materials at 164 K by suitable chemical substitutions."

Jim Thompson and Dave Christen, both of the Solid State Division, and Don Kroeger of the Metals and Ceramics Division have been characterizing the materials for their magnetic properties and their capabilities for pinning magnetic flux lines (produced when superconductors are placed in a magnetic field) to ensure that electrical conductivity will continue without energy loss. Based on their work, several papers have been published already. Christen and Thompson have also reviewed the current problems at high T_c in the July 1993 issue of *Nature*.

ORNL Helps Set Fusion Record

At the Princeton Plasma Physics Laboratory in Plainsboro, New Jersey, late Friday afternoon, December 11, 1993, more than 150 researchers and staff applauded the achievement of a historic first: the controlled production in a fusion reactor of more than 6 million watts of power.

ORNL researchers Masanori Murakami and Charles Bush were present at the Tokamak Fusion

Test Reactor (TFTR) as scientists beat by 4 times the previous record of 1.7 million watts, set in 1991 by a European reactor. This record-setting experiment used a fuel mixture composed of equal amounts of deuterium and tritium, the mixture required for practical amounts of fusion power.

ORNL researchers began participating in the TFTR experiments more than 10 years ago. Murakami, who served as group leader of the 15-member ORNL team, returned to the Princeton Plasma Physics Laboratory 2 years ago and was present at the record-setting event. "We have been dreaming about producing fusion power for a long time," Murakami says. "It was a real honor that we could participate in the actual experiment."

A future goal will be to sustain a fusion reaction that requires no input of energy after the reactor starts.

Experiments at the TFTR, which will continue through most of 1994, will yield data important to the design of future reactors. For the first time, these experiments will enable researchers to confirm that the particles produced will help sustain the temperature of the fusion reaction.

Fusion, the process that powers the sun, is a reaction in which lightweight atoms, such as hydrogen, are squeezed together at high temperatures until they fuse, releasing energy in the process. The researchers' goal is to harness more energy from the reaction than is needed to run a fusion reactor.

"We felt really honored to be part of this event, as well as participants in the development of a process that eventually should benefit mankind," says Bush, who has participated in the fusion work at Princeton University for nearly 10 years. "Our next goal will be to increase the output to 10 million watts."

As part of the effort leading to the historic accomplishment in December 1993— which scientists compared to the Wright brothers' initial flight or the first time humans rubbed sticks together to make fire — ORNL researchers helped monitor the temperature (up to 400 million degrees Celsius, or 720 million degrees Fahrenheit) of the reacting materials, which included mixtures of special forms of hydrogen. They also helped to determine how efficiently reactions occurred, how well the materials burned, and how effective the reactor was in containing the energy.

In citing key benefits of fusion, Bush says, "It would replace fossil-fuel burning plants that put a lot of pollutants into the air. It would create less waste than that produced from the current fission method. Fusion is a clean energy source, and the radioactivity produced is much less than that from a fission reaction."

Murakami says that achievement of the goal of using fusion to generate electric power is probably still billions of dollars and three or four decades away. A near-term goal is to sustain a fusion reaction that requires no input of energy after the reactor starts.

Other scientists from ORNL's Fusion Energy Division most recently involved in experiments leading up to and including the historic experiment include Larry R. Baylor, Timothy S. Bigelow, Stephen K. Combs, George R. Dyer, Charles R. Foust, Michael J. Gouge, Gregory R. Hanson, Stanley L. Milora, A.L. (Lou) Qualls, David A. Rasmussen, and John B. Wilgen.—*Brian Daly*

ORNL Helps Understand Better Fusion Performance

Recent improvements in the performance of experimental fusion devices have been achieved by enhancements in confining a fusion plasma, a superhot gas made of hydrogen nuclei and electrons. A new mode of operation has been found for better confining plasma, and researchers at ORNL's Fusion Energy Division have provided a theoretical basis for its understanding.

A major problem facing researchers in their effort to achieve fusion energy—the release of considerable energy from the joining of light nuclei to form heavier nuclei—is containing the plasma. To achieve fusion, matter must be heated to hundreds of millions of degrees. At such temperatures, matter exists only in the form of plasma, so solid surfaces cannot be used to contain the plasma. Thus, magnetic fields are used to confine plasmas.

"It is critical that plasmas stay confined long enough for the necessary fusion reactions to take place," says Benjamin Carreras, a researcher in ORNL's Fusion Energy Division and one of the leading theoreticians in the international fusion program. "However, the time they remain confined is limited by turbulence. Plasma turbulence is the major cause for energy losses from the plasma. The understanding of plasma turbulence is the outstanding physics problem for magnetically confined plasmas."

Carreras, a corporate fellow of Martin Marietta Energy Systems, Inc., says that turbulence creates disorder and increases energy losses within the fusion device, causing the "magnetic bottles" to be less effective in holding a plasma in place. However, under certain conditions, turbulence can heal itself and confinement of the plasma improves. The normal mode of operation is called the low-confinement mode, or L mode, and the improved mode is called the high-confinement mode, or H mode. "The L mode is disordered," Carreras says, "and the H mode is ordered."

Carreras compares the laboratory plasmas to the sun. He says that the sun's intense heat causes turbulent motions and loss of its internal heat. However, part of the turbulent energy goes into the rotation of the solar atmosphere, which is an organized process. This process is similar to the H mode of fusion device operation.

Carreras, Ker Chung Shaing, Donald Spong, and others in the Fusion Energy Division in collaboration with researchers at the University of California at San Diego have provided theoretical understanding of the transition of plasma from the L mode to the H mode in the DIII-D Tokamak operated by General Atomic in San Diego, California. They have modeled the plasmas on supercomputers using the equivalent of a million coupled nonlinear differential equations.

"Because plasmas have charged particles that spiral around magnetic field lines, they can induce their own currents in the confining magnetic fields," Carreras says. "These induced currents modify the magnetic field and can break confinement, leading to plasma instabilities, turbulence, and energy loss."

In the normal low-confinement mode, the time of plasma confinement (energy confinement time) decreases as heating power increases. However, as the injected power increases further, a sudden transition occurs from the L mode to the H mode. At this transition, there is a sharp increase in the plasma rotation, and as a consequence, a radial electric field is generated. The generation of this electric field, which leads to "shear flow," creates a transport barrier at the plasma edge and the plasma confinement goes from L mode to H mode.

Through plasma modeling, Carreras says, ORNL researchers have linked shear flow to turbulence. "When shear flow is up," he says, "the turbulence fluctuation level is low."

The ORNL researchers use the same mathematics as population biologists, Carreras explains, noting that shear flow may be compared to cats and turbulence fluctuations to mice. "When the cat population is up," he says, "the mouse population is down, and vice versa."

A new mode of operation has been found for better confining plasma, and ORNL fusion researchers have provided a theoretical basis for its understanding.

The high plasma confinement in the H mode has a potential negative effect: It can retain the helium ash produced by the deuterium-tritium fusion reactions. Because helium particles can radiate away the energy of fusion, the plasma could cool down, degrading tokamak performance. Don Hillis of the Fusion Energy Division and his collaborators have experimentally investigated this effect in the DIII-D Tokamak. They have shown that edge-localized modes (ELMs), naturally occurring periodic losses of helium particles near the plasma edge, provide a mechanism for removing the helium ash (which can be exhausted from the tokamak vessel by a vacuum system). These results show the importance of the H mode operation for fusion reactors. They also point out the need to develop control systems—ways to change heating power and magnetic field configurations to regulate ELM behavior—to ensure effective operation of fusion devices.

Another important effect of the helium, or alpha, particles produced by deuterium-tritium fusion is a new form of turbulence recently observed in experiments. This turbulence is driven by the alpha particles' initial velocity, which exceeds the rate at which magnetic oscillations can propagate in the plasma, roughly analogous to the atmospheric disturbances produced as an

Scientific visualization of a toroidal surface inside a tokamak plasma with associated magnetic field lines. The shading of the toroidal surface is proportional to levels of turbulent fluctuation from a plasma instability in an experimental fusion reactor.

Under certain conditions, turbulence can heal itself and confinement of the plasma improves.

accelerating airplane exceeds the velocity of sound. A new theoretical approach to understanding this phenomenon was presented in a recent paper by Spong, Carreras, and Lew Hedrick. For this paper Spong received the 1994 Author of the Year award from Martin Marietta Energy Systems, Inc. The fluid model they developed also indicates the linkage between shear flow generation and plasma stabilization. Products of the model include scientific visualizations available to computer network users through the Fusion Energy Division home page of ORNL's World Wide Web server (an example is shown above). The ORNL model is being used to predict plasma stability limits for the TFTR device and is expected to be relevant to the design and operation of the proposed International Thermonuclear Experimental Reactor (ITER).

Carreras' leadership has led to the development of new improved magnetic configurations for two experimental devices— ORNL's Advanced Toroidal Facility stellarator and a related Spanish experiment under construction known as the TJ-II flexible heliac. The theoretical understanding provided by Carreras and his group should continue to guide improvements in plasma confinement.—*Carolyn Krause* ornl

Inside of the General Atomic Company's DIII-D Tokamak in San Diego, California. The wall tiles are specially coated to reduce impurities in the plasma.

Drought Tolerance of Trees Probed

Some plants tolerate water shortages by accumulating high concentrations of solutes.

Tim Tschaplinski (left) and Jerry Tuskan study the drought tolerance of poplar trees by characterizing their growth and photosynthetic responses to water shortages as well as carbon and nitrogen metabolism under stress.

Drought tolerance of various species of poplar trees *(Populus)* and their hybrid offspring is the subject of a cooperative research and development agreement recently signed by Energy Systems and Boise Cascade Corporation. The purpose of the CRADA is to verify that certain biochemical indicators can be used to predict the clones of poplar that best survive episodic periods of little or no rain and remain productive.

Principal investigators of the CRADA at ORNL are Tim Tschaplinski and Jerry Tuskan, both members of the Environmental Sciences Division (ESD). They are also researchers in ORNL's Biofuels Feedstock Development Program.

Scientists have shown that some individual plants and plant species tolerate water shortages by maintaining or accumulating high concentrations of dissolved compounds, including nutrients. Such solutes may serve as biochemical indicators of drought tolerance. Mechanisms of drought tolerance vary among species and individuals.

The ORNL researchers published two papers in the *Canadian Journal of Forest Research* that describe their earlier research detailing the biochemical basis of drought tolerance in six poplar clones. They isolated 60 to 80 plant compounds, or metabolites, that may be involved. High concentrations of several metabolites were found in poplar tree species identified as drought tolerant.

For the CRADA, ORNL researchers will validate the use of these plant metabolites as biochemical indicators, or molecular selection criteria, for drought tolerance in poplar trees. Boise Cascade will grow 2-year-old hybrid *Populus* trees from seven clones under six levels of moisture stress at each of two sites in their drought-stress facility in eastern Oregon and Washington. ORNL will collect leaf samples from these trees, measure the total amount of solutes, and analyze the samples to determine the concentrations of the most abundant solutes that may be indicators of drought tolerance.

In work related to the CRADA, ORNL researchers will screen 60 genotypes—individuals sharing a unique genetic makeup—to assess the validity of using metabolites as drought-tolerance indicators in large-scale field trials. Molecular markers that prove to be correlated with drought tolerance will be mapped on the *Populus* genome.

The ability of *Populus* clones to tolerate drought is critical to short-rotation hardwood culture for the production of wood fiber. Because much of the hardwood fiber will be grown under irrigation to maximize production, the identification of drought-tolerant genotypes will enable industry to manage water resources more efficiently. Boise Cascade, a major U.S. producer of *Populus* fiber, hopes to use the technology to maintain improved growth rates in hybrid *Populus* while minimizing use of irrigation water.

If the biochemical and molecular markers are validated, *Populus* clones found to be most drought tolerant may be used as dedicated energy feedstocks—sources of wood used for production of liquid transportation fuels—in a renewable energy industry. The ability to use biochemical and molecular markers will reduce the amount of time, money, and effort needed to identify and test drought-tolerant genotypes.

One of the goals of the Energy Policy Act of 1992 is to demonstrate the commercial use of renewable energy and dedicated energy feedstocks. The development and selection of drought-tolerant *Populus* clones and the large-scale field testing of such genotypes will help the Department of Energy meet its goals.

Gas Heat Pump Licensed to Carrier Corp.

A heat pump technology developed under ORNL's technical oversight has been transferred to a leading manufacturer of heating, ventilation, and air-conditioning equipment. The heat pump uses natural gas as the energy source and ammonia and water as substitutes for ozone-depleting refrigerants.

A licensing agreement has been signed between United Technologies Carrier Corporation and Phillips Engineering Company, a small business in St. Joseph, Michigan, that has been developing heat pump technology under ORNL's oversight (under a subcontract) since October 1982. The agreement gives Carrier the right to manufacture and market natural gas absorption heat pumps based on a proof-of-concept design developed by Phillips Engineering.

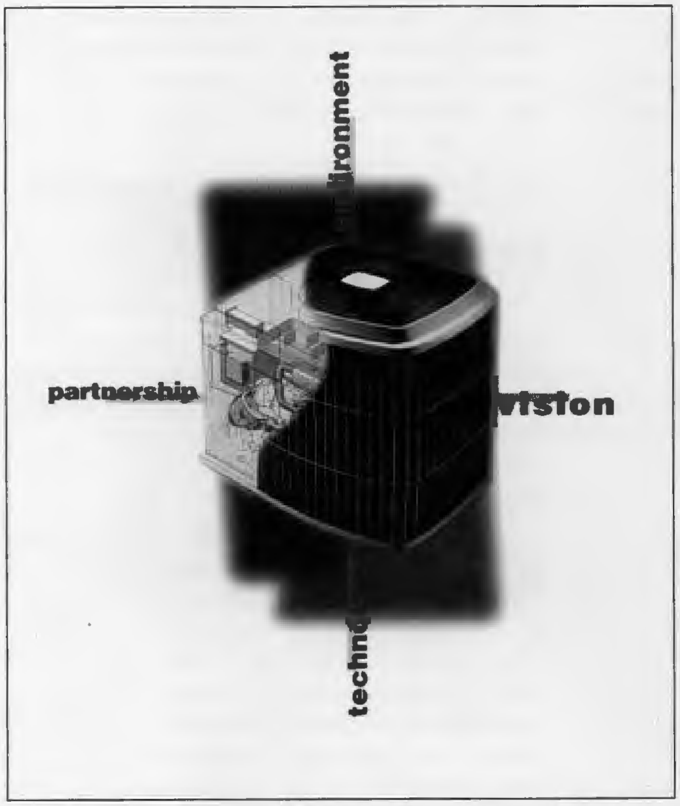
The development work was funded by DOE through ORNL's Buildings Technology Program, and the technical monitor for the project was Robert C. Devault and his colleagues in ORNL's Energy Division.

DOE is forming a new partnership in which the Gas Research Institute, American Gas Cooling Center, Carrier Corporation, and ORNL will work together to support final development and commercialization of the generator-absorber heat exchange (GAX) technology pioneered by Phillips Engineering under ORNL's guidance.

The goal of the new National GAX Heat Pump Program partnership is to introduce GAX heat pump products into residential and commercial markets. The GAX cycle represents a revolutionary advance over the absorption technology used in the gas-fired absorption air-conditioning market of the 1960s and 1970s.

ORNL will provide technical support and program guidance in an effort to achieve even higher heat pump efficiencies. DOE will provide

The heat pump uses ammonia and water as substitutes for ozone-depleting refrigerants.



An agreement involving ORNL and two private companies will bring highly efficient generator-absorber heat exchange, or GAX, heat pump technology to the market.

funding for the partnership through its Building Equipment Division's Office of Energy Efficiency and Renewable Energy; the DOE program manager for the partnership is Ronald J. Fiskum.

A major advantage of the GAX cycle is its use of ammonia and water as working fluids, rather than chlorofluorocarbons or hydrochlorofluorocarbons, refrigerants that contribute to ozone depletion and global warming.

For utilities, GAX technology is desirable because it uses gas and is more efficient than current heating and cooling systems. Hence, it reduces peak demands for electricity in summer and gas in winter, thus leveling annual energy use and reducing the need for more power plants. For consumers the cycle's higher efficiency translates into lower monthly energy bills.

The GAX technology is also envisioned to make the United States more competitive in world markets, fostering economic growth—a goal of DOE's strategic plan. Energy efficiency and security, global economic opportunities that create U.S. jobs, and environmentally sound technology all are considered benefits from the cooperative pursuit of this new technology.

Computer Models Car Crashes

Automobile manufacturers must crash models of their new cars to determine if they meet safety and crashworthiness standards for protecting passengers during accidents. Because the cost of a single car crash test is $50,000 to $750,000, an attractive alternative to crunching metal is crunching numbers.

Inexpensive car crash simulations that give about the same information as an actual car crash have been performed in a few days to a few weeks on supercomputers. But at ORNL, a car crash can be simulated and analyzed on the Intel Paragon XP/S supercomputer in 8 hours at an even lower cost. The ORNL supercomputer consists of 512 parallel processors that can work on many parts of the same problem at the same time.

"Using data supplied by the U.S. Department of Transportation, we have done a half-day analysis of a 4-door sedan crashing into a lamppost at 35 miles per hour and of a head-on collision between two cars," says Thomas Zacharia, a group leader in ORNL's Metals and Ceramics Division.

Zacharia is currently serving as acting director of the new Computational Center for Industrial Innovation in ORNL's Center for Computational Sciences. This new center will be a focal point

At ORNL, a car crash can be simulated and analyzed on the Intel Paragon computer in 8 hours.

View of the 512-processor Intel Paragon XP/S computer at ORNL. It is being used to not only to solve Grand Challenge problems but also to model car crashes.

for ORNL's interaction with industry on high-performance computing.

Zacharia is also ORNL's representative to the Supercomputing for Automotive Applications Partnership of the U.S. Consortium on Automotive Research (USCAR). Other representatives on this committee are from Chrysler, Ford, and General Motors and from Argonne, Livermore, Los Alamos, and Sandia national laboratories.

USCAR is one of the chief participants in the Clean Car Initiative announced by President Clinton in 1993. The goal of this initiative is to design new cars that emit less pollution and are safer and more efficient than current vehicles. To make cars that travel 60 to 75 miles per gallon of fuel (compared with 20 to 30 mpg in today's cars), the engine system must be redesigned for more efficient combustion and lighter materials must be used.

"ORNL is a leader in using massively parallel supercomputing for simulating car crashes and modeling materials and manufacturing processes for cars," Zacharia says. "The information generated can be used to analyze the efficiency and safety of new car designs for the automotive industry."

Lighter-weight materials—aluminum alloys, magnesium, and polymer composites—will be used in new cars to make them more energy efficient. Parallel supercomputing, Zacharia notes, will help the automotive industry design next-generation vehicles using lighter materials while meeting safety standards.

Zacharia, who came to ORNL 7 years ago to do process modeling, first used parallel computers to model the impacts of dropping or crushing a radioactive waste container during a truck or train crash. This work was performed in collaboration with Gus Aramayo of the Engineering Organization of Martin Marietta Energy Systems, Inc. Then, with support from the Laboratory Director's Research and Development Fund, Zacharia showed the same code could be used to simulate the results of car crashes.

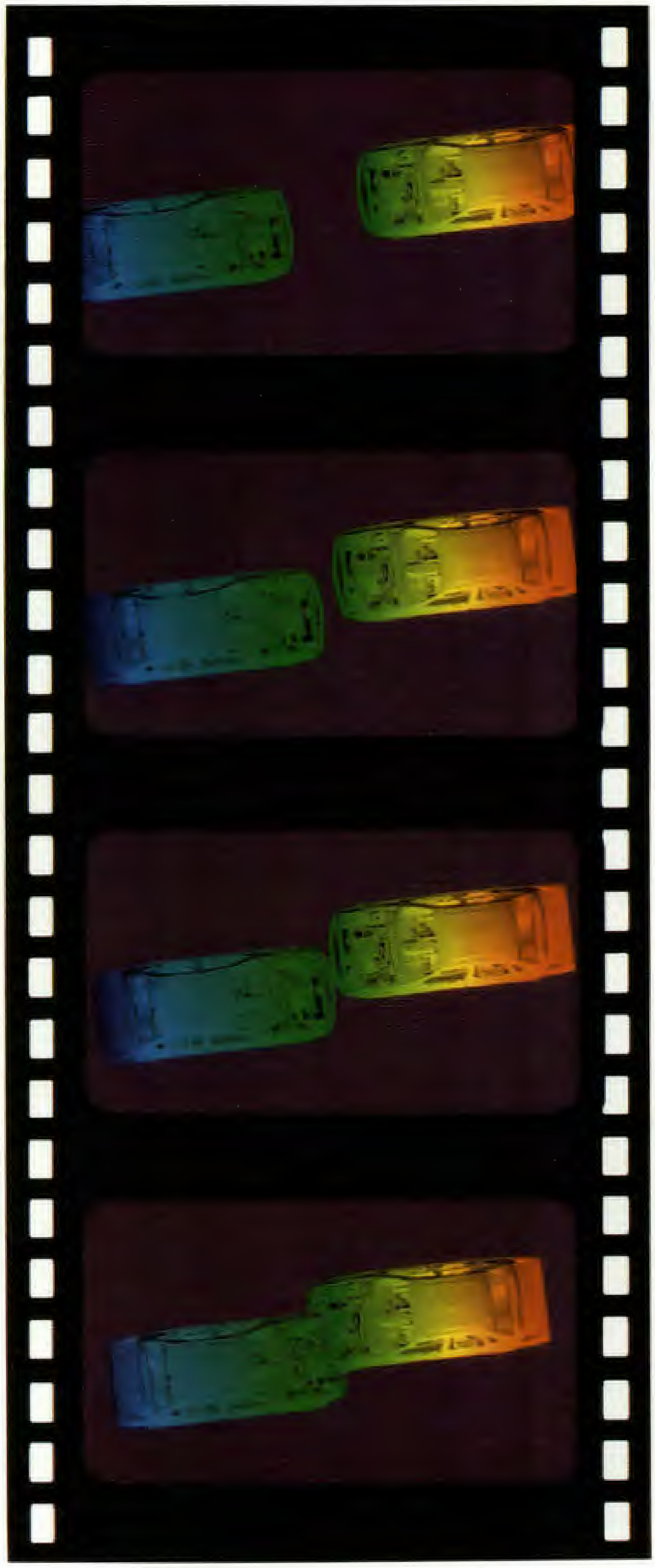
Zacharia and his group are working with USCAR and in a project under a cooperative research and development agreement involving DOE national laboratories called Materials by Computational Design. The results of these collaborations, he says, will likely influence the designs and choices of lightweight materials for American cars of the future.

In car crash analysis at ORNL, the processors calculate the local deformation and the energy absorbed during a car crash for each of 56,000 points, or finite elements. These include 3000 spot welds as well as 248 different structural materials. Zacharia, his research group, and Ross Toedte of Energy Systems' Visualization Laboratory have produced colorful still and animated images of smashed cars, showing the dramatic impacts of collisions.

Zacharia and his colleagues also have used parallel computing to simulate shape changes during the forming of superplastic aluminum components. This lightweight material, which is as stretchable as chewing gum, is a candidate for car hoods and doors. The capability to form superplastic aluminum was developed at the Oak Ridge Y-12 Plant for use in weapons components.

"Strains in superplastic aluminum have been modeled on the Y-12 Plant serial computer in a month," Zacharia says. "We did this modeling on 128 processors of the 512-processor Intel Paragon in 6 hours."

Zacharia says he and other DOE national laboratory scientists are working on developing the next-generation computer codes for car crash analysis and engine combustion analysis. ornl



Visualization on a film strip of the effects of a head-on collision of two cars based on calculations by ORNL's massively parallel Intel Paragon XP/S computer.

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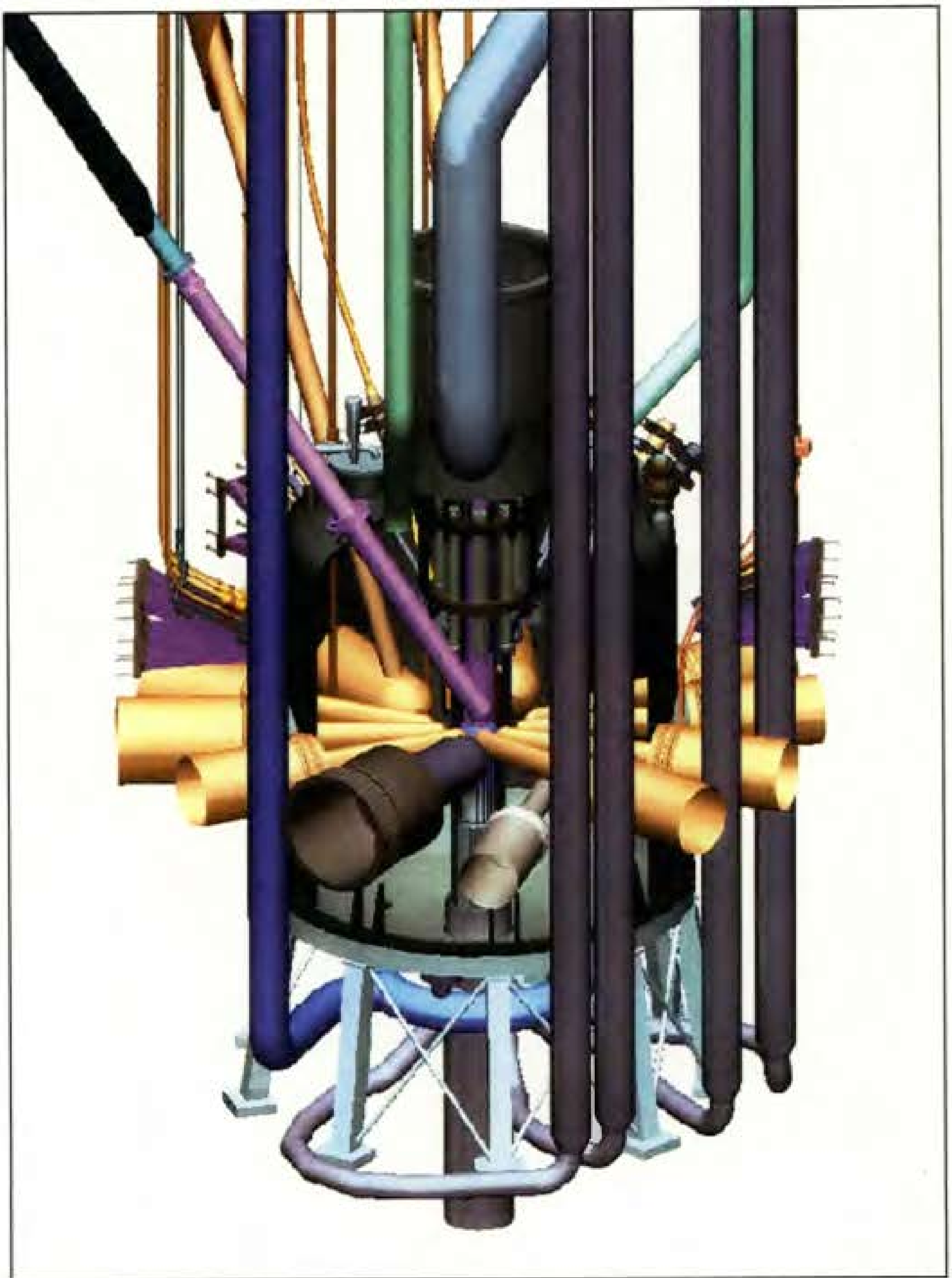

Drawing of the proposed Advanced Neutron Source research reactor showing the core and neutron beam tubes. See articles beginning on p. 2.

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