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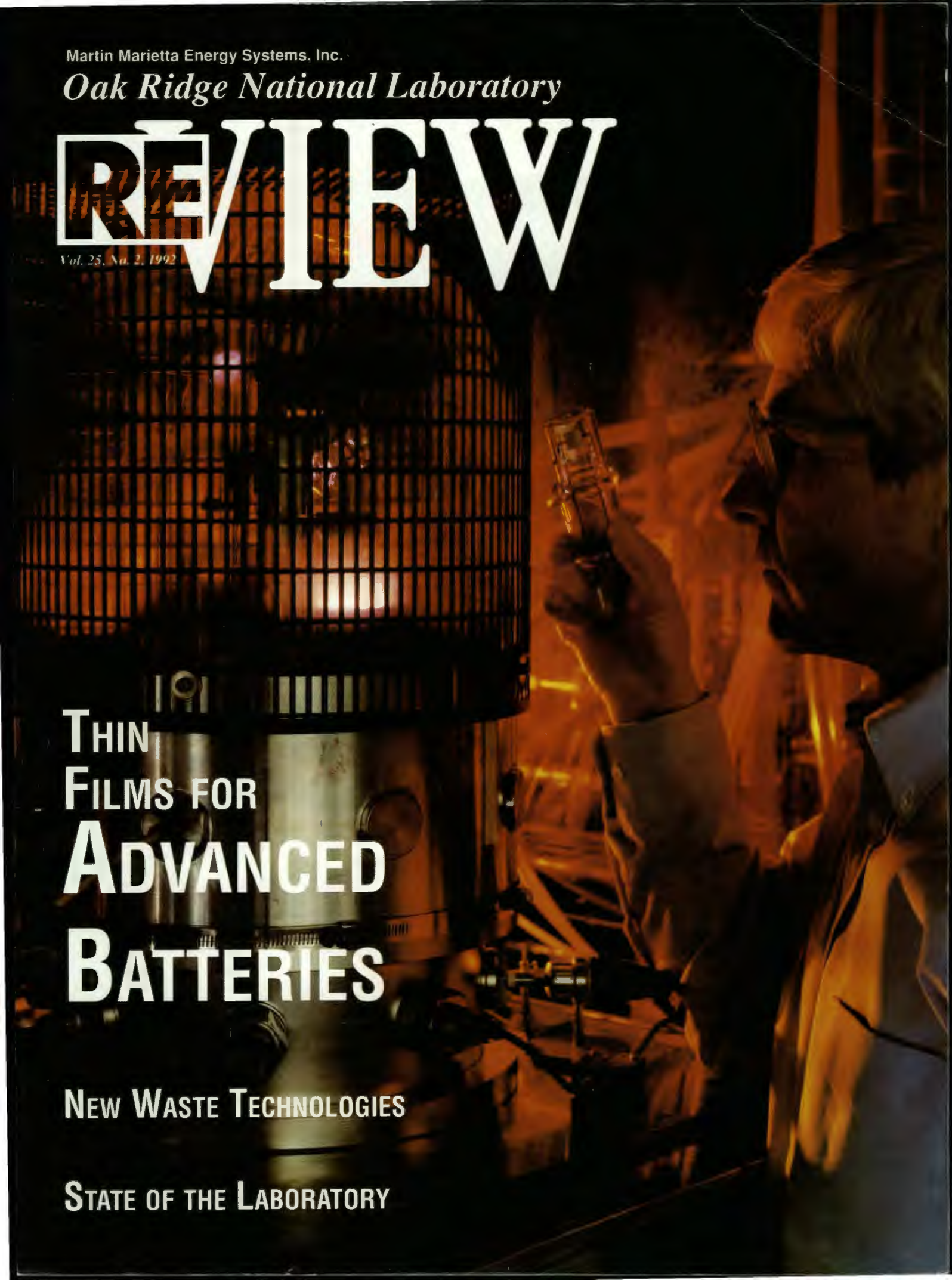

THIN FILMS FOR ADVANCED BATTERIES

NEW WASTE TECHNOLOGIES

STATE OF THE LABORATORY

ON THE COVER

John Bates examines a thin-film lithium battery in the light of the nitrogen glow discharge in the vacuum deposition chamber used to produce microbatteries at ORNL's Solid State Division. The nitrogen gas reacts with lithium orthophosphate to form a new battery electrolyte film discovered at ORNL. See the article on p. 46. *Photo 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 technologies.

State of the Laboratory—1991: Strengthening R&D

By Alvin W. Trivelpiece

Editor's note: On February 6, 1992, ORNL Director Alvin W. Trivelpiece delivered his third State of the Laboratory address at the American Museum of Science and Energy in Oak Ridge. The following is an updated, edited version of his talk.

In his third State of the Laboratory address, Trivelpiece emphasized the role of organizational changes and enhanced computing capabilities in supporting research and development.

As I look back on 1991 at Oak Ridge National Laboratory, some famous quotations come to mind. The first is the ancient Chinese curse, "May you live in interesting times." The second, from Charles Dickens' *A Tale of Two Cities*, is, "It was the best of times, it was the worst of times." These quotations certainly hit the mark for this past year.

I suppose that if we had invented a new Chinese calendar, 1991 would be "the Year of the Frog" because of the media attention we received when some frogs left a contaminated ORNL pond and, after being run over by cars, were found to be slightly radioactive. By the same token, 1990 was the Year of the Tiger because of the Department of Energy's Tiger Team assessment to determine whether ORNL was in compliance with environmental, safety, and health (ES&H) regulations.

Because peace broke out all over the world, 1991 qualified for a "best-of-times" rating. But I suspect that some of our friends and colleagues in the former Soviet Union may have regarded 1991 as the worst of times. The U.S. economy doesn't seem to be in a favorable state either. We have a deficit and a foreign trade imbalance, and we certainly have an unemployment rate that is higher than desirable. The U.S. government is now under a great deal of pressure to both control spending and support projects in environmental restoration and waste management that a few years ago wouldn't even have been considered.

I want to remind you of some of the events that may be responsible for our current situation. Because these events may color our attitude, we should examine them and perhaps even adjust our thinking about our situation so that we are prepared to strengthen research and development (R&D) at the Laboratory and in this community.

Many of you remember—some perhaps fondly—the U.S. Atomic Energy Commission (AEC). This administratively lean and technically rich organization employed many scientists and engineers in key management positions. For some of its years, it even had a Nobel Prize–winning chemist, Glenn Seaborg, as its chairman.

The AEC had a clear mission to produce nuclear weapons, enrich uranium, do fundamental research in physical and life sciences, and advance the cause of nuclear power. To meet its mission, the AEC used industry, universities, and its own facilities. It performed its mission in a way that seems almost pastoral compared with today's mode of operation.

The AEC had many ups and downs. For example, a test ban in the late 1950s resulted in a substantial cutback of activities. However, our stable, reliable enemies in the former Soviet Union began firing off a bunch of weapons at their test site, so the AEC's weapons production activities picked up again. In the late 1960s, the

"Because peace broke out all over the world, 1991 qualified for a "best-of-times" rating."

A few dozen frogs that migrated from an ORNL pond were found to be radioactive after they were run over by cars. The incidents attracted the attention of the news media, even though the radioactive frogs posed no health hazard unless eaten in quantity. (The crushed frogs were disposed of as radioactive waste.)

Enjoying the social hour after the State of the Laboratory address were, from left, Clyde Hopkins, president of Martin Marietta Energy Systems, Inc.; Alvin Trivelpiece, ORNL director and an Energy Systems vice president; Herman Postma, former ORNL director and retired senior vice president of Energy Systems; and David Reichle, ORNL associate director for the Environmental, Life, and Social Sciences.

AEC fusion program enjoyed a burst of activity because of the interest in conducting fusion experiments on tokamaks (conceived by the Soviets), and ORNL benefited by being one of the first laboratories to build and operate a tokamak outside the Soviet Union. Those were really exciting, fulfilling times when the employees of the AEC and its contractors thought their work was important to the nation's survival. We had no doubt, uncertainty, or anxiety about what we were doing.

When I worked for the AEC from 1973 to 1975, Americans began experiencing lines at the gasoline pumps because of shortages of imported oil—the so-called energy crisis. Dixy Lee Ray, AEC chairman at that time, convened an AEC group and asked it to determine ways to make the United States less dependent on oil imported from unstable countries; as a result, the AEC issued a report generally known as the "Ten Billion Exercise." Some of its proposed elements for making the United States energy independent actually were implemented.

Bureaucratic Enrichment

For the AEC, the chief issue of the day was not the energy crisis. Rather, it was the concern that people had over the AEC's dual role as both promoter and regulator of civilian nuclear power. That concern resulted in considerable pressure to break up the AEC, and, at the beginning of 1976, it was divided into the Nuclear Regulatory Commission and the Energy Research and Development Administration (ERDA). The creation of two agencies from one is important because it started a process I call bureaucratic enrichment.

Bureaucratic enrichment profoundly affected us all. Suddenly, nonnuclear and other programs began to sprout up everywhere. The weapons laboratories began experiencing severe cutbacks and considerable uncertainty, but the ERDA programs were stable. However, as the political winds shifted in Washington, ERDA was replaced by the Department of Energy in 1978. James Schlesinger, a former AEC chairman, became the first Secretary of Energy, and bureaucratic enrichment was probably even accelerated at that time. Whether that's good news or bad news, I don't know; it's in the eye of the beholder. Certainly, the energy crisis is still a major concern.

DOE started programs to build plants for producing synthetic fuels. Some of the national laboratories even bought their first lumps of coal for experiments related to liquefying and gasifying coal. Americans lowered their

thermostats and drove 55 miles per hour. As a result of some other political events, it was suggested that DOE be abolished. DOE survived, but changes occurred, such as a reduction in a major program to build coal gasification plants, a rapid growth of weapons production, and a shift away from applied research in favor of basic research.

Watershed Events

From 1981 through 1987, I served as director of DOE's Office of Energy Research. In 1983, a woman entered my office and said, "Do you know there are 2.4 million pounds of mercury in the ground at Oak Ridge?" I was really tempted to say, "No, but if you hum a few bars, I'll see if I can pick up the melody," but I didn't. I was certain that this was a joke or a mistake and that several of those zeros should be taken off. It couldn't be that bad, I thought, but it turned out to be true that there was a lot of mercury that had been spilled, although the actual number turned out to be 350,000 pounds. I suspect that day was no better for Joe La Grone, manager of the DOE Oak Ridge Field Office, than it was for me when we learned about this heavy metal contamination resulting from weapons production at the Oak Ridge Y-12 Plant. The news resulted in some truly bad jokes about 6-inch fish that weighed 20 pounds.

The 1983 revelation about mercury in the soils and waters of Oak Ridge was the watershed event that resulted in a buildup of pressure nationally to clean up DOE production and research sites. Before then it was fairly easy for DOE managers to say, "Look, we are making realistic progress at a reasonable rate in cleaning up many of the sites for which we have responsibility."

After the mercury revelation, ES&H matters received substantially more attention. Some might say that another watershed event was the 1979 nuclear power plant accident at Three Mile Island. It was serious and clearly had a profound effect on the nuclear industry and the management of civilian nuclear energy programs. But I think the Three Mile Island accident was insignificant in comparison with the 1986 accident at the

Fred Hartman, director of ORNL's Biology Division, chats with Trivelpiece following the State of the Laboratory address.

Chernobyl reactor. I got caught up in all the department's activities concerning Chernobyl as I helped set up new committees and reviewed documents for Congress. It was a frantic period, but it was necessary because of the importance of preventing a repetition of the Chernobyl disaster. Direct consequences of that watershed event were the permanent shutdown of the N-Reactor at the Hanford Engineering Development Laboratory and the temporary shutdown of ORNL's High Flux Isotope Reactor (HFIR).

As a result of the Chernobyl accident, ES&H programs received increased emphasis at DOE facilities. The department began to focus on identifying the facilities that needed to be cleaned up first as well as the best methods to remediate them. It was clear that it would be just a matter of time before business changed.

Another watershed event was the surprise that Admiral James Watkins, the Secretary of Energy, experienced on Thanksgiving of 1989. A Federal Bureau of Investigation team came to DOE's Rocky Flats Plant in search of criminal environmental violations. This investigation led to the development of comprehensive environmental and safety audits. These are now called Tiger Team audits, and they are done at

"The 1983 revelation about mercury in the soils and waters of Oak Ridge was the watershed event that resulted in a buildup of pressure nationally to clean up DOE production and research sites."

"The American public is more concerned about the environment than ever before."

DOE facilities to ensure that they are complying with environmental laws, rules, and regulations.

Many of us look back with a certain fondness or nostalgia for the good old days of the AEC, but I don't think there is any way we can work as we did back then. The Laboratory staff has learned to operate in its present circumstances. The AEC and ERDA are gone, and the old ways of doing business are not coming back.

The American public is more concerned about the environment than ever before. Today, the public does not trust DOE. Members of the public want independent verification of the many facts we generate, and their demand for more audits and oversight will continue. Such audits are intrusive, invasive, and a fact of life. We are going to have to learn to work in this climate and compete for scientific and technical programs at the same time. It is not easy now, and it is not likely to get any easier.

In early 1991, the on-site Tiger Team assessment at ORNL had just concluded, and we prepared an action plan to correct some of the cited deficiencies. I am pleased to report that we have made really good progress, and I think we have some prospects for funding for some expensive projects. But correcting the deficiencies is not going to get easier either. We will experience conflicts between the need to clean things up to comply with regulations and the desire to operate scientific programs to serve our customers.

In the Year of the Tiger, we did the right thing. By meeting our goal of surviving those difficult circumstances, we are really better prepared and well positioned to work through the tough times ahead.

DOE Summit Meetings

A watershed event that occurred in 1991 may have as much effect on the Laboratory's future as any event mentioned thus far. It was the so-called "summit meeting," which took place September 17 and 18 in Leesburg, Virginia. There Secretary Watkins urged the DOE laboratory directors to hold off-site meetings with political appointees and DOE field office managers to discuss the problems of managing the laboratories.

By my recollection, it really was a unique event in the entire history of any of the government energy agencies. Secretary Watkins got intensely involved, rolled up his sleeves, participated with us, got into the arguments with everyone, and, although he clearly was the boss, he certainly behaved in many respects as an equal and worked very effectively during that period. As a result of that meeting, several working committees have been set up to look into new issues, and an agreement was made to involve the laboratory directors in developing and writing DOE orders.

The summit meeting may prove to be one of the really important events in the history of the DOE laboratories. The Secretary of Energy says he will meet with us periodically. The second meeting was held in March 1992, and we discussed a number of the issues we had no time for at the September summit meeting. The summit meeting focused primarily on roles and missions and ways to improve our laboratory performance. Already the summit meeting has proven to be a best-of-times event.

One of the ironies is that, over the years, the laboratory directors complained bitterly that DOE paid no attention to

To make ORNL's east parking lot safer and brighter, new holophane high-tower lights have been installed, replacing the old lighting system. The new energy-efficient lights, one of which is shown here, will provide more illumination over a larger area of the parking lot.The lighting system was installed by Allegheny Industrial Electric of Oak Ridge at a cost of $150,000.

Malcolm Stocks, sitting, and Al Geist discuss computer simulations of materials properties using the multi-processor Kendall Square system (shown in the photo), which was recently obtained by ORNL's new Center for Computational Science.

Julie Robinson works at an engineering workstation, which can run complex calculations that once could be done only by large mainframe computers.

them. Well, now the department is paying attention to us laboratory directors, and because such attention creates a lot of work, we are complaining about it. DOE just can't win!

Strengthening R&D: Bureaucratic Changes

An event that I hope will have some influence on the future of ORNL is the establishment of the R&D Strategic Planning Committee. The intent of this committee is to respond to a legitimate, longstanding complaint: management isn't paying any attention to the scientific and research programs at the Laboratory. Guilty as charged. The extenuating circumstances are that ORNL managers had to

concentrate on certain activities to ensure that the Laboratory would survive the Tiger Team audit. True, we diverted our attention away from research, but our intention now is to return to it. This new committee, which includes research associate directors and division directors as well as some working scientists and engineers, is a good group. We have met only a few times. We are still trying to feel our way along, but I think that this approach will improve our ability to compete for funding for research projects that would best use our experience and expertise.

A new Operations Committee will try to improve operations at the Laboratory. This committee includes representatives from research divisions and operating divisions. Its purpose is to find ways for the people who are responsible for operations to be more responsive to their customers. This committee will also look at the management work load and find ways to delegate management responsibilities to various groups through the empowerment of ORNL employees. A related activity is the establishment of new review committees for the operations divisions, similar to the review committees for our scientific programs. In this way, the customers who serve on a committee can evaluate a particular operating division and make recommendations for its improvement. We will also include on these committees some experts from outside laboratories and elsewhere within Energy Systems.

Strengthening R&D: Computing Capability

Besides these bureaucratic changes, the Laboratory can strengthen its R&D by using increasingly powerful computers. Research and development has embraced computers as much as the commercial world. In fact, a relatively new branch in the taxonomy of science is computing science, which complements experimental science and theoretical science.

One of my concerns when I first became director of the Laboratory was that we were not competing very well with our sister institutions in computing science, even though the Laboratory has more than 5000 computers of various sizes. Very few individuals in the Laboratory were working on problems on which progress could be made without access to a world-class supercomputer. As a result of this concern, I recruited Ed Oliver and appointed him director of the Office of Laboratory Computing. Oliver; Bob Ward, director of ORNL's Engineering Physics and Mathematics Division; Al Geist and Richard

Chuck Scott examines a tapered column of gelatin beads containing microorganisms that could be used for removing contaminants or producing chemicals. Scott is director of ORNL's new Bioprocessing Research and Development Center.

"To achieve excellence as an institution, we should strive to attract more graduate students and postdoctoral fellows."

Sincovec, both of Ward's division; Malcolm Stocks of the Metals and Ceramics Division; and others drafted a proposal in 1991 requesting funding under the new high-performance computing initiative that had been working through the DOE system. The competition was very tough, because competitors with whom we were playing had great resource advantages. But, because of our growing expertise in parallel computing, I am pleased that ORNL was one of the two sites selected by DOE to become high-performance computer research centers. Our goal will be to start solving complex scientific problems, called Grand Challenges, using a parallel supercomputer. We will first focus on modeling the transport of pollutants in groundwater and designing new alloys. We will receive $120 million over the next five years to establish and operate a new Center for Computational Science, and we will recruit a director to manage the center.

Let me comment on our success in becoming a computer center. It is often assumed that all it takes to win a project is a good proposal. We tend to forget that many dedicated employees at DOE and other government agencies actually fight hard for budget items that are important for our nation. Members of Congress and their staffs have also worked to ensure funding for the high-performance computing initiative. Many people deserve our collective thanks for bringing ORNL this opportunity. We have an obligation to do a good job for them and I am quite confident that we will do so.

Engineering workstations are powerful intermediate computing tools that are gaining wide acceptance. They can perform many calculations that once were run only on large mainframe computers. Unfortunately, ORNL has less than 100 engineering workstations, whereas some of our competitors have a few thousand. This is one area in which we hope to improve.

Computers are also important tools for educating future scientists. On Saturdays, high school students come to the Laboratory to attend the Saturday Academy of Computing and Mathematics. We patterned this school after the Fermi Laboratory's Saturday Academy for High-Energy Physics. We encourage high school students to work on computers in what is turning out to be a very effective and popular program.

Interdisciplinary Research Programs

From my experience in teaching physics for about 20 years at several universities, I learned that universities have a difficult time operating interdisciplinary research programs. It is difficult for two faculty members to do collaborative research within one department, let alone across departmental lines. ORNL has its share of problems, but one of them is not setting up and managing interdisciplinary research programs. In 1991, in addition to the Center for Computational Science, we started or became involved in several interdisciplinary programs.

First, we established the Center for Risk Management, headed by Curtis Travis. It is important to understand the risks and benefits of various activities, including remediation of hazardous waste sites.

We also established the Bioprocessing Research and Development Center, headed by Chuck Scott. This center will develop bioprocesses that economically produce fuels and chemicals from fossil materials and renewable feedstocks, including recycled waste material such as paper. In addition, it will develop bioprocessing systems to remove and degrade pollutants. Emphasis will be on expanding interactions with academia, other national laboratories, and industry and on technology transfer. (See "R&D Updates" for more details.)

In addition, ORNL has joined the University of Tennessee and the Tennessee Valley Authority in establishing the Joint Institute of Energy and the Environment. It will promote cooperative research and educational programs involving all three institutions. In this way, we can help each other provide even better services.

In 1991 the HFIR completed its 300th reactor fuel cycle. To help us celebrate, we were sort of visited by a president of the United States. Some of Zachary Taylor's remains were sent to ORNL for neutron activation analysis at the HFIR to

determine if he had died of arsenic poisoning as a historian had theorized. Neutrons were used to irradiate samples of his hair, fingernails, and bones, because various substances irradiated with neutrons give off characteristic gamma-ray signatures that make possible a determination of the elemental composition of the samples. Analytical chemists Larry Robinson and Frank Dyer found that the samples contained virtually no arsenic. And President Bush might be interested to know that they had no reason to suspect broccoli poisoning as the cause of Zachary Taylor's death, either.

Recruiting and Retaining Staff

To achieve excellence as an institution, we should strive to attract more graduate students and postdoctoral fellows. Many of these may fit into permanent positions at ORNL after they complete their scientific or technical education here. In this way, we lower the average age of the scientific and technical staff at the Laboratory, which is around 46. It is nice that everybody loves it here and that we have a good stable population. But the Laboratory would benefit from having a greater number of young researchers to offer us energy, enthusiasm, and new ideas. We need a higher turnover rate, and we should hire more young researchers.

How do we go about recruiting and retaining staff? One way is to offer fellowships, such as the nationally competitive Hollaender and Householder Fellowships. An appropriations bill contains language establishing a High Temperature Materials Laboratory (HTML) Fellowship Program, which would make the HTML an educational vehicle for both industrial and university materials researchers. Fellowships are a good way to attract prospective scientific staff members. We look each other over, and some of them will stay.

One problem I asked our Corporate Fellows to look at was the fact that few people know that ORNL has been sponsoring postdoctoral research programs. They came up with a plan for a new ORNL Postdoctoral Program, which was approved by the Laboratory's Executive Committee. One of the features of the plan is that Oak Ridge Associated Universities will still operate the program but increase the Laboratory's visibility as the sponsor of these postdoctoral fellowships.

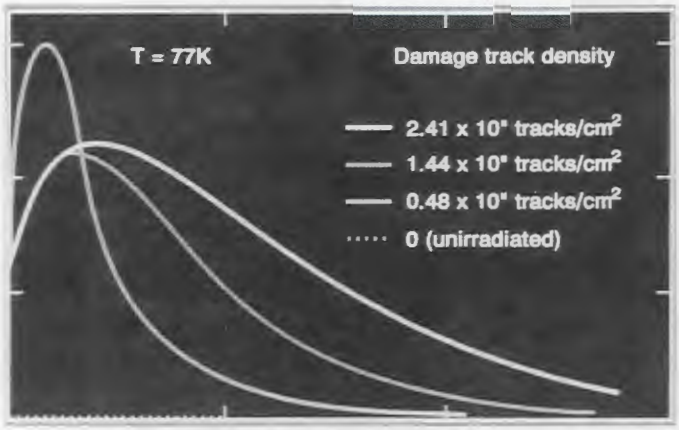
Another way to attract highly capable researchers is through new programs such as the Visiting Distinguished Scientists and Engineers Program. The first Visiting Distinguished Scientist is E. Ward Plummer, the William Smith Professor of Physics at the University of Pennsylvania and an internationally renowned surface physicist. He is going to collaborate with the Surface Physics and Theory Groups in the Solid State Division. Through this program, we can call attention to what we are doing, involve some renowned experts in our activities, and give them the recognition that they deserve.

Interaction with External Groups

We are not an island. The Laboratory staff must interact with people in external organizations to survive. Energy Systems' Office of Technology Transfer and ORNL's High Temperature Superconductivity Pilot Center, which has 17 active agreements with industrial firms, have done fine jobs of bringing people together to help move Laboratory developments into the marketplace—one of DOE's goals. Technology transfer is really a contact sport—a way of getting people from various disciplines to rub shoulders and play a game in which everybody should be a winner.

One good example involves a partnership between IBM and ORNL in research in high-temperature superconductivity. If the new high-temperature superconducting materials are placed in a magnetic field, the magnetic flux will move under the influence of an electric current, causing the material to dissipate energy. But if the magnetic flux lines can be pinned—say, by some defects in the material—it will continue to conduct without energy loss. Working with IBM researchers, ORNL researchers bombarded samples of yttrium, barium, and copper oxides (YBCO) with a beam of high-energy tin ions at

"Technology transfer is really a contact sport—a way of getting people from various disciplines to rub shoulders and play a game in which everybody should be a winner."



ORNL and IBM researchers have demonstrated that they can improve a high-temperature superconducting material (oxides of yttrium, barium, and copper, or $YBa_2Cu_3O_7$) by bombarding it with heavy ions of tin at the Holifield accelerator. The resulting defects pin the magnetic flux lines. This pinning causes the material's ability to carry electrical current to decline much more slowly in a magnetic field as the density of the defect tracks increases.

the Holifield Heavy Ion Research Facility and then placed the samples in a magnetic field at low temperatures for measurements of superconductive properties. They found that the heavy-ion-induced defects are very effective in pinning the magnetic flux lines, especially when the magnetic field is parallel to the defect tracks. As a result, the material's ability to carry electrical current declines much more slowly in a magnetic field as the density of the defect tracks increases. The ORNL researchers were Jim Thompson, Dave Christen, Rich Kerchner, Brian Sales, Bryan Chakoumakos, and Lynn Boatner. Such cooperation between ORNL's Solid State Division and IBM helps increase our researchers' basic understanding of superconducting materials and helps move IBM closer to making practical devices using these materials.

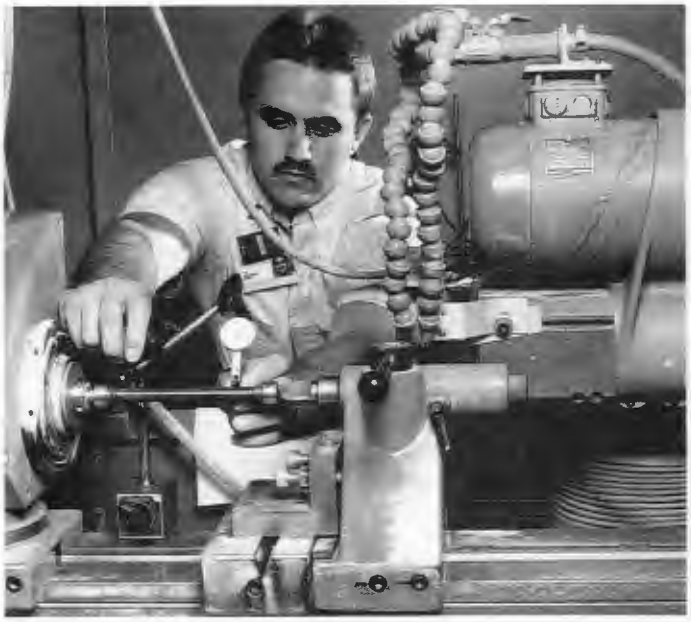
Phil Childs sprays loose-fill insulation into an attic to study the role that convection plays in causing heat losses from roofs. ORNL's findings have led to changes in the guidelines on installing attic insulation.

Through the Roof Research Center, a DOE user facility at ORNL, our researchers have helped the roofing industry understand which types of attic insulation are most effective and why. Some of my colleagues still don't believe that there is roof research in Oak Ridge. They think the most recent research on roofs was probably done about 6000 BC in the south of France when people painted the ceilings in their caves. Our researchers can explain why Minnesotans have such high heating bills even after they paid for loose insulation sprayed into their attics. It turns out that spraying some types of

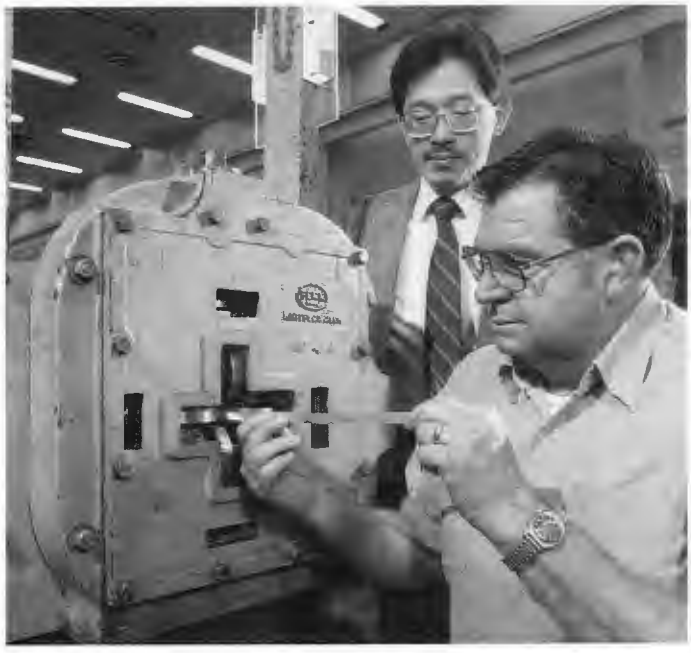
loosefill insulation permits air movement within the insulation, resulting in natural convection. Compared with conduction, natural convection in attic insulation can result in the escape of more heat from within a building to the outside. In measuring the effectiveness of attic insulation in houses during the winter, ORNL researchers led by Jeff Christian have confirmed that natural convective heat loss in some loosefill fiberglass insulations can be responsible for as much as half of the heat loss at very low temperatures. This particular piece of research at the Roof Research Center is leading to changes in the handbooks on installing attic insulation, a major accomplishment for the Laboratory.

To increase our interactions with industry, two new user centers were created in the HTML. The Ceramic Specimen Preparation User Center will provide basic facilities for studying the effects of machining and fabricating ceramic specimens for use in evaluating the mechanical performance of structural ceramics. The Residual Stress User Center will seek to better understand the behavior of composites and the effects on materials of grinding, forming, joining, finishing, and thermally treating them.

Another way we are helping industry is by providing our expertise on microwave processing, a rapidly growing industrial tool used for sintering ceramics, plasma processing of semiconductor wafers, and accelerating the curing of polymers. Traditionally, such processing has been carried out at fixed frequencies, which results in nonuniform heating of materials. Bob Lauf of the Metals and Ceramics Division and Don Bible of

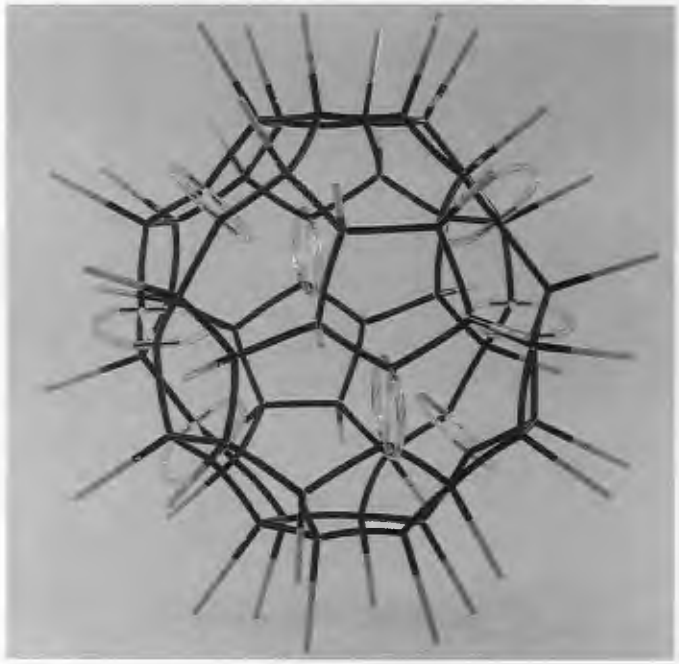


Tyler Jenkins adjusts the alignment of a silicon nitride test specimen in a four-axis grinder. Precise alignment is required to ensure proper machining tolerances, which are critical for successful tensile testing. Such testing will be done in one of the new user centers in ORNL's High Temperature Materials Laboratory.



Huey S. Hsu, former ORNL researcher and a consultant to American Superconductor, watches Charlie Dunn, a technician in the Metals and Ceramics Division, extract a thin ribbon of lead-doped bismuth superconducting material. This wire is produced in the laboratory apparatus by rolling and compressing a tube containing powder. Short superconducting wires have been made at ORNL, and their electrical performance has surpassed DOE goals.

Gerry Bunick removes the cover from a neutron diffractometer he plans to return to operation for studies of the structure of biological materials at ORNL's High Flux Isotope Reactor.



This is a model of the suggested structure of a fluorinated buckyball. ORNL and University of Tennessee researchers have produced fluorinated buckyballs (ranging from $C_{60}F_{44}$ to $C_{60}F_{48}$), which may have applications as lubricants.

the Instrumentation and Controls Division have developed a variable frequency microwave furnace. This unique device, which provides a range of frequencies, uses a wideband traveling wave tube originally developed by Microwave Laboratories, Inc. (MLI), for electronic warfare. Through a cooperative research and development agreement (CRADA), ORNL has transferred the technology to MLI, which is now manufacturing complete furnace units.

ORNL researchers have worked with industrial researchers through the High Temperature Superconductivity Pilot Center to develop a lead-doped bismuth superconducting material. By developing and using innovative powder-in-tube processing methods adaptable to continuous manufacturing processes, they have made short wires whose electrical performance exceeds the interim DOE goal for superconducting wire.

Some of our most successful research projects start internally, from the bottom up. Our people propose projects and receive enough internal funding to prove their ideas will work. The really successful projects grow into programs that receive funding from DOE and other outside agencies. A few years ago, DOE started the Human Genome program. Six of the nine human genome projects at ORNL were started with support from our Laboratory Director's Research and Development Fund. Because of the merit of these projects, ORNL is now receiving outside funding from DOE's Human Genome program. This is an important area for the Laboratory to be involved in.

One current internally funded project that may prove beneficial for human genome studies is the use of

neutron diffraction at the HFIR for determining the properties of biological materials (see photograph of Gerry Bunick setting up neutron diffraction equipment at the HFIR). ORNL's biology R&D will be strengthened by the availability of more experimental equipment at the HFIR for studies of the structure of biological materials.

The Director's Fund was also used to support studies of the formation of negative ions of buckminster fullerenes, or buckyballs, molecules made of 60 carbon atoms that may have uses as lubricants and superconductors. Our research successes should give ORNL a major role in developing applications for buckyballs.

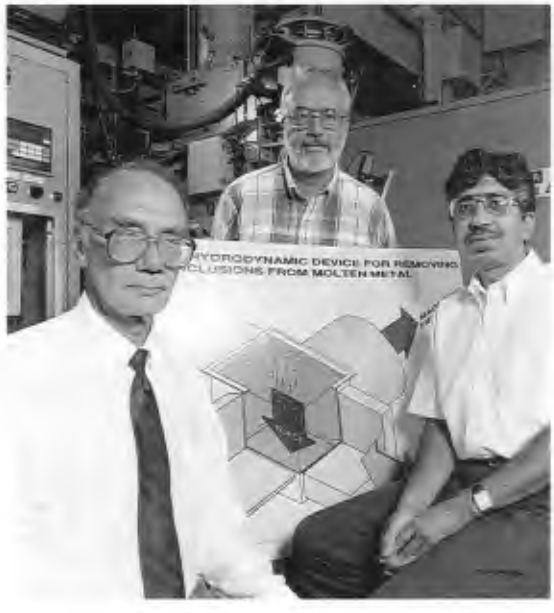
Our internal funding is one of our most precious resources. In 1992, we may be allowed up to $10 million for internal support of research.

While at DOE, I was always fascinated by the ability of the department's national laboratories to do such original and innovative work with just a few dollars. A fascinating inverse correlation exists between the quantity of dollars spent on this research and the quality of its results. On the other hand, DOE spends substantial programmatic dollars over which it has considerable control and direction, yet these programs don't seem to produce quite the same frequency of hits. There is probably a message there, but I've not figured out how to get it across in a way that would benefit government-sponsored research.

One measure for judging the performance of the Laboratory is by assessing how well others think we are doing. The Laboratory staff continues to receive its fair share of awards and honors. Such successes help establish our expertise, attract funding and personnel, and strengthen our R&D programs.

Every year, our staff members continue to be elevated to the rank of fellow in numerous professional societies, such as the American Physical Society, American Chemical Society, American Association for the Advancement of Science, ASM International, and the American Nuclear Society. In 1991, 32 of our staff members were named fellows of professional

Larry Hawk demonstrates the Direct Braille Slate, a writing tool for the blind that he and Joe Turner (left) invented.



Igor Alexeff (left), an ORNL consultant and professor at the University of Tennessee, and David Hobson and Vinod Sikka, both of ORNL, invented the electromagnetic liquid metal inclusion removal device.

Paul Haubenreich

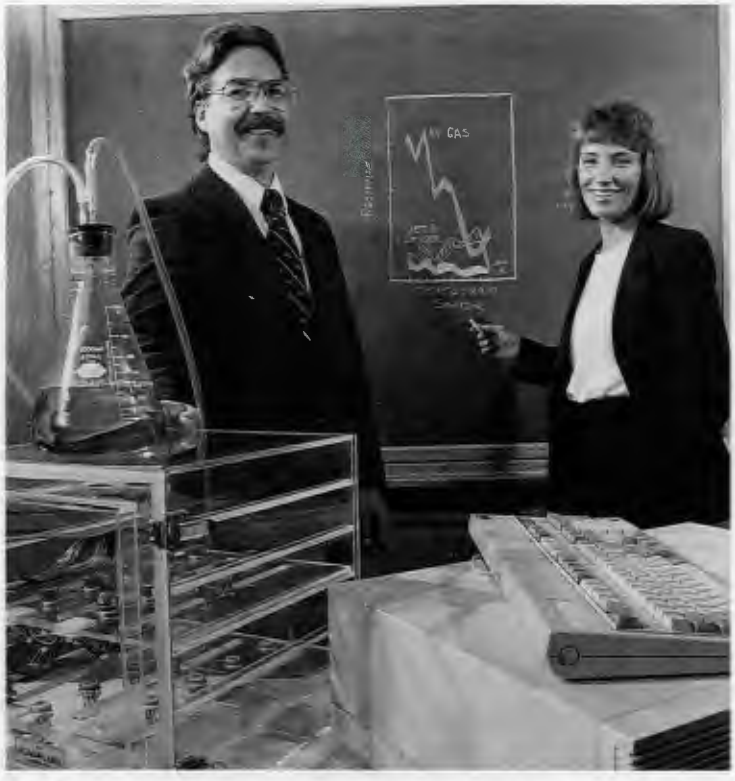
Michael Wilkinson

Herman Postma

Ralph Moon

Thomas Shannon

Loucas Christophorou



Bob Lauf and Barbara Hoffheins devised a rapid fuel analyzer for applications such as detecting hazardous chemical spills.

societies; altogether, ORNL has 212 fellows. Nine of our people were elected officers of national professional societies. Election to a society board is usually a recognition of a person's scientific and technical accomplishments and willingness to take on some mundane jobs to benefit the society.

Among the awards we value highly are the R&D 100 awards given each year by *Research & Development* magazine. Perhaps the award-winning innovation of 1991 that will have the most human impact is the Direct Braille Slate, which allows blind people to write in braille directly on paper. It was invented by Joe Turner and Larry Hawk, both of ORNL's Applied Technology Division. This invention has been nominated for the National Medal of Technology and President Bush's 1000 Points of Light Award. Hawk recently received the Advanced Technology Award from the International Hall of Fame of the Inventors Clubs of America.

Another R&D 100 Award–winning entry works on the principle that, if a conductor and a nonconductor are placed in a magnetic field, the first will experience a force when moved but the second will not. ORNL consultant Igor Alexeff and David Hobson and Vinod Sikka, both of the Metals and Ceramics (M&C) Division, have applied this principle to removing nonconducting impurities from conducting liquid metals used to make consumer products such as beverage cans.

When consumers buy gasoline for their cars, they like to think they are getting the octane level they paid for. But is it possible to measure octane to determine the quality of the fuel being purchased? Bob Lauf of the M&C Division and Barbara Hoffheins of the Instrumentation and Controls Division have developed a rapid fuel analyzer, which can measure gasoline octane and also identify spilled fuels. Their device, which includes a neural net, received an R&D 100 Award.

Another award that is very important to us is the one given by DOE's Division of Material Science. The Department of Energy has a competition among the projects that it sponsors and, over the past three years, the Laboratory staff has won eight awards—more than any other laboratory.

DOE Associate Awards were given in 1991 to Paul Haubenreich, a recent ORNL retiree, for his leadership in the International Large Coil Task; Mike Wilkinson, for his neutron research accomplishments, his leadership in the Solid State Division, and his service as a member of the Advisory Committee for DOE's Basic Energy Sciences (BES) Program and of the BES Program Council on Materials; and Herman Postma, former Energy Systems senior vice president, for his leadership as ORNL director from 1974 through 1988. In 1991, Energy Systems selected Ralph Moon and Tom Shannon as Corporate Fellows and Loucas Christophorou as Senior Corporate Fellow. These individuals richly deserve this recognition.

Technical Achievements

ORNL researchers achieved some outstanding technical feats in 1991. These are summarized here and in two sidebars.

We have made contributions to the development of modular high-temperature gas-cooled reactors (MHTGCR), which may revitalize the nuclear industry. We are addressing safety concerns through tests done in the furnace of our Core Conduction Cooldown Test Facility, which was developed to heat irradiated particles up to 2000°C for hundreds of hours for studies of the released fission products.

The information obtained is used to evaluate MHTGR fuel performance during accident conditions and to develop computer models of fission product releases.

A portable, lightweight, accurate system for weighing vehicles in motion was developed by the Applied Technology Division. This system, which is based on fiber-optic technology, is packaged in six portable canvas cases. The system's accuracy has been demonstrated; its measurements of the weights of moving vehicles, ranging from lightweight vans to large cranes, deviated by only 0.5 to 3.0% from the known weights of these vehicles standing still. As a result of a successful series of competitive evaluations by the Army Corps of Engineers, the Defense Nuclear Agency has provided funding for an advanced system (for additional details, see sidebar on p. 26).

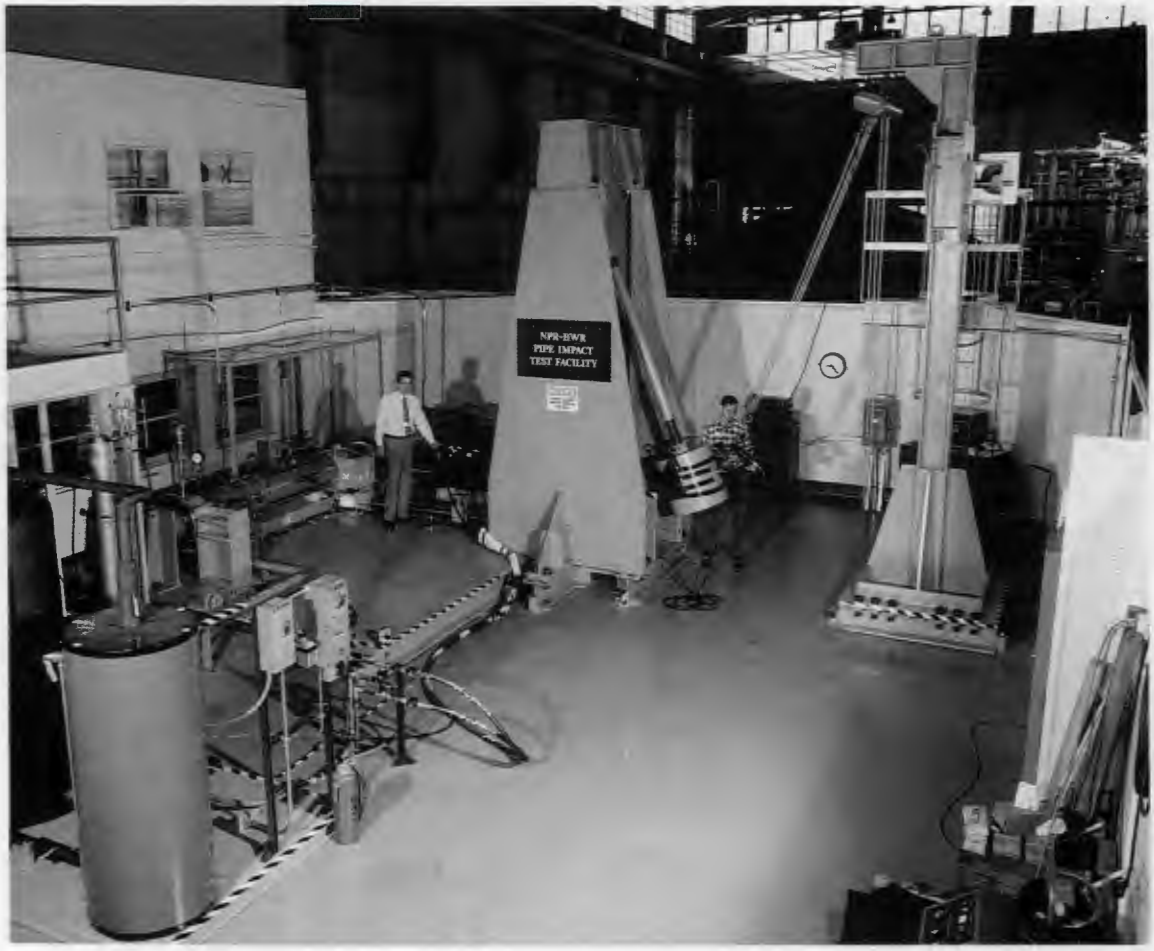
As part of the research for DOE's proposed Heavy Water Reactor for the tritium-producing New Production Reactor project at the Savannah River Site, ORNL's Engineering Technology Division was asked to determine whether the proposed primary piping for carrying the reactor coolant is safe. Specifically, we were asked to demonstrate that the primary piping cannot break instantaneously and cause a loss-of-coolant accident, which has been considered a credible possibility. If research results show that such a double-ended guillotine pipe break (DEGB) is not credible, the potential savings are considerable. The first stage of the research is now complete. A pipe was fabricated to nuclear industry standards, and a flaw larger than any seen in piping in service in 60 years was machined into it. ORNL's Pipe Impact Test Facility was used to apply loads to the pipe 30 times at levels equal to and greater than the impacts of a major earthquake. In addition, the pipe was put through some 200,000 fatigue cycles and two crack-tearing overloads to confirm fracture mechanics theories and demonstrate that a DEGB is not possible.

Joe Wright adjusts the furnace of the Core Conduction Cooldown Test Facility. It will be used to help researchers predict the fission product releases that would result during an accident involving the fuel of the proposed modular high-temperature gas-cooled reactor.

An automated surface-mapping system developed by ORNL's Robotics and Process Systems Division as part of a DOE robotics project was successfully operated in the waste storage silos of what used to be the Fernald Feed Materials Production Center in Ohio. The maps of the surface topology of the silos, obtained by computer-based laser imaging techniques, were used to plan the deposition of a 31-cm (12-in.) bentonite clay cap over the silos to absorb the radon emitted by the stored uranium ore residue. Because accurate surface maps made possible deposition of the bentonite only where it is needed, excess placement of the material (and removal of it later) was minimized, saving the Fernald Environmental Management Project approximately $25 million in remedial action costs (for additional details, see Waste R&D sidebar on p. 87).

ORNL's expertise in environmental impact assessment has received international visibility. Scientists in the Environmental Sciences Division are assisting the Environmental Protection Agency

"We have developed the parallel virtual machine, a network of computers throughout the country that work together on the same complex technical problem, doing the job of a super-computer."



Bruce Poole, left, and Rick Battiste inspect ORNL's Pipe Impact Test Facility for the proposed Heavy Water Reactor for tritium production at the Savannah River Site. ORNL researchers used the facility to prove that an instantaneous break of the primary piping, which would lead to a loss-of-coolant accident, was not a credible possibility.

in heading a United Nations Task Force on Applications of the Principles of Environmental Impact Assessment to Policies, Plans, and Programs for the European Economic Community. ORNL also prepared an environmental impact statement for the National Science Foundation (NSF) to address the extent to which research activities in Antarctica harm its pristine environment. We are also conducting other assessments for the NSF to help improve management of the U.S. Antarctic Research Program to minimize its environmental effects.

We have developed the parallel virtual machine, a network of computers throughout the country that work together on the same complex technical problem, doing the job of a supercomputer (see the sidebar on p. 24).

We have shown that a cold source for producing very slow neutron beams from the Advanced Neutron Source (ANS) is feasible. Using a scanning tunneling microscope, we have taken a picture of a complete gene-containing DNA molecule. We have developed an automated system for reloading ammunition in armored tanks and, as a result, the U.S. Army has cited ORNL as a world-class research and development institution.

Outlook

The proposed ANS, which we hope to build at ORNL by 1998, continues to be supported. This year the President's budget calls for $22 million to support the design of and related R&D work on the ANS. This amount is less than we hoped for. We

are still working vigorously to persuade DOE to make the ANS a line item for fiscal year 1994.

The Holifield Heavy Ion Research Facility, which had been identified as a candidate for closing by DOE, will be temporarily shut down for development of a radioactive ion beam capability. Its new ability to produce exotic beams will make it a unique facility for studies of astrophysical phenomena, providing a strong rationale for the accelerator's continued operation.

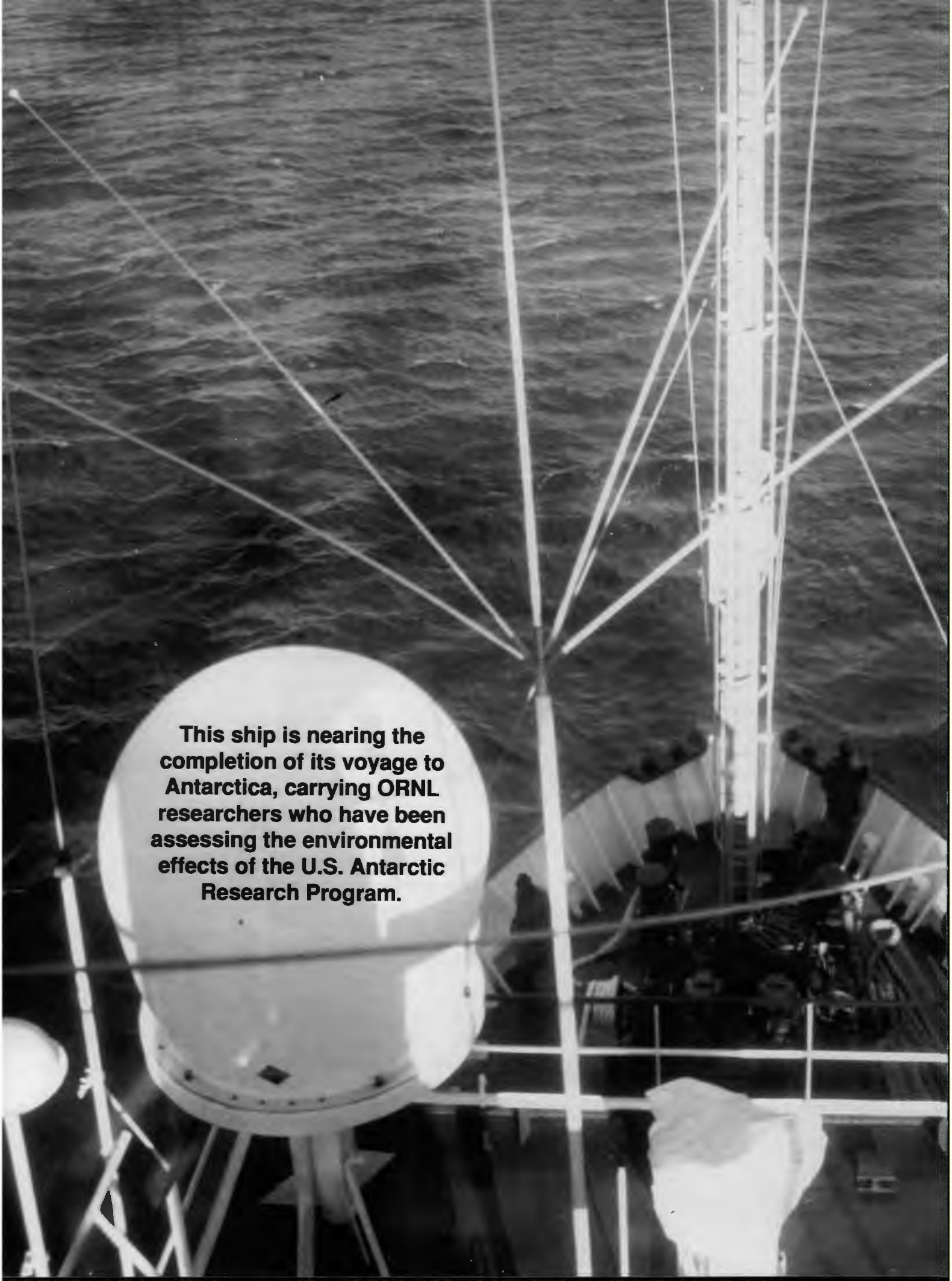
Barry Burks (left) of ORNL's Robotics and Process Systems Division and David Jacoboski and Dennis Nixon, both of the Westinghouse Environmental Management Company of Ohio, test the ORNL-developed automated surface-mapping system. It is being used here for the Fernald Environmental Management Project to obtain accurate data on the contour of waste surfaces. Such information was used to plan the cost-effective deposition of bentonite clay caps over the surface of radon-emitting uranium ore wasteforms.

We have been making plans for some time to relocate ORNL's Biology Division from the Oak Ridge Y-12 Plant to the west end of the X-10 site. Relocation requires a new building, called the Center for Biological Sciences, which would cost around $100 million. Because it takes a concerted effort to persuade people in the government to make such a commitment, we have made a new biology building at ORNL one of our higher-priority activities. This is one of the goals on which the R&D Strategic Planning Committee will focus. It never works to have as many as 20 "first-priority" activities. We must get behind and really push one or two projects that are at the top of the list.

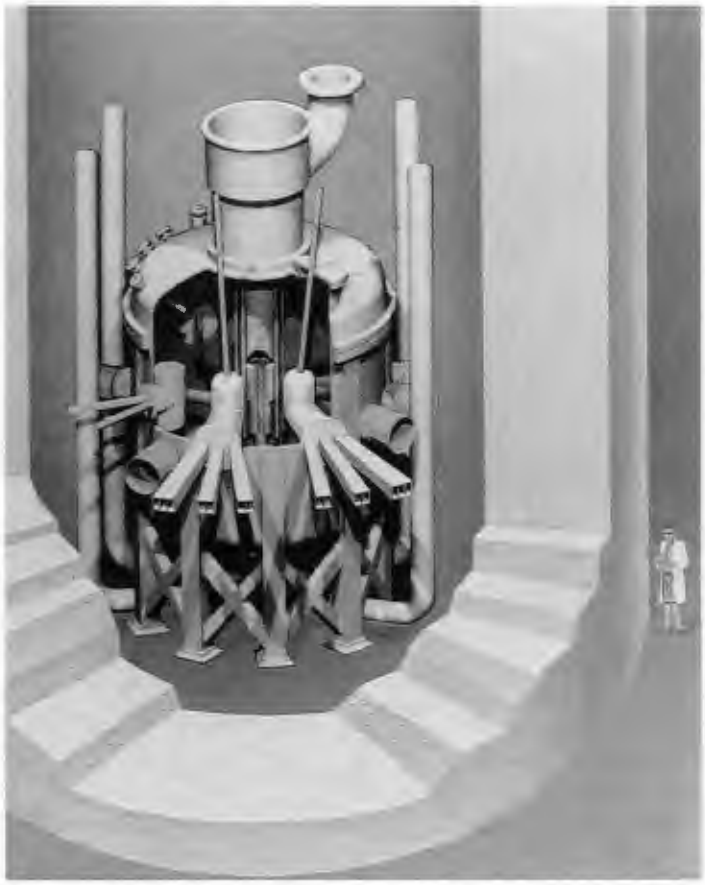
Closing Observations

I would like to close with some observations that may seem a little unusual. Over the years, I have written and evaluated many proposals. I know that it is necessary to have a good proposal, but that it is never sufficient. What scientists and engineers often don't see is the amount of competition involved in developing budgets. We probably underappreciate the friendly bureaucrats in Washington who engage in the full contact sport of the budget battle—fighting for a budget and getting it through the internal departmental process, fighting with the Office of Management and Budget, and fighting with the Congress, which sometimes does—and sometimes doesn't—help secure funding for programs of importance to ORNL.

At times it seems that we at this end are a little contemptuous of their efforts and don't appreciate them. It doesn't hurt to say thanks to people who



This ship is nearing the completion of its voyage to Antarctica, carrying ORNL researchers who have been assessing the environmental effects of the U.S. Antarctic Research Program.



This computer-generated drawing shows the reactor assembly for the proposed Advanced Neutron Source reactor.

The Holifield Heavy Ion Research Facility has a new mission. It will reopen in 1994 with a radioactive ion beam capability that will contribute to astrophysics research.

Trivelpiece congratulates Charlie Kuykendall, director of the Laboratory Protection Division, on the success of the division. It received a 1991 Director's Award for having been ORNL's best service division. Trivelpiece recognized it "for addressing all activities effectively and efficiently, in a manner consistent with the Laboratory's values, and with a special emphasis on friendliness."

work in our behalf. I think that we have turned the corner in our relationship with the DOE Oak Ridge Field Office. Without their cooperation and assistance, we wouldn't achieve some of the things we need to do. Now, relations are sometimes strained, and there is a tendency to point fingers at each other for things that should have been done and weren't or shouldn't have been done and were. But I believe that most of the federal employees really want to do a good job, and we should take that into account. Probably we collectively suffer from a little hubris. I hope that doesn't come as a shock. Sometimes we probably believe we don't need the help of federal employees. But after our proposals are sent in, we do need them. It is important to keep that in mind.

I am pleased that our relationship has improved with our DOE field office, and I think it is only fair to give Joe La Grone, Oak Ridge Field Office manager, a good deal of credit for that. I think I probably have a better understanding than most of field office problems because of my experience in the Department of Energy. The past year has not been easy for DOE field offices or the department. We need to show more understanding of their situation as we try to improve our situation in regard to doing research.

I think that 1991 was a tough year for Clyde Hopkins, Energy Systems president. The Laboratory causes him problems from time to time. I do appreciate the fact that he treats us with a good sense of humor, and we appreciate his friendship and support in this, the Year of the Frog.

Director's Awards

Each year I give Director's Awards to outstanding divisions. In 1991, I started giving one award to the best service division and the other to the best research division or program for the year. I will do the same this year.

Because of the extra security required at ORNL during the Persian Gulf War and other important security activities, the group that deserves the most recognition is the Laboratory Protection Division, headed by Charlie Kuykendall. The award citation recognizes this division "for addressing all activities effectively and efficiently, in a manner consistent with the Laboratory's values, and with a special emphasis on friendliness."

Roger Carlsmith, manager of ORNL's Conservation and Renewable Energy Program, received the 1991 Director's Award for the best research division.

The Director's Award for a research program goes to the Conservation and Renewable Energy Program, the largest program at ORNL. Funded at $60 million, it is the largest conservation program at any of the national laboratories. The person who built it as an outgrowth of an NSF program started at ORNL in 1970 is Roger Carlsmith. He conceived the idea for the program and obtained support for it over the years from the NSF, ERDA, and DOE. Its successes include the development of high-efficiency heat pumps, high-temperature superconductors, and advanced materials for heat engines. Policy studies done by program participants have influenced electric utilities and legislation dealing with the use of conservation technology. The program includes research performed at DOE user facilities at ORNL, especially the High Temperature Materials Laboratory and the Roof Research Center. The program was responsible for the first instances of technology transfer from ORNL that used CRADAs. Industrial partners have collaborated extensively with program researchers through subcontracting and joint efforts. The Conservation and Renewable Energy Program is really a great model for a successful energy program. The award citation recognizes this outstanding program for "its contribution to increased energy efficiency and its responsiveness to industry's needs." ornl

Linking Many Computers To Do a Supercomputer's Job

"By using PVM to link many workstations together, researchers get the best computer performance for the price."

Thanks to new computer programs co-developed at ORNL, researchers throughout the world can use the combined power of many desktop computers to solve complex technical problems that once could be addressed only by a supercomputer. The supercomputing capability is now available to researchers through a software package called the parallel virtual machine (PVM).

Created by a team from ORNL, the University of Tennessee, and Emory University, PVM is one of the first software systems to enable computers varying greatly in architecture and data format to work together at the same time on a single computational task, such as a complex calculation. Linked together by a network, these computers form a "virtual machine," a configuration having the power of a multi-million-dollar parallel super-computer.

PVM functions in a computer network something like a police officer directing traffic. The software monitors the informational traffic moving among the various computers in the network and ensures that it flows as efficiently as possible.

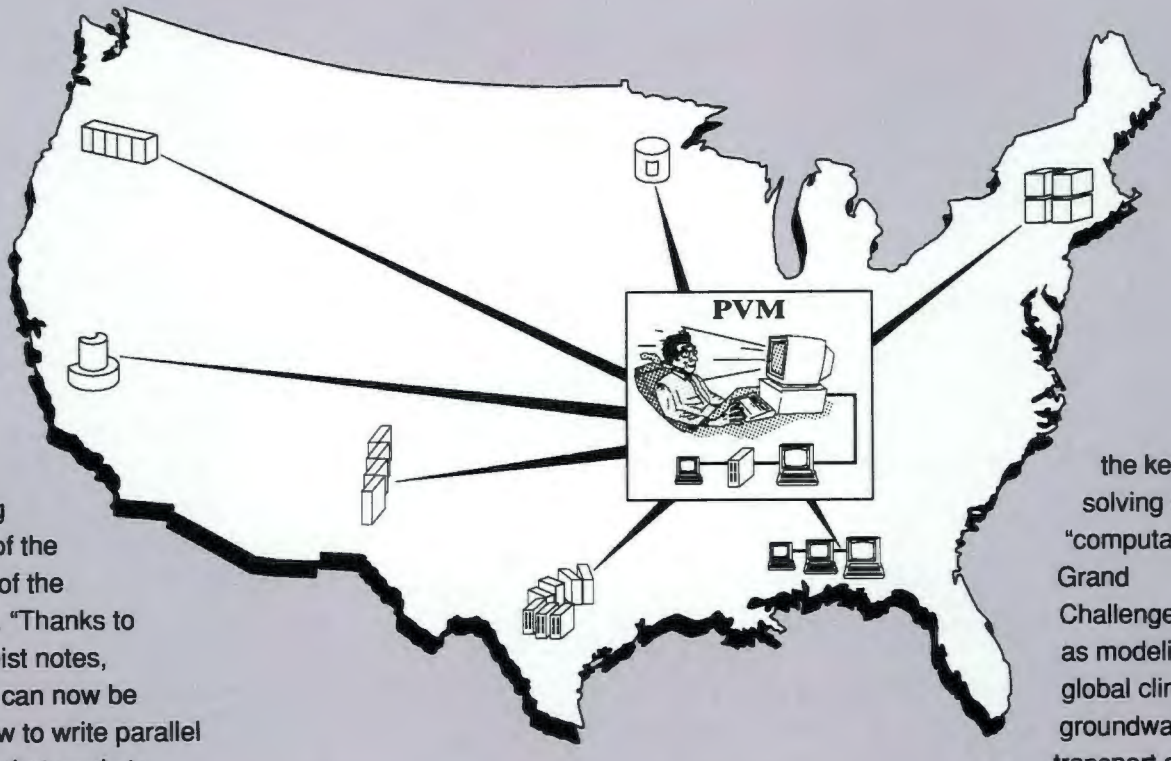
PVM can increase the cost effectiveness of research operations by harnessing computer workstations when their users do not need them. During off hours, several workstations linked by PVM can solve problems that normally would be submitted to a more powerful mainframe computer. In addition, the software is publicly available through an ORNL electronic mail network.

According to Al Geist, a co-developer of the software and a researcher in the Engineering Physics and Mathematics Division, use of the PVM system to tap the aggregate power of workstations having a combined cost of roughly $250,000 has resulted in computing speeds rivaling those of $20 million supercomputers. The package has been used to operate as many as 105 workstations simultaneously. "By using PVM to link many workstations together," Geist says, "researchers get the best computer performance for the price."

For those with the resources, PVM can also be used to connect supercomputers. "It has been used to link multiple supercomputers around the world to achieve the very high computational performance needed to solve problems such as weather modeling and materials design," says Geist. "The amount of work achieved is limited only by the number and power of the computers accessed."

PVM, which has been dubbed the "poor man's supercomputer," will be particularly beneficial to universities that have not been able to offer courses

Heterogeneous Distributed Computing



in super-computing because of the high cost of the hardware. "Thanks to PVM," Geist notes, "students can now be taught how to write parallel programs that apply to supercomputing, even though their university could never afford an actual supercomputer." In the fall of 1991, five universities used PVM in this way. They were Emory University, Florida State University, the University of Maine, the University of Tennessee, and the University of Utah.

Use of the program is not limited to scientists. "Individuals and businesses who have a need for this type of application and who have access to an electronic mail network can also obtain PVM through the Laboratory," Geist said. To obtain the PVM User's Guide and source code, send e-mail to netlib@ornl.gov with this message: "send index from PVM."

The PVM package is small (requiring only 400 kilobytes of memory) and easy to install. A single installation on each machine in a network provides accessibility to all users, each of whom can create his or her own virtual supercomputer, which overlaps with other users' virtual supercomputers.

Parallel computing using the PVM system may be the key to solving so-called "computational Grand Challenges," such as modeling the global climate, groundwater transport of hazardous waste, and the structure of super-conductors. "At this time," Geist says, "these problems can't be solved by any one of the large serial computers because they lack the power as a result of their physical limitations. Thus, parallel computers will be required to solve these problems."

—Wayne Scarbrough

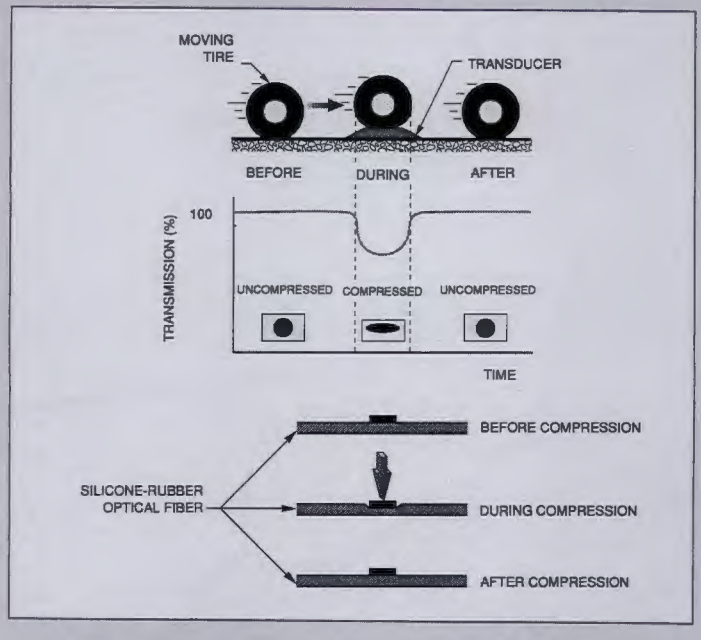
ORNL's Vehicle Weigh-in-Motion System: Things That Go Whump in The Night

"Even though the ORNL system was built from the ground up in nine months, it outperformed the competition in Army Corps of Engineers tests."

Whump, whump! To the discriminating motorist this sound usually means one of two things—either Mr. Possum zigged when he should have zagged, or one of those anonymous traffic monitoring devices has counted another vehicle. Thanks to Jeff Muhs of ORNL's Applied Technology Divison, we can add another potential source of whumps in the road—the fiber-optic weigh-in-motion (WIM) system.

The portable, lightweight WIM system uses an array of fiber-optic sensors and contact switches mounted on the road to determine a vehicle's weight, speed, acceleration, number of axles, and several other characteristics.

The system consists of eight contact switches, two fiber-optic transducers (one for each side of the vehicle), an interface that converts optical signals to electronic data, a battery pack, and a computer control system. When a vehicle's tire rolls across one of the system's transducers, it compresses optical fibers in the transducers, reducing the amount of light they transmit. The greater the weight of the vehicle, the less light is transmitted.



The weigh-in-motion system uses an array of fiber-optic sensors mounted on the road to determine a vehicle's weight. When a vehicle rolls across the system, it compresses the fibers, reducing the amount of light they transmit. The greater the weight of the vehicle, the less light is transmitted.

The light that passes through the compressed fibers is translated into a weight for each wheel of the vehicle, and data for all wheels are summed to determine gross vehicle weight. In addition, each transducer is paired with a set of four contact switches that measure the time it takes for the vehicle to pass over the system, its lateral position in the roadway, and other parameters to determine other vehicle

Members of ORNL's Applied Technology Division (shown here) developed a portable, lightweight, accurate system for weighing vehicles in motion. The highly accurate system, which is based on fiber-optic technology, can provide weight measurements for moving vehicles (ranging from lightweight vans to large cranes) that deviate by only 3% from the known weights of static vehicles.

characteristics, such as speed and acceleration.

To convince potential sponsors of the system's capabilities, Muhs and his colleagues took the system to an Army Corps of Engineers test facility in Vicksburg, Mississippi, for a head-to-head competition with an established piezoelectric system developed by the Texas Transportation Institute. Even though the ORNL system was built from the ground up in nine months, it outperformed the competition. As a result, further development is now being funded by the Department of Defense, which is interested in the WIM as a method of monitoring traffic moving in and out of military installations and regulating the loading of ships and transport planes. The WIM has also been proposed as a method of ensuring proper weight distribution in aircraft taxiing for takeoff.

In tests with loads ranging from a light van to a 60-ton crane, the system produced readings accurate to within 3% of the known weight of the vehicles. Currently, the system is limited to vehicles moving at less than 16 kph (10 mph), but Muhs says he sees no practical limit to the system's speed range if money is available for further development.

Several private companies have also expressed an interest in the WIM system for speeding up the process of weighing trucks on the highway and assessing use fees for vehicles hauling waste to landfills.

Muhs sees applications for the WIM systems in the traffic control systems of the near future. "The system could be used to assess tolls on vehicles without requiring them to stop," says Muhs. "It would also provide a more equitable assessment of tolls, based on vehicle weight." Other potential uses include characterizing traffic by speed or type of vehicle or detecting commercial truck traffic trying to avoid weigh stations.—*Jim Pearce*

An Eye on Reactor and Computer Control

By Jack Schryver and Bill Knee

Eye-gaze measurement technology improved by ORNL software may have fascinating uses.

A nuclear power plant operator stared at the computer screen and yawned. As the end of a long shift approached, he was feeling very tired as he looked at icons of pumps, pipes, and turbines. Even so, it was still early in the reactor startup sequence. When an indication that the reactor had gone critical appeared on the screen, the operator tried to rouse himself. There was no need for him or anyone else to be alarmed, however. Based on the way the operator *looked* at the screen, the computer had already sensed that he was tiring and had begun to assist the operator in reactor control. The computer zoomed in on the displays the operator needed to monitor reactivity and highlighted the important data. It would even be capable of assuming partial reactor control if necessary.

At a research laboratory, a cognitive scientist put a diskette in her computer and studied the screen. The data indicated that a reactor operator had been glancing at a number of widely scattered points in a short time on the computer screen in the reactor control room. "All these eye movements," said the scientist, "tell me the operator is experiencing excessive mental work load. It seems that several displays associated with reactor control must be redesigned to make it easier for the operator to understand quickly what's going on."

A teenager who lost the use of both hands as a result of an automobile accident had found a way to write again. His father bought him an "eye typewriter"—a computer that displays and prints letters from a display of the alphabet on the screen in the order in which they are stared at. The boy enjoyed his ability to control a computer simply by looking at it.

These futuristic scenarios suggest that information on eye gazes—the way people look at an object—can be put to use to determine a person's mental work load and level of fatigue, to guide the design of computer displays to speed human processing of information, and to control computers. Other applications include controlling camera positions on robots and guiding an artificial intelligence system in recognizing enemy targets.

At ORNL computer software has been developed to make possible an improved eye-gaze measurement technology. Such an innovation could be the basis for advanced eye-gaze systems that may have applications such as those mentioned above.

The Problem of Reactor Control

The nuclear power plant, like many other process control environments, is an extremely complex system. Control rooms of conventional nuclear power plants reflect the complexity of the systems they control. Visitors are usually overwhelmed by the hundreds of meters, gauges, and switches that are arranged on vast control panels. Even a trained operator finds it difficult to be totally aware of all the information available in the control room and to make decisions about plant operation under time pressure. Thus, it is not surprising that human error in the control of nuclear power plants is often implicated in incident reports concerning a compromise of plant safety or unnecessary plant shutdown.

The physical functions of the nuclear power plant are relatively well understood by designers. However, little is understood about mental tasks performed by operators and the associated types of cognitive error. Furthermore, little is known about the types of information actually required to perform these cognitive operations and about the form in which they should be represented to support the operator's mental model of the plant. A central concern is how to provide critical cognitive support to the operator to ease the effects of excessive mental work load, which can lead to human error. These concerns are also important for other complex human-machine systems, including teleoperated systems,

chemical processing plants, spacecraft, airplanes, and other transportation vehicles. One approach to reducing operator error is the use of advanced eye-gaze measurement technology.

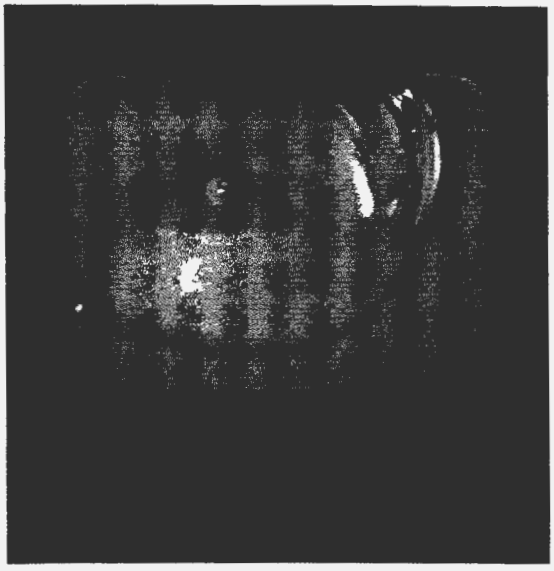
A Window to the Mind

It has been said that you can sometimes tell what a person is thinking "by the look in his eye." The look, or eye gaze, can be measured by an eyetracker, an unobtrusive device that can determine the spot on a computer monitor at which a person is looking. Eyetrackers can measure eye-gaze direction 30 times per second. Cognitive psychologists have been using eye-gaze measurement methods for over 15 years to capture "direct" snapshots of mental processes, including how people read. According to the "eye-mind hypothesis," the eye fixates on the symbols currently being processed by the brain.

Several experiments have demonstrated that the eye can be a window to the mind. In a typical experiment, human subjects were shown a small array of simple drawings of common objects. When the subjects were asked, "What makes of car can you name?", they tended to look at the drawing of a car while responding. Furthermore, if the subjects were asked the same question after the display was removed, they still fixated on the same position in space where the drawing of the car had been located. These results suggest that eye fixations play an important organizational or place-keeping role in cognition.

In ORNL's Engineering Physics and Mathematics Division, the Cognitive Systems and Human Factors Group is now using eye-gaze data to increase our understanding of how operators view and use data shown in information displays for complex systems. Eye-gaze data are enabling us to gain a better understanding of how

Jack Schryver works with the Eyegaze™ Development System, which consists of a standard VGA color monitor (upper left), eye-image television monitor (lower left), personal computer with frame-grabber board (not shown), and an infrared-sensitive CCTV camera with an infrared light-emitting-diode source positioned over the camera lens. The camera is mounted under a Sun Workstation. A serial port connection permits tracking of the eye movements of a user at the workstation as well as storage of eye-gaze data on disks for future analysis.
Photographs in this article by Tom Cerniglio



The eye-image monitor shows the human eye as it scans a stimulus display. The eye-gaze system grabs 30 frames per second for image processing and computes eye-gaze direction based on the relationship between pupil center and corneal glint.

"When the human eye is focused in the camera lens, infrared light from the LED is reflected off the eye."

information should be presented so that it can be easily understood and used.

Curiously, the operator is the only control element in the plant whose behavior cannot be described in terms of a known set of equations, because little is known about the cognitive activity of operators. Because the cognitive activity of the brain cannot be observed directly, little attempt was made for many years to understand what operators were actually thinking while controlling the plant. System designers most likely assumed that a plant could be operated safely and efficiently if operators were trained to follow procedures and that, consequently, it was not necessary to understand the mental processes of the operator.

An obvious alternative approach in the study of cognitive behavior is to ask operators what they are thinking and use their answers to suggest ways to better support cognitive tasks. Verbal protocol analysis techniques have been used with some success, but they suffer from several weaknesses. Psychological research has shown that verbal reports are biased toward the expectations of the questioner, or what the respondent believes are questioner expectations. Answers often conform to textbook statements of written procedures. Verbal explanations usually reveal the tip of the iceberg, but a vast store of tacit knowledge often remains hidden during the fast pace of events.

On the other hand, eye-gaze data are quantitative and can be treated as any other quantitative data. The scan path the eye traces over a display is objective and unbiased. Finally, eye movements can occur rapidly and keep pace with high-speed cognitive processes.

The Eye-gaze System

Eyetracking technology has undergone a slow evolution over the past 20 years. The new eye-gaze system marketed by LC Technologies of Fairfax, Virginia, offers state-of-the-art eyetracking. Most of the hardware is off the shelf. Eyetracking is done with a standard personal computer equipped with a video frame-grabber board. An infrared-sensitive high-speed camera is mounted under a standard high-resolution computer screen. A small light-emitting diode (LED) is positioned at the center of the 75-mm camera lens.

When the human eye is focused in the camera lens, infrared light from the LED is reflected off the eye. A simple algorithm takes advantage of two optical phenomena resulting from infrared illumination. One of these effects is the bright-eye effect, an illumination of the pupil similar to the red-eye effect that photographers try to avoid. The other is a bright spot created on the surface of the cornea, known as corneal glint. If the vector relationship between the pupil center and corneal glint can be determined, then the direction of the eye gaze can be calculated. Furthermore, if someone is calibrated to a particular display screen (a simple procedure involving fixating on a series of circles presented on the screen), then the point being looked at can also be calculated.

This simple method of determining eye gaze was discovered by Tom Hutchinson of the University of Virginia in the early 1980s, and it was licensed for commercial production to LC

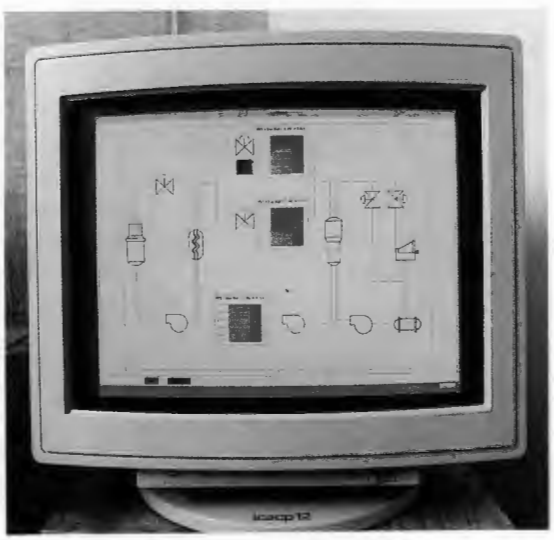
Technologies in 1988. LC Technologies developed some very efficient image-processing software to locate the pupil center and corneal glint in real time. This software is able to discriminate these phenomena from extraneous effects, such as reflections from spectacles and other bright spots on the eyeball surface.

Application Software Developed at ORNL

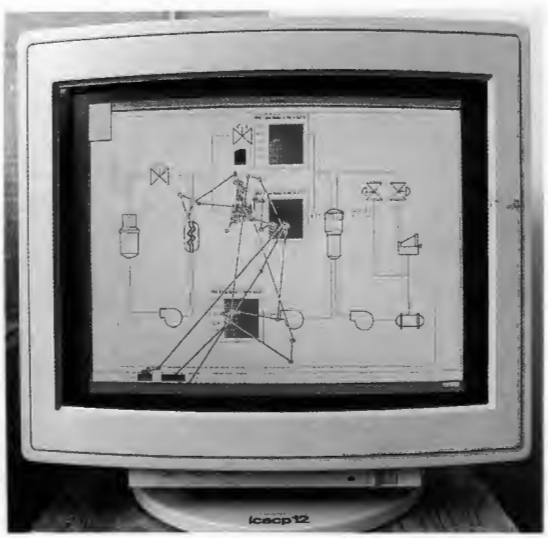
At ORNL we have developed application software for the eye-gaze system to fulfill two broad purposes. First, we want to provide the researcher with a visualization tool to immediately show the scan path taken by the operator's eyes while inspecting a display screen for process control. The trace playback software displays the graphical interface, and a drawing of connected line segments is overlaid on the monitor. Each new point in the connected line drawing represents a new gaze point in the protocol. Playback speed is user-selectable and the playback may be paused at any point. The total number of line segments visible in the drawing is also user-selectable to avoid excessive clutter on the monitor for long protocols. When the trace reaches the maximum length, old gazepoints and line segments are erased and replaced by new gazepoints and segments.

Using the trace playback tool, the analyst may test a new graphical user interface and immediately view the trace laid over the screen. It is possible to see successive fixations at the desired speed and correlate the trace with meaningful objects in the underlying display. This tool can help the analyst build intuitions about connections between eye-gaze activity and graphical user interfaces. It is also useful for quickly evaluating displays for human factors engineering.

Second, we are also building a library of quantitative tools for analysis of eye-gaze protocols. The data analysis tools use an output file containing records of successive gazepoints collected while the operator inspects a graphical user-interface. These tools can be used off-line to analyze multiple data sets. We have identified at



A simplistic operator interface to a fictitious nuclear power plant. The operator scans the data displays while performing a task such as diagnosis or prediction.



A playback over the operator interface of the scan path of the eyes of a user performing a validation task.

"The eye scan path reveals the order in which the pilot fixates on the instruments."

least three layers in eye-gaze protocols to reduce the large number of data that must be analyzed. The gaze point—the spot on the screen where the user is looking—is the lowest level of data; it is sampled at a rate of 30 Hz by the eye-gaze system. At this rate of sampling, 1800 gaze points will be determined for every minute of data collection.

An intermediate level of analysis is the fixation—a sequence of gaze points within a small area that occurs over a short time. Eye fixations are closely related to detailed visual processing of objects in the scene, and they occur in the foveal or central region. Virtually every object is recognized when the eye fixates on it, and not while the eye is engaged in rapid, or saccadic, movement. The fixation lasts from 200 ms to several seconds. Even while the eye is fixated, gaze-point activity is characterized by slight jitters and perhaps some drift. New fixations are characterized by sudden movement. At ORNL we have developed a fixation post-processing routine to analyze raw data on gaze points and identify the location and duration of fixations. This procedure reduces the number of data by up to an order of magnitude.

The highest level of analysis is the area of interest, which corresponds to a meaningful region in the graphical user interface. For example, if the display shows a plant schematic, the area of interest might correspond to a region containing drawings of valves, pumps, or turbines as well as connections such as pipes. Eye-fixation protocols can be analyzed to determine how much scan time is given to each area of interest. This measure indicates the relative depth of cognitive processing given each area on the display.

We can also study the transfer of attention from one area of interest to another by assembling an area-of-interest transition matrix. This matrix shows the number of fixations between each area-of-interest pair, indicating that the user is combining information from several areas of interest before making a decision. The complexity of the scan path is reflected in the number of successive fixations between areas of interest as compared with the number of successive fixations within areas of interest. We are trying to determine whether the complexity of transitions among several areas of interest, based on eye-fixation data, is related to the mental work load of inspecting a graphical user interface.

Cognitive Engineering Experiments Planned

We are preparing to conduct cognitive engineering experiments using a UNIX workstation at ORNL. We selected a UNIX platform to separate the development platform from the eye-gaze system. The goal of much of our development work on the UNIX workstation has been to create experimental tasks for which eye-gaze data can be captured. In addition, we want to store keyboard strokes and mouse clicks to correlate with eye-gaze protocols. Some of our original graphical user-interfaces were created using the X Window System on the UNIX platform to ensure portability of the software.

Controlled experiments are needed to standardize procedures for collecting eye-gaze protocols. In the standard experimental setup, a volunteer is seated at the workstation and an infrared-sensitive camera, calibrated to the monitor, is mounted underneath. A series of graphical user interfaces to various human-machine systems are presented to the volunteer subject, who is charged with a specific task or responsibility. In a prediction task, for example, each volunteer is shown initial conditions of a transient event, such as loss of a primary pump, and a candidate outcome state, such as elevation of coolant temperature, is displayed in another window. The subject's task is to verify the plausibility of the outcome state.

A related task is diagnosis. Each volunteer is shown an outcome state and is asked to choose among alternative initiating events that could lead to this state. In this example, to get the right answer, the subject must select "loss of power to pump" instead of "turbine trip" or "feedwater valve fails to open." In fault detection, a normal transient is depicted. The subject monitors the transient and is asked to respond appropriately to the fault when it is detected. In this example, the subject first notices the temperature change or

pump coastdown. For implausibility detection a subject views a display showing dynamic data from a simulated system and attempts to determine the validity of the data.

Evaluation of Displays

Scan path traces from early eyetracking instruments in human-machine systems were first used to analyze the arrangement of displays. The aviation industry used eyetracking in the cockpit because each pilot is faced with a cluttered arrangement of displays on an instrument panel. When monitoring the status of the aircraft, the pilot views the displays in a relatively fixed order. If the pilot is required to repeatedly scan back and forth across the panel to locate and read instruments, monitoring becomes quite cumbersome. This situation will be reflected in an extended and convoluted scan path. The eye scan path reveals the order in which the pilot fixates on the instruments. From this information, instruments that are fixated on in succession can be grouped to simplify scan paths during monitoring.

Scan paths can reveal more than the best way to arrange instrument displays. The eye-mind hypothesis suggests that stages of an operator's cognitive processing can be inferred while this individual inspects graphical user interfaces. The actual stages of processing inferred from the data can then be compared with an ideal cognitive model to determine how actual processing departs from the intended use of the display. This comparison provides the analyst with a powerful basis upon which to evaluate the effectiveness of advanced interface concepts.

In addition, types of cognitive error and their frequency will be observable in eye-gaze protocols. Such errors may include reading a display incorrectly, forgetting to perform an action, and reaching the wrong conclusion. Models of cognitive error during inspection of operator interfaces offer a powerful new dimension of evaluation. Eye-gaze protocols both suggest and validate sources of cognitive error. We believe that "natural" interfaces that conform to the mental model of the operator ought to minimize opportunities for cognitive error.

Prediction of Mental Work Load

The complexity of control rooms of conventional nuclear power plants is well-documented. The need to integrate diverse information simultaneously can produce periods of peak overload for the operator. Therefore, it is important to be able to predict those situations that may result in excessive mental work load for individual operators. During the onset of an accident such as loss of coolant, the operator would be inundated by a large number of alarms and annunciators. Identifying the relevant alarms is a difficult pattern-recognition problem that may induce high work load and stress.

Indications of mental work load can be found in eye-gaze protocols as operators extract information from displays showing relevant data about plant status. Psychologists have long known that pupil diameter is related to cognitive arousal or the need for information, and hence, the degree of mental work load. Scan path complexity is another estimator of mental work load. We have performed pilot testing with problems in mental multiplication of numbers. Our results indicate that difficult problems tend to generate longer and more complex scan paths. We believe that eye-gaze data reflect not only the degree of effectiveness of interfaces but also task complexity.

"We believe that eye-gaze data reflect not only the degree of effectiveness of interfaces but also task complexity."

A correlation may exist between mental work load and scanning strategies employed for different tasks. We suspect that low-work-load activity such as passive monitoring leaves a distinct eye-gaze signature. Eye movements during passive monitoring are referred to as open-loop scanning; the next fixation does not depend on the information content of the present fixation. Displays may be scanned according to a simple predetermined sequence. On the other hand, fault diagnosis is probably characterized by closed-loop scanning, in which the location of the next fixation is not determined until cognitive processing of the present fixation is completed. If

this hypothesis is true, closed-loop scanning should be detectable in the correlations between eye fixations and the information content of displays.

As suggested in the introduction, a possible future application of eye-gaze measurement technology is determining when reactor operators are too fatigued to do their jobs effectively. In such cases, detection of excessive mental work load by a computer could activate it to assist the operator in reactor control.

"The human eye may also be used to control a computer."

Intelligent interfaces could guide the operator's attention to relevant displays by highlighting, blinking, or zooming in on the appropriate information. Real-time expert systems could present the operator with an estimate of current plant status together with an explanation of what happened. Many other kinds of cognitive assistance are possible under conditions of peak work load.

Telerobotics and Human-in-the-Loop Target Recognition

The human eye may also be used to control a computer. In this case, eye-gaze measurements can be entered into the computer as a substitute for keystrokes and mouse clicks. An individual facing a graphical user interface can issue a specific command to the computer merely by looking at a specific region on the monitor. Controlling a computer by looking at it promotes a feeling of power in the user. It is almost as if the user commands the computer directly with the mind. The interface, if properly designed, can become so natural that the user forgets it is present, leaving the impression of mind control.

LC Technologies has produced several impressive applications for the disabled. One of the most useful programs is an eye typewriter. A graphical keyboard is presented to the user who types by focusing, or "dwelling," on the region containing the next letter of text to be generated. When dwell time exceeds the user-selected threshold, the letter appears in the text at the top of the monitor. A special "key" is used to delete mistaken picks. One problem with eye input is the so-called "Midas touch" situation. When the user is searching an area for a particular letter, many false positives can be created: such items are evaluated and then rejected. The incidence of false positives can be lowered by increasing the dwell threshold for selection, but the trade-off for increased accuracy is decreased processing speed.

Teleoperated vehicles and robots that have many degrees of freedom that may be manually controlled may benefit from eye input. For example, a legged vehicle under manual control while climbing stairs may require both hands of the teleoperator to control leg motions. Eye input could be used to control additional degrees of freedom, such as video camera position.

We are now engaged in a proof-of-principle project that will demonstrate eye-gaze control of the perspective view of a 3-D interactive graphical interface. The new interface is "natural" because object rotation responds to the user's active search for information. When the user shifts the eyes to see hidden parts around the edge of an object such as an airplane or robot arm, it automatically rotates toward the user and reveals the areas of interest.

Data on human eye gazes may also enhance computer vision, one of the most difficult problem areas in robotics and automatic target recognition (ATR). ATR systems have not achieved the reliability and robustness required for this difficult task. The human visual system is highly advanced and able to use the parallel architecture of the brain to perform visual tasks unequaled by computer systems. Human-assisted ATR may be able to improve the performance of such systems.

For example, if a simplistic ATR computer is asked to search for enemy tanks, it may scan the entire scene, including the sky, for such objects. A human would look at the ground, not the sky, for such targets. In human-assisted ATR, real-time eye-gaze data taken as a person surveys the scene would be used to guide the ATR in identifying regions of that scene where targets

most likely will be located. As a result, computing time is saved because the ATR can avoid scanning regions not considered likely to have potential targets.

Future Directions for Eye-gaze Systems

A limiting feature of the eye-gaze system is intolerance to head motion. The head must be kept stationary within a tight volume to keep the eye focused in the center of the camera lens. It is possible to mount a camera on specially constructed headgear to ensure that the eye is always in focus. But this sort of gear is obtrusive and can provide eye-gaze direction relative only to the head. It is difficult to correlate the eye-gaze data to the spatial coordinates of a display. Some systems have a headtracker that allows the camera to follow the eye as the head moves through a larger volume of space. The camera remains fixed in its mounted position, but a motorized rotating mirror and motorized focus ring track the eye to keep it in focus. Image processing, ultrasound, and a second camera can all be used to predict the direction of head movement to control the motorized mirror. Such systems are in various stages of development, but none, as yet, are very reliable.

The headtracker described above operates in an environment comparable to the volume occupied by a user seated before a workstation monitor. Future eye-gaze systems will be able to perform unobtrusive computation of head position and eye-gaze direction in a small control room. Because future systems will simultaneously calibrate several displays, it will then be possible to collect eye-gaze data from an entire control room crew while using multiple displays to control a complex system. As eye-gaze systems evolve from the laboratory to real-life situations, they will become valuable tools for understanding human-machine systems, improving communication of information, and easing the mental work loads of operators of process systems, including nuclear power plants. ornl

Biographical Sketches

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Helmut E. (Bill) Knee is leader of the Cognitive Systems and Human Factors Group. He has an M.S. degree in nuclear engineering from UCLA and an M.S. degree in business administration from the University of Tennessee. His research interests include human performance and visualization in complex control environments, human and system reliability, and behavioral and cognitive modeling.

Seeking Order in Chaos

By Stuart Daw

A mountain stream, a beating heart, a smallpox epidemic, and a column of rising smoke are all examples of dynamic phenomena that sometimes seem to behave randomly. In actuality, such processes exhibit a special order that scientists and engineers are only just beginning to understand. This special order is "deterministic chaos," or chaos, for short.

Today chaos theory is employed to monitor and control the interaction between particulates and gases in the turbulent flow of a fluidized bed, thus improving its performance and reducing emissions of gaseous pollutants. In the future chaos theory may be used to smooth airplane flight and reduce fuel consumption. Heart pacemakers may someday be tuned to issue warnings when they detect undesirable heartbeat patterns that signal a heart attack days or weeks away.

As a researcher in ORNL's Engineering Technology Division, I am particularly interested in applying the new discipline of chaos theory to engineering. Chaos theory seems to be especially suited for dealing with a major difficulty that has puzzled engineers for centuries: how to describe processes that are governed by explicit laws of cause and effect but seem to behave almost randomly in practice.

Turbulent fluid flow, as in fluidized beds used in industry, is a good example of such an unruly process. Even though the governing physical laws are known, under many conditions—such as in a mountain stream or near the wing of an airplane—the mathematics of fluid flow becomes extremely complicated, and the actual behavior becomes so erratic that making detailed predictions is impossible. Attempts to understand this problem have prompted some of the deepest questions in modern physics.

To make at least some headway in practical situations, engineers have traditionally relied on statistical descriptions or "correlations" of irregular phenomena. These summarize empirical experience—that is, measured data—in some convenient form, usually guided by general physical constraints or relationships. In cases where only gross or average behavior patterns are important, these descriptions have often been useful. The development of aircraft design correlations from wind tunnel measurements is a good example of empirical engineering.

Unfortunately, empirical engineering can be costly and inefficient. Numerous trial-and-error experiments must be performed to generate correlations relevant to situations of interest. Correlations are also only valid for the parameter ranges tested; extrapolation to untested situations is risky at best.

More recently, engineers have attempted to go beyond empiricism by developing computer models that simulate physical laws and details to a high degree of precision. This approach has been made possible by the increasing availability of high-speed, large-memory computers. Although successful in some cases, such "number-crunching" approaches are often costly and complicated, may contain many untestable assumptions, and frequently yield little improvement in fundamental understanding.

Another important problem with detailed computer models is that they are sometimes "linearized" to make them more tractable. In other words, all physical influences are assumed to be directly additive; that is, if a given magnitude of cause A produces X units of effect B, then twice the previous magnitude of A produces 2X units of B. Nonlinear relationships are not so straightforward. For example, doubling A might cause B to increase fourfold. We now know that nonlinearities are often essential to the behavior of many systems and that their removal can completely change the resulting dynamics.

Chaos theory offers a new approach for explaining and dealing with complicated behavior. As more engineering problems are

ORNL is applying chaos theory to engineering problems such as fluidized beds.

Stuart Daw (left) and Ke Nguyen of the University of Tennessee examine a fluidized-bed column whose pressure differences are displayed on the oscilloscope (see photo on p. 45). The researchers are studying chaotic fluctuations in fluidized-bed pressures.

considered in light of this theory, it is becoming increasingly apparent that irregularity is often a key to understanding the fundamental nature of dynamic systems. Apparent randomness can result not just from unknown physical parameters, measurement error, and outside noise, but also from simple, nonlinear deterministic components. In fact, many systems appear to be dominated by deterministic randomness.

"The word chaos was coined by early investigators because the structure can be invisible to the casual observer, thus giving the impression of randomness."

Chaos vs Randomness

Deterministic chaos should not be confused with the common notion of total disorder. In a sense, deterministic chaos is the opposite of disorder because it actually refers to highly structured behavior. The word chaos was coined by early investigators because the structure can be invisible to the casual observer, thus giving the impression of randomness.

As the adjective deterministic implies, this type of chaos arises in physical processes or systems that follow explicit rules of cause and effect. Thus, in practice we can model the current state of a deterministic system as a unique function of its previous state. Typically, the relationship between past and future is expressed in terms of finite difference or differential equations.

The motion of a satellite around the earth is a familiar deterministic system. Given an initial satellite position and velocity, the laws of Newtonian mechanics make possible construction of a model that unambiguously predicts the satellite's position and velocity at the next moment. By contrast, in processes such as the decay of an atomic nucleus or the motion of an electron in an atom, the governing laws of quantum physics allow predictions only of the probabilities of succeeding states. In these latter cases an unambiguous relationship no longer exists between conditions at one instant in time and the next.

What Causes Chaos?

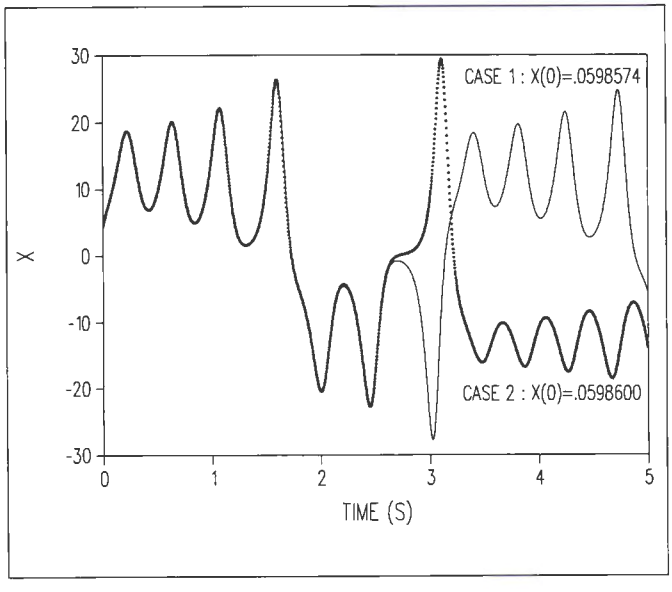
At first glance, the idea that irregularity can arise from deterministic behavior would seem to be a contradiction. In mathematical terms, deterministic irregularity is related to a property known as sensitivity to initial conditions. This is a technical form of the more common notion that sometimes even very slight changes in starting conditions can result in drastic changes to the final outcome. A familiar example of this notion is the saying: "For want of a nail the shoe was lost, for want of a shoe the horse was lost, for want of a horse the rider was lost, for want of a rider the battle was lost," and so on.

When dynamic systems exhibit sensitivity to initial conditions, our ability to predict what will happen next decreases exponentially over time. Even if we know the deterministic law relating the states at time t and time $t+1$, we will never be able to know the starting state at time t with infinite precision. We may be able to predict the next state with acceptable accuracy, but as we extrapolate farther into the future, the effect of the initial uncertainty grows so rapidly that it soon dominates our result. Before long we have no hope of making an accurate prediction. To a casual observer it can appear that the system is being perturbed by some random influence.

The most common cause of sensitivity to initial conditions is the presence of nonlinearities in the governing relationship between sequential states in time. As described previously, nonlinearities are characterized by nonproportional changes in the result for a given change in input. For example, the equation $y = x^2$ is a nonlinear relationship between x and y. Doubling x quadruples y. The equation $y = 2x$, on the other hand, is linear. The first equation can be linearized by assuming that, for cases of interest, x is nearly constant at some value k and rewriting the relationship as $y = kx$. In effect, this change forces the equation to be linear. The importance of nonlinearities was almost completely unrecognized by the scientific and engineering communities until within the past two years or so. Before that time nonlinearities were basically ignored because they were mathematically "messy." Most models that contained nonlinearities were linearized so that they could be solved in analytical form.

With the advent of modern computers, it became possible to observe the results of nonlinearities directly without the need to resort to analytical solutions. As a result, a few key researchers

quickly began to realize that science had been systematically excluding (albeit unknowingly) a major reality in the behavior of the natural world. Surprisingly, this realization has been slow to take hold in the technical community as a whole. Scientists and engineers still have a strong tendency to linearize models, even though they may be solving those models using a computer. We are still strongly influenced by a legacy of linear thinking.



Two time series plots of flow from the Lorenz model of thermal convection illustrating the rapid divergence in behavior resulting from slight changes in the initial condition.

Chaotic Structure in Thermal Convection

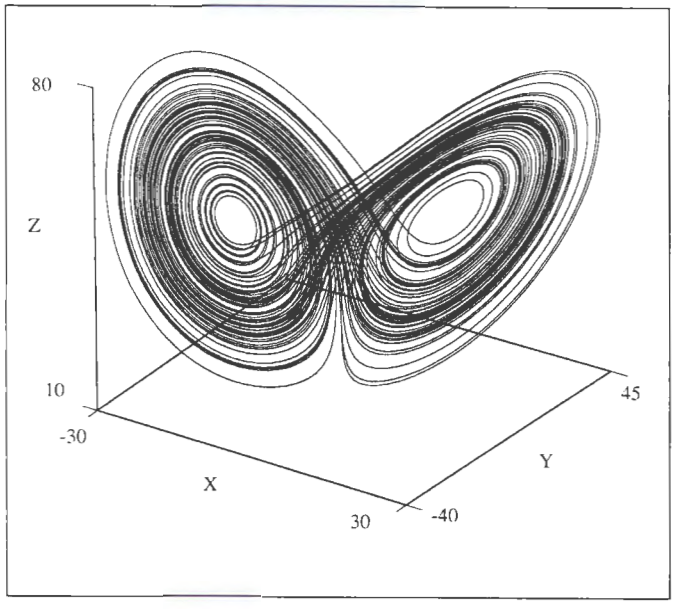
To better understand how the inherent order in chaos can be visualized, it is helpful to consider another simple example. Anyone who has driven on a hot desert road during the day has seen the dancing mirages produced by the air as it rises from the heated surface. The motion of the air in this case is a form of natural thermal convection, induced by the air's lowered density as it warms near the road. This same basic process produces the thermals exploited by birds and hang glider pilots. A simplified mathematical model of this process was developed about 30 years ago by Professor Edward Lorenz of the Massachusetts Institute of Technology. Mathematically, the model consists of three ordinary differential equations that describe how the global patterns of air flow and temperature change over time. Nonlinearities are prominent in two of the equations.

Integrating the model over time produces a simulation of the patterns that would be observed in the layer of air. The figure on this page is a depiction of the Lorenz variable representing the air flow (designated by convention as *X*) plotted against time. The figures show two different traces, each representing the behavior that would occur for slightly different starting conditions. Note the rapid divergence in similarity between the two traces after an initial period during which they remain close together.

We could be content to just observe the variation of flow and temperature patterns individually over time, but a much more useful approach is to plot the flow and temperature variables against each other as in the figure on p. 40. Recall that *X* represents flow; *Y* and *Z* represent horizontal and vertical temperature variations. At each moment in time, the Lorenz model produces values for *X*, *Y*, and *Z* that represent a complete description of the dynamical state of the convecting air layer. When continously plotted, the *XYZ* combinations produce a "map," or "trajectory," of the patterns produced over time. Such plots are termed state-space or phase-space trajectories.

As we see in the figure on p. 40, the *XYZ* patterns produced by the Lorenz model vary continually over time, never settling down to a single point and never exactly repeating. Nevertheless, over relatively long periods of time the Lorenz phase-space trajectory begins to fill in a distinctive shape called the attractor. Magnifying this structure reveals an endless level of repeating detail that can be described in terms of a new mathematical tool called fractal

"Anyone who has driven on a hot desert road during the day has seen the dancing mirages produced by the air as it rises from the heated surface."



Graphical representation of the simultaneous variations in flow (X), horizontal temperature gradient (Y), and vertical temperature gradient (Z) produced by the Lorenz model of thermal convection. Deterministic chaos causes these variables to oscillate in a pattern that never exactly repeats.

"Fourier analysis is clearly appropriate when the governing relationships and resulting patterns are linear, but it is inadequate when the data being analyzed are chaotic."

geometry. Fractal geometry is a universal characteristic of chaotic processes involving friction, which are of primary interest to engineers. Nonchaotic systems also have attractors, but their attractors are not fractals.

To distinguish chaotic attractors from ordinary ones, the former are called strange attractors. Attractors provide a unique way of defining and comparing the structure of different chaotic processes. In effect, it is possible to use the attractor as a kind of dynamic "fingerprint." Not only do attractors allow us to more conveniently picture the underlying patterns, they can be mathematically analyzed to obtain numerical descriptions. Even slight changes in the chaotic behavior (when the system parameters, operating conditions, or inputs are changed, for example) are readily detectable as changes in the attractor characteristics. Much of chaos theory focuses on the proper methods for visualizing and describing attractors.

Chaotic Time Series Analysis

About three years ago I began collaborating with three other ORNL colleagues in applying chaos theory to engineering systems. Our principal interests were (and still are) to determine if particular systems are, in fact, deterministically chaotic, to visualize and quantify the chaotic patterns if they exist, and to use the resulting information in practical ways such as improved design and control. After considering various approaches, we decided that the best approach would be to focus on the analysis of time series measurements.

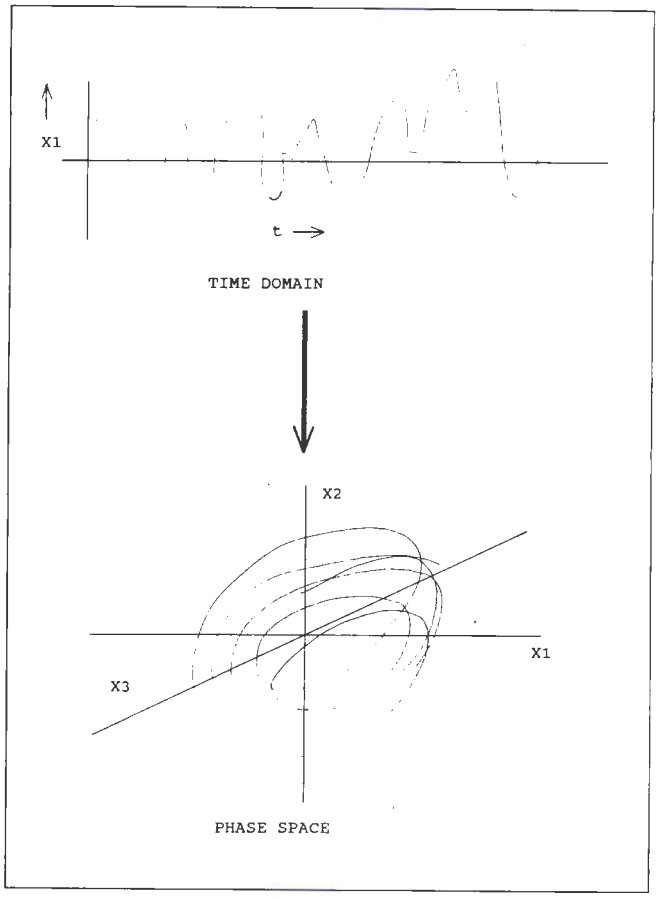
Time series measurements are sequential records of physical variables such as velocity, temperature, or pressure that are collected for some period of time from a process or system. Typically, such measurements are depicted graphically as time traces like the Lorenz X variable in the figure on p. 39. Other familiar examples of such data are stock prices, temperature and rainfall records, and the speed of a car's engine.

The analysis of nonchaotic time series is highly developed and relatively routine. One common technique used by engineers is Fourier analysis, a mathematical procedure that models variations over time as combinations of sine waves (that is, regular waves of constant amplitude and frequency). Fourier analysis is clearly appropriate when the governing relationships and resulting patterns are linear, but it is inadequate when the data being analyzed are chaotic.

In evaluating chaotic time series measurements from engineering systems, we have found that the most productive approach is to construct phase-space trajectories analogous to those shown in the figure on the opposite page. Because it is usually not possible to measure all of the dynamic variables in a system, trajectories must typically be constructed from a small set of selected time

series measurements. Construction is accomplished using a mathematical technique called embedding. The embedding technique is, in fact, so powerful that it is theoretically possible to construct a representation of the behavior of all of the dynamical variables of a system from measurements of a single variable. Thus, for example, it is possible to reconstruct the contributions of Y and Z in the Lorenz model (and thus a dynamically equivalent facsimile of the figure at left) from measurements of the X variable alone!

The final result of the embedding procedure is a transformation of the original time series data into a reconstructed phase-space trajectory as shown in the figure at right. Once this reconstruction has been accomplished, the resulting patterns can be analyzed in detail to determine whether or not the system is chaotic, linear, or purely random. If it is chaotic, the distinctive measures of the attractor can be used to uniquely define the underlying structure and compare it to other systems, conditions, or models.



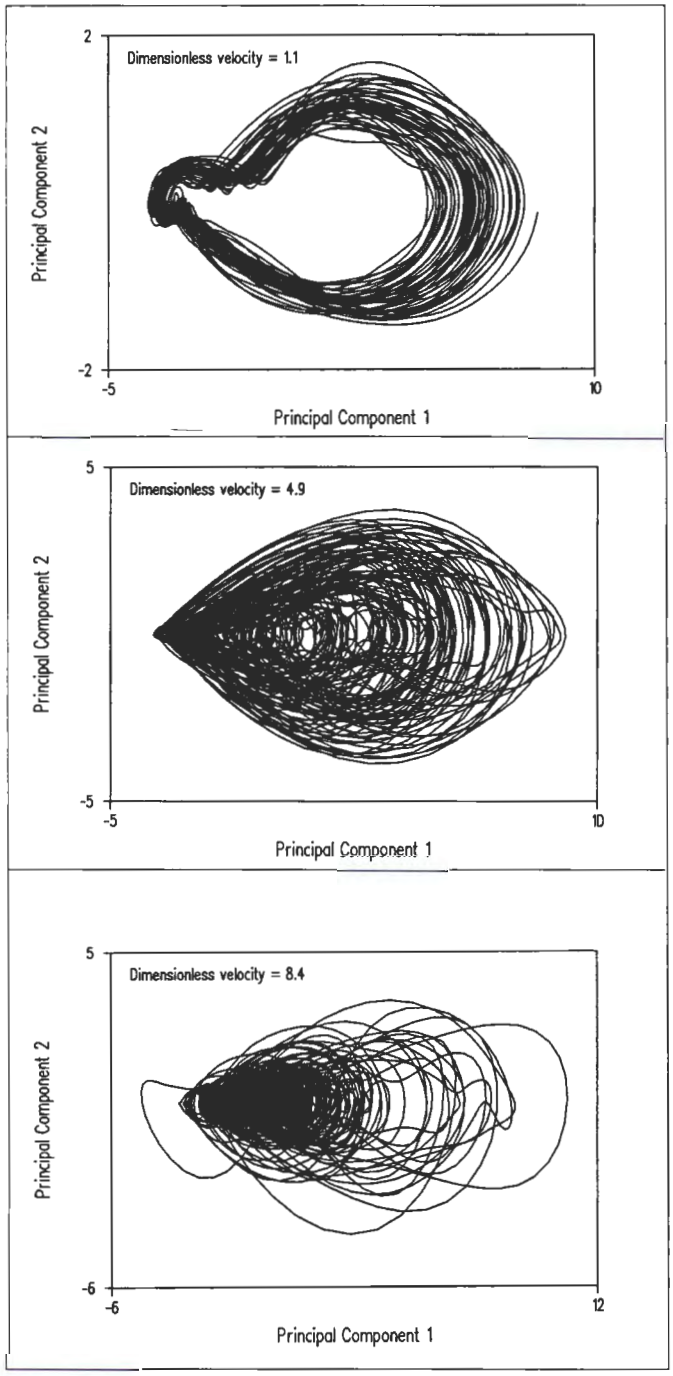
To analyze chaotic time series, the original data are transformed into a "reconstructed" phase space. The phase-space reconstruction represents a kind of "fingerprint" of the dynamical patterns in the data.

Dynamical systems often have more than three important components, and the resulting phase-space can be difficult to visualize directly because it requires more than the three dimensions encountered in everyday experience. One approach to this problem is to make projections of the trajectory in two or three dimensions. Mathematically, however, the analytical procedures are identical, and no serious problems occur in making quantitative descriptions of trajectories in more than three dimensions.

Specific Applications

We initially selected fluidized beds as a trial engineering system for applying chaotic time series analysis. Fluidized beds are widely used in industry to promote intimate mixing between particulate solids and fluids (either liquids or gases). Briefly, they consist of vertical chambers containing "beds" of solids through which fluid flows upward. The fluid flow is sufficiently high to suspend the solids, which swirl about the chamber in turbulent patterns reminiscent of thermal convection. Commercially important processes using fluidized beds include refining petroleum and minerals and fluidized combustion of waste and high-sulfur coal.

The turbulent flow of fluid and solids in fluidized beds is one of the most desirable characteristics for mixing, but it is also the source of much complexity and engineering uncertainty. Although fluidized beds have been prominent in



Phase-space patterns reconstructed from fluidized-bed pressure measurements. Each pattern is a two-dimensional projection of a five-dimensional trajectory. Note the significant pattern changes that occur as a result of changes in fluidization state.

the chemical and petroleum industries for several decades, their design and control is still largely empirical. It is still common to find large multimillion-dollar facilities initially constructed for specific performance specifications (such as yield of a particular chemical product or degree of sulfur removal) only to discover after startup that expensive testing and trial-and-error equipment modifications must be made to meet the original design goals.

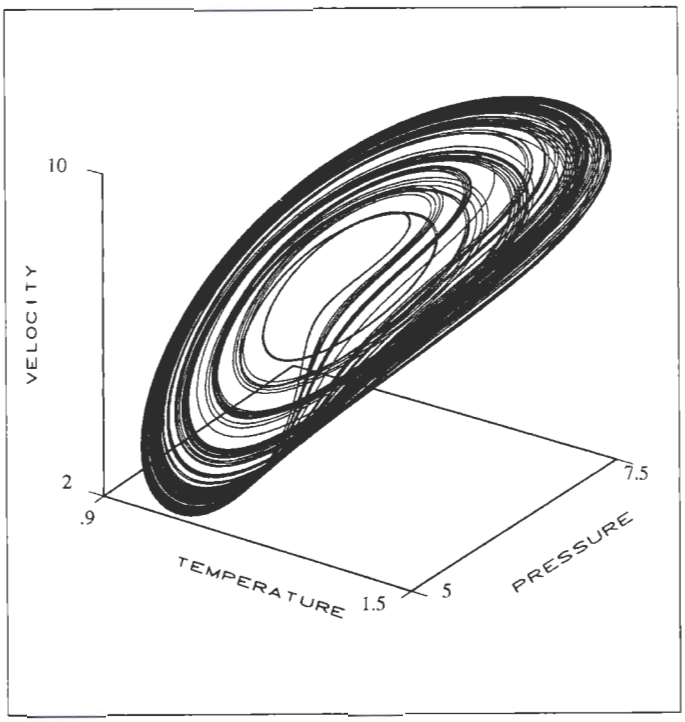
Our approach in applying chaos theory to fluidized beds has been to analyze the experimental chaotic time series of pressure and voidage measurements taken from several different test facilities here and at other collaborating DOE laboratories and universities. From past experience we know that pressure and voidage fluctuations are good indicators of the fluidization state. The results to date clearly demonstrate the presence of deterministic chaos and suggest the possible ranges of chaotic behavior that can be expected in commercial fluidized beds. The figure at left illustrates three examples of chaotic attractors constructed from fluidized-bed pressure signals. Note that the plots shown are two-dimensional projections of five-dimensional trajectories.

Our experience with fluidized beds demonstrates that chaotic time series analysis is a much more discriminating method for characterizing and monitoring fluidization state than conventional methods such as Fourier analysis. Thus, it should be possible to use chaotic measures to design and control fluidized beds more effectively than in the past.

One control application that has already been developed is a fluidization control module now being incorporated into uranium processing facilities at the Oak Ridge Y-12 Plant. An essential

component in the Y-12 control scheme is a device that reconstructs the fluidized bed's attractor from pressure measurements and continually analyzes its key features. When the attractor structure begins to deviate significantly from optimum values, a control signal is sent to correct the bed operation, making it operate more efficiently than was previously possible.

While continuing to work with fluidized beds, we have expanded our scope of potential chaos applications into other areas such as pulsed combustion, motor current signature analysis, nuclear reactor monitoring, and internal combustion engine diagnostics. Results from preliminary investigations in several of these areas are very encouraging.



Phase-space trajectory of a thermally pulsed combustor illustrating chaotic fluctuations in combustion temperature and pressure.

For example, using simplified computer models, we and collaborators from DOE's Morgantown Energy Technology Center have demonstrated that chaos can result from interactions among the basic heat, mass, and momentum balances in pulsed combustion (see the figure at right). Because these same basic balances are present in most flames, we believe that chaos may affect many types of combustion. It is known that fluctuations of flow, concentration, and temperature in flames are often major factors in the production of pollutants such as nitrogen oxides and unburned hydrocarbons. If such fluctuations are the product of deterministic chaos, it should be possible to use chaos theory and chaotic time series analysis to develop totally new methods for reducing undesirable combustion emissions from automobile engines, power plants, and waste incinerators.

Future Plans and Possibilities

We plan to continue exploring the use of chaos theory as a basis for engineering diagnostics. As described previously, we will attempt to use chaotic time series analysis on systems of interest to detect subtle changes in their attractors that indicate the onset of undesirable performance or imminent failure of critical components.

Beyond providing improved diagnostics, we anticipate that chaos theory will contribute to the development of radically new control strategies. For example, chaos theory may be combined with pattern-recognition techniques, parallel computers, and high-speed algorithms for extremely rapid "on-line" decision making. Sufficient data processing speed would allow the introduction of real-time control changes to force the system to behave in a particular fashion. An example of an application of this idea would be in the development of "smart" monitors for automobile engines. Such monitors could evaluate an attractor representing engine performance and determine if the pattern meets certain criteria (e.g., less than some allowable maximum for production

of nitrogen oxide, an air pollutant). If the desired performance criteria are not met, some appropriate parameter adjustment would be made (e.g., increasing the spark advance). Such adjustments, or "perturbations," could be made almost continuously to effectively mold the engine's attractor into its optimum form.

In summary, because it is appropriate for many technical disciplines and applications, use of chaotic time series analysis as a basic research tool and engineering methodology will likely expand widely over the next few years. ornl

Suggested Reading

The following short list of references is recommended for those interested in learning more about chaos:

James Gleick, *Chaos: Making a New Science*, Viking Press, New York. Nontechnical but very readable review of major developments and players.

Ian Stewart, *Does God Play Dice?*, Basil Blackwell, Cambridge, Massachusetts. Very readable introduction to the basic concepts and philosophy behind chaos theory.

G. L. Baker and J. P. Gollub, *Chaotic Dynamics: An Introduction*, Cambridge University Press, New York. Technical presentation of chaos at the undergraduate and first-year graduate student level.

Francis Moon, *Chaotic Vibrations*, John Wiley and Sons, New York. Technical introduction to chaos for engineers and applied scientists.

J. P. Eckmann and D. Ruelle, "Ergodic theory of chaos and strange attractors," *Rev. Mod. Phys.*, Vol. 57, No. 3, Part 1, pp. 617–656. Highly technical discussion suitable for those familiar with chaos theory but not specifically acquainted with chaotic time series analysis.

Biographical Sketch

Stuart Daw (on left) is a development staff member in ORNL's Engineering Technology Division. He holds a Ph.D. degree in chemical engineering from the University of Tennessee. He served as a research and development engineer at E. I. du Pont de Nemours and Company before coming to ORNL in 1979. Three years ago, he became interested in using chaos theory to describe behavior in fluidized-bed reactors. Since then he has collaborated with researchers from ORNL's Engineering Physics and Mathematics Division and Instrumentation and Controls Division to develop chaotic time series analysis as a generic research tool. As a result of this collaboration, Daw was a co-winner of a 1991 Technical Achievement Award from Martin Marietta Energy Systems, Inc. He is a member of the ORNL Graduate Fellow Selection Panel, the Board of Advisors of the Central States Section of the Combustion Institute, and the American Flame Research Committee.

Thin Films for Advanced Batteries

By Carolyn Krause

Batteries are a familiar part of everyday life. Many of us depend on heavy lead-acid batteries to start our cars; a variety of dry cells to operate cameras, toys, and portable sound systems; small lithium-iodine batteries to power cardiac pacemakers; and tiny lithium–magnesium oxide coin cells to run watches.

Packing more power into batteries while reducing their size and weight has become a goal for researchers because of growing interest in smaller, lighter batteries for a variety of purposes. Tiny batteries smaller than a button are needed to provide electrical energy for computer memory chips, medical implant devices, and radiofrequency transmitters in car key sets to prevent car theft. Medium-size batteries are useful for consumer electronics, such as laptop computers and cellular phones. Large-scale, lightweight batteries are needed to power electric cars.

A major issue in the development of new batteries is the materials used. Many household batteries contain lead, cadmium, and mercury—all toxic materials. New Jersey now has a law that requires manufacturers to eliminate mercury from batteries by the end of 1995 and mandates that collection programs be set up for certain batteries containing mercury, lead, or cadmium.

The focus of research is to create batteries that contain fewer toxic materials, are rechargeable, and are able to pack in more energy per unit weight and volume. Batteries using lithium have yielded promising results.

The size and weight of a battery are generally thought to be related to the amount of energy it stores. Hence, the larger a battery, the more electrical energy it can supply. Electrical energy is expressed in watt-hours—the product of the current, voltage, and discharge time when the battery is in use. However, more important figures of merit for a battery are the energy density, which is watt-hours divided by battery volume in liters, and specific energy, which is watt-hours divided by battery weight in kilograms. Although a lead-acid battery in a car can produce a large amount of energy, its energy density and specific energy are low. On the other hand, lithium–manganese oxide coin cells in watches cannot supply the same amount of energy, but their energy density and specific energy are much higher.

At ORNL a group led by John Bates of the Solid State Division has developed a thin-film lithium microbattery for computer memory chips that is much thinner than plastic wrap. "The purpose of these batteries is to hold the memory until the power comes back," says Bates. If such a battery could be scaled up to propel electric vehicles, he calculates it would be an improvement over the lead-acid battery by a factor of 8 in energy density and a factor of 10 in specific energy.

ORNL has developed a thin-film lithium microbattery for computer memory chips.

The main goal of the ORNL work, however, is to find ways to develop microbatteries for microelectronics. Integrated circuits on silicon chips have made possible the reduction of computer size. As a result, modern appliances and cars are now controlled by microprocessors. However, partly because of differences in the levels of research activity and money, reduction in the sizes of batteries has not kept pace with the reduction in the sizes of electronic devices.

For example, consider nonvolatile computer memory chips. They have nonrechargeable batteries as backup so that the information stored as electronic charges is not lost in case of a power failure. However, each lithium battery is many times larger than the chip using it. ORNL's development of thin-film lithium batteries offers the means to scale down the sizes of batteries to more closely match the sizes of microelectronic components. The ORNL work may result in the first practical rechargeable microbattery.

John Bates examines a thin-film lithium battery in the light of the nitrogen glow discharge in the vacuum deposition chamber used to produce microbatteries at ORNL's Solid State Division. The nitrogen gas reacts with lithium orthophosphate to form a new battery electrolyte film discovered at ORNL. *Photographs in this article by Bill Norris.*

Battery on a Chip

Solid-state processes for depositing thin films on a substrate are being used at ORNL and elsewhere to increase the amount of energy that can be stored in a battery per unit weight and volume. ORNL's Ceramic Thin Films Group in the Solid State Division has made a number of thin-film lithium microbatteries that have remarkably high specific energies and energy densities. The cells have open circuit voltages at full charge of 3.7 to 3.8 volts, the highest achieved to date in a thin-film battery. This success has attracted the attention of the Eveready Battery Company, which has also been developing thin-film batteries. In March 1992, ORNL and Eveready signed a cooperative research and development agreement (CRADA) to facilitate the commercialization of thin-film batteries (see the section on "CRADA with Eveready" on p. 53 and the item in "Technology Transfer" on p. 154).

According to Bates, the current goal of the ORNL group, which includes Nancy Dudney, Greg Gruzalski, and Chris Luck, is to make thin-film batteries that can be deposited directly either on the reverse side of a computer memory chip or onto the chip's protective ceramic package. "The idea," he says, "is to incorporate the battery into the integrated circuits of computer memory chips during their manufacture. This approach would eliminate the manufacturing step of soldering large batteries onto circuit boards."

Bates believes that these solid-state thin-film batteries will also offer these advantages over competitive technologies:

- They are rechargeable.
- They have high power and energy densities.
- They can be fabricated to virtually any size onto a variety of substrate materials, such as semiconductors, ceramics, and plastics.
- They can be fabricated using standard deposition techniques and mild deposition conditions.
- They can operate over a wide temperature range, even at temperatures near the melting point of lithium; ORNL cells have been operated between –15°C and 150°C.
- They contain no liquid components and produce no gases.

Chris Luck shows a display model of a thin-film lithium battery that he fabricated. The 3.7-V battery can power the attached digital watch. On the computer screen is a schematic of the thin-film battery.

"Our thin-film battery," Bates says, "can be deposited onto any substrate that can withstand a temperature of 50°C, including a variety of polymers. In addition, the shape of the battery can conform to the shape of the support. For example, it could be fabricated on a cylinder. Our battery can be made as small as any multilayer device or as large as the deposition equipment allows. For example, a thin-film battery could be deposited onto an entire sheet of window glass."

Bates and his colleagues have been searching for the right combination of materials to make reliable backup power sources for computer memory chips based on complementary metal oxide semiconductor (CMOS) technology. Currently, standby power for computer memory chips is supplied by nonrechargeable lithium–manganese oxide or other lithium batteries, which are soldered to circuit boards or incorporated into a self-contained package. These batteries are

larger than the chips for which they provide backup energy. Someday they may be replaced by smaller thin-film lithium batteries based on the ones developed at ORNL using a newly discovered material for the electrolyte.

The ORNL group is also adapting this microbattery technology for use in miniature radiofrequency transmitters expected to be commercially available someday. The group hopes to contribute to the development of scaled-up batteries for consumer electronics and electric cars (see sidebar on p. 56).

Why Thin-Film Lithium Cells?

Why did Bates and his colleagues choose to investigate thin-film lithium cells? First, they were attracted to lithium's advantages. Because lithium has a small atomic mass and the highest electrochemical potential for a metal, it makes a good reactant for a battery that must have high cell voltage and high specific power. They chose thin films for batteries because they make an effective cell which can be manufactured by the same processes used by the electronics industry. Battery cell components can be prepared as thin (~1μm) sheets built up as layers. The area and thickness of the sheets determine battery capacity.

Deposition of thin films increases the contact area of the cell components, resulting in a high fraction of reactants. Thin films result in higher current densities and cell efficiencies because the transport of ions is easier and faster through thin-film layers than in bulk materials.

The major challenge to the development of the lithium cells was to find an electrolyte that satisfactorily conducted ions and was stable in contact with lithium. In the fall of 1991, groups at Eveready and the University of Montpellier in France reported the development of solid-state rechargeable thin-film cells with lithium anodes. The French group's cells had low current densities and short lifetimes, but the Eveready cells had excellent current densities and were charged and discharged hundreds of times. The Eveready cells use a titanium sulfide cathode and an oxysulfide-based electrolyte. In both cases, however, the cells required an extra layer of lithium iodide to protect the electrolyte from attack by lithium. At ORNL Bates' group has developed an even better cell using an oxynitride-based electrolyte, which is stable with a lithium anode.

Building a Better Battery

The ORNL research program began in November 1986 at a Materials Research Society meeting when Jim Roberto, director of the Solid State Division, heard a talk on microbatteries by Minko Balkanski of the Universiti Pierre et Marie Curie in Paris, France. There Roberto discussed with Bates the possibility of ORNL conducting research in support of microbattery development. In April 1987, Bates and Dudney submitted a seed money proposal entitled "Micropower Sources" and obtained internal funding from ORNL. By November 1987, they had their first vacuum chamber for film deposition. In June 1988, Bates and Dudney submitted a proposal on "Microionics: Materials and Devices" and received support for fiscal year 1989 from the Director's R&D Fund at ORNL. In November 1988 Bates' group fabricated the first vanadium oxide cell ever made at ORNL and possibly anywhere else. It marked the beginning of a series of successes for the group in microbattery development.

"Our work started from scratch," Bates says. "We had no deposition equipment and no experience in thin films. We began our electrolyte studies using a lithium phosphosilicate system."

The electrodes of the ORNL thin-film battery are lithium (Li) and noncrystalline vanadium oxide (V_2O_5). Vanadium oxide was selected as the cathode because it is an intercalation compound that permits a lithium ion to move into and out of a framework without causing more than a small expansion or contraction of the structure. Lithium ions move into the V_2O_5 structure during discharge of the cell and are forced out of the structure during recharge. The amorphous material is preferred over the crystalline form because three times more lithium ions can be inserted into the amorphous cathode, thus making a battery that has a higher capacity.

Thin Films for Advanced Batteries

Battery Basics

"The first electric battery may have been made in ancient Egypt, but historians often credit Italian physicist Alessandro Volta, who in 1800 assembled a series of silver and zinc disks that sandwiched cardboard disks soaked in saltwater."

A battery is one of two kinds of electrochemical devices that convert the energy released in a chemical reaction directly into electrical energy.

In a battery, the reactants are stored close together within the battery itself, whereas in a fuel cell the reactants are stored externally. This conversion of chemical energy to electrical energy is potentially 100% efficient, whereas the conversion of chemical energy to mechanical energy via a thermal conversion (e.g., internal combustion of gasoline in cars) always results in heat transfer losses limiting the intrinsic efficiency.

The first electric battery may have been made in ancient Egypt, but historians often credit Italian physicist Alessandro Volta, who in 1800 assembled a series of silver and zinc disks that sandwiched cardboard disks soaked in saltwater. The disks served as electrodes, and the saltwater was the electrolyte.

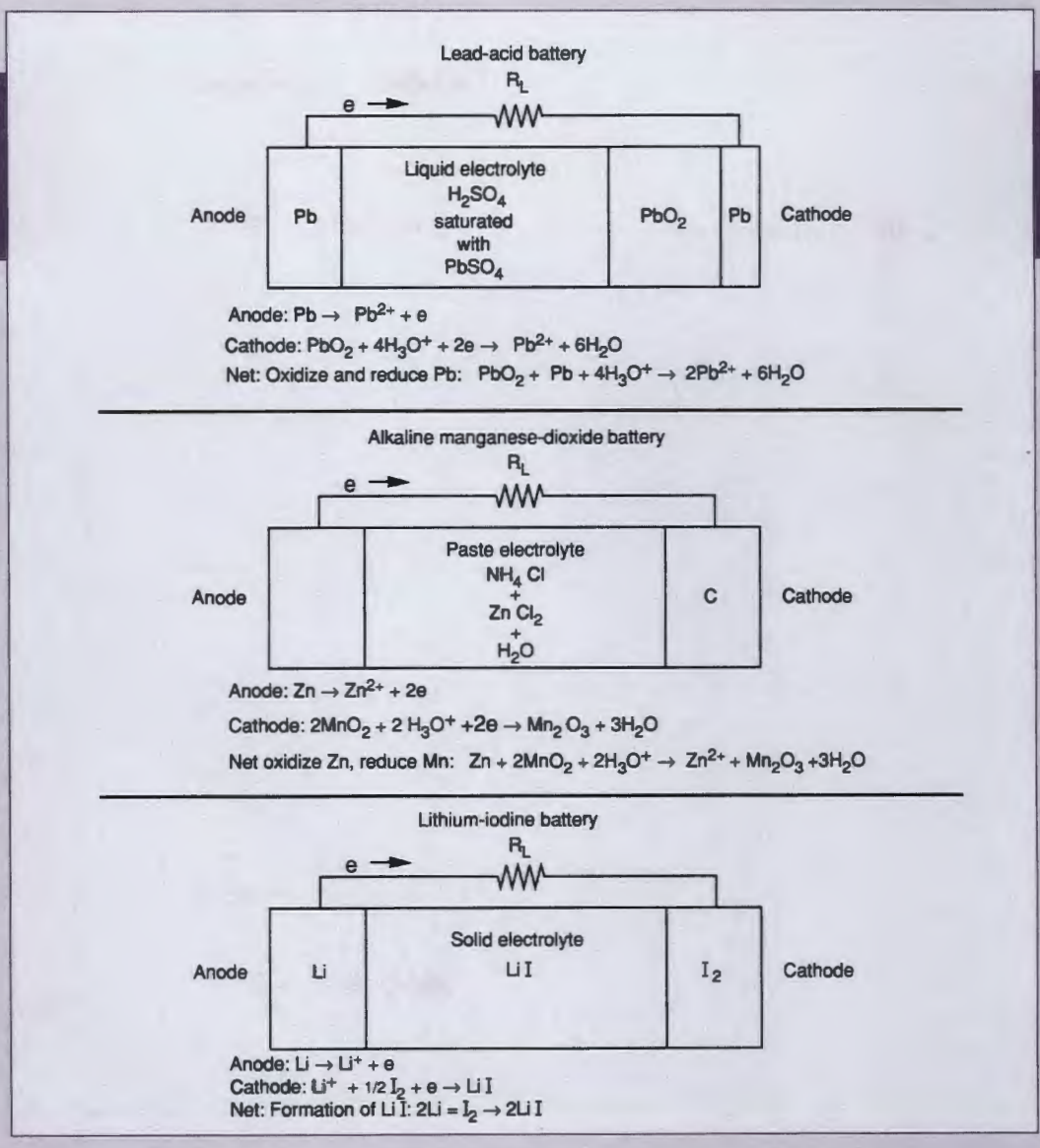
Familiar batteries of today are the flashlight (or dry cell) battery, which uses manganese oxide and zinc for the electrodes and a paste as an electrolyte, and the lead-acid car battery, which uses lead and lead oxide for the electrodes and sulfuric acid for the electrolyte. The lead-acid battery, which was invented in 1860, is unsurpassed for vehicle uses because it can deliver a large current.

The electrodes are the positively charged pole (cathode) and the negatively charged pole (anode) of a storage battery. The electrolyte is a chemical compound that separates the electrodes and conducts ions released during discharge. The electrolyte forces the electrons to flow in the device's external circuits.

Chemical energy is converted into electrical energy by an oxidation reaction in which electrons are released to an external circuit through the anode. Simultaneously, a reduction reaction removes electrons from the external circuit through the cathode. The electrolyte functions to "control" the rate of reaction between the anode and cathode by forcing electrons to move through external circuits, producing energy. However, the electrodes must not touch each other to avoid internal short circuits. (See the examples of battery reactions shown in the schematic.)

Some cells operate as two independent half cells in which reactions occur by ion exchange with the cell electrolyte. For others, a net cell reaction results in the formation of a new compound such as lithium iodide or sodium sulfide. Such a reaction requires the transport of an ion through the electrolyte from one electrode to the other.

Among the important characteristics of battery cells are



The schematic shows the chemical reactions in three different batteries that produce electrical current. R_L represents the resistance of the external circuit.

- **Cell voltage**—ideal or open circuit voltage, which is higher than the actual cell voltage when the current flows through the cell (cell efficiency is determined by the ratio of actual voltage to the ideal voltage)
- **Power output**—the magnitude of the current that can be delivered at a given voltage
- **Power density**—power output per weight or volume of the battery system, which includes the cell materials, reactants, and necessary packaging
- **Capacity**—the amount of chemical reactants that can be stored and effectively used in the battery. Batteries rarely can be used until fully discharged, so that one of its reactants is totally consumed
- **Shelf life**—the amount of time a battery can retain its original properties when not in use
- **Rechargeability**—the ability of the battery to be restored to a useful condition.

Batteries are designed differently for various applications. "For computer memory backup power," Bates says, "the battery should have the appropriate cell voltage, a long shelf life, rechargeability, and the ability to be integrated with the memory chips during electronic fabrication. For vehicle applications, the battery should offer high energy density, large current output, full rechargeability, rapid recharge, safety, and a reasonable cost."

—Carolyn Krause

Nancy Dudney examines a thin-film lithium battery in the protective atmosphere of a glove box.

In a thin-film lithium cell (see the schematic diagram of its operation on p. 53), lithium ions leave the anode, diffuse through the electrolyte film, and reach the V_2O_5 cathode. At the same time, electrons travel through the external circuit to power a device and then to the cathode to "combine" with the Li^+ ions so that the compound retains a net neutral charge. The cell reaction can be represented as

$$xLi + V_2O_5 = Li_x V_2O_5.$$

In their effort to develop an improved electrolyte, the ORNL scientists took into account the fact that many inorganic compounds are better ionic conductors in the amorphous state than in the crystalline form. For example, the conductivity of amorphous lithium phosphate having the composition $0.6Li_2O{:}0.4P_2O_5$ is 10^9 times as high as that of crystalline lithium orthophosphate (Li_3PO_4).

To avoid the need for a layer of lithium iodide to protect the electrolyte from being attacked by lithium, Bates consulted the literature for some clues. "I learned that adding nitrogen to sodium metaphosphate glasses improves their durability in contact with air and water vapor. So we decided to sputter the lithium orthophosphate in nitrogen rather than the standard gas mixture of argon and oxygen. The resulting film was an oxynitride that contained about 3 at. % nitrogen. It seems that nature much prefers oxygen to nitrogen in compounds such as these, but the presence of this small amount of nitrogen greatly improves the performance of the electrolyte."

Currently, the electrolyte used exclusively in ORNL's thin-film lithium batteries is lithium phosphorus oxynitride (LiPON), the first film of which was grown at ORNL in February 1991. The LiPON electrolyte, which is deposited over the cathode, outperforms competitive electrolytes, such as the oxysulfide electrolytes employed by Eveready.

To analyze the composition of the electrolyte, the group has relied on resonance ion backscattering performed by Ray Zuhr of the Solid State Division, electron spectroscopy for chemical analysis and Auger electron spectroscopy carried out by Ashok Choudhury of the Metals and Ceramics Division, and proton-induced gamma emission analysis conducted by their collaborator, Dave Robertson, of the University of Kentucky at Lexington.

"Tests show that the nitrogen-containing electrolyte has 30 times the lithium ion conductivity of a film of pure amorphous lithium ortho-phosphate," Bates says. "This is important because

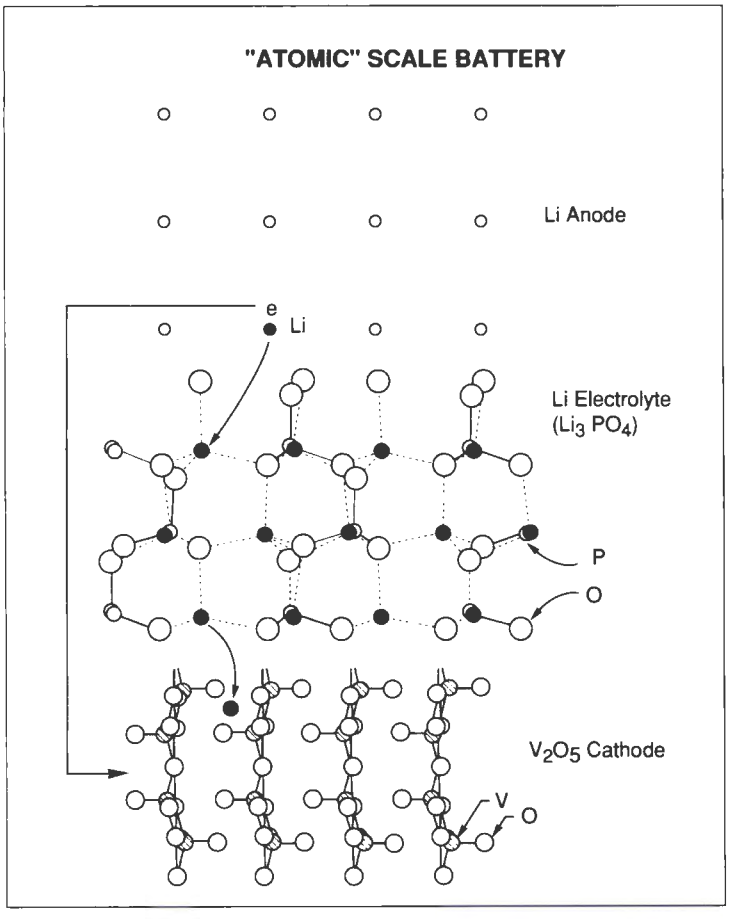
every battery has an internal resistance to ion transport. Our goal is to overcome this resistance by increasing the ion conductivity of the electrolyte. The result will be a better battery."

How Film Is Deposited

The thin-film lithium cell is fabricated at ORNL by depositing successive layers of the cathode, electrolyte, and anode using direct-current and radiofrequency magnetron sputtering and thermal evaporation. The battery is only 6 microns thick, or one-third the thickness of plastic wrap (a micron is a millionth of a meter), and cells have been deposited on alumina or glass substrates.

Magnetron sputtering is done in a vacuum chamber at near room temperature in pure argon, oxygen, and nitrogen gases. A thin 2.5-cm-diam disk of a target material is loaded into a commercial magnetron sputter source. The targets are vanadium metal for the cathode and Li_3PO_4 for the electrolyte. A high voltage is applied to the target material. At low gas pressures, the voltage generates a plasma discharge. The positively charged ions in the plasma are accelerated to the target material because of its negative charge, and upon bombardment, some of the target atoms are ejected, or sputtered.

The sputtered atoms then condense on the battery substrate positioned about 5 cm from the sputter target. Permanent magnets positioned beneath the target enhance the sputtering efficiency by confining the electrons in the plasma close to the target surface, thereby increasing the ionization of the atoms in the sputtering gas.



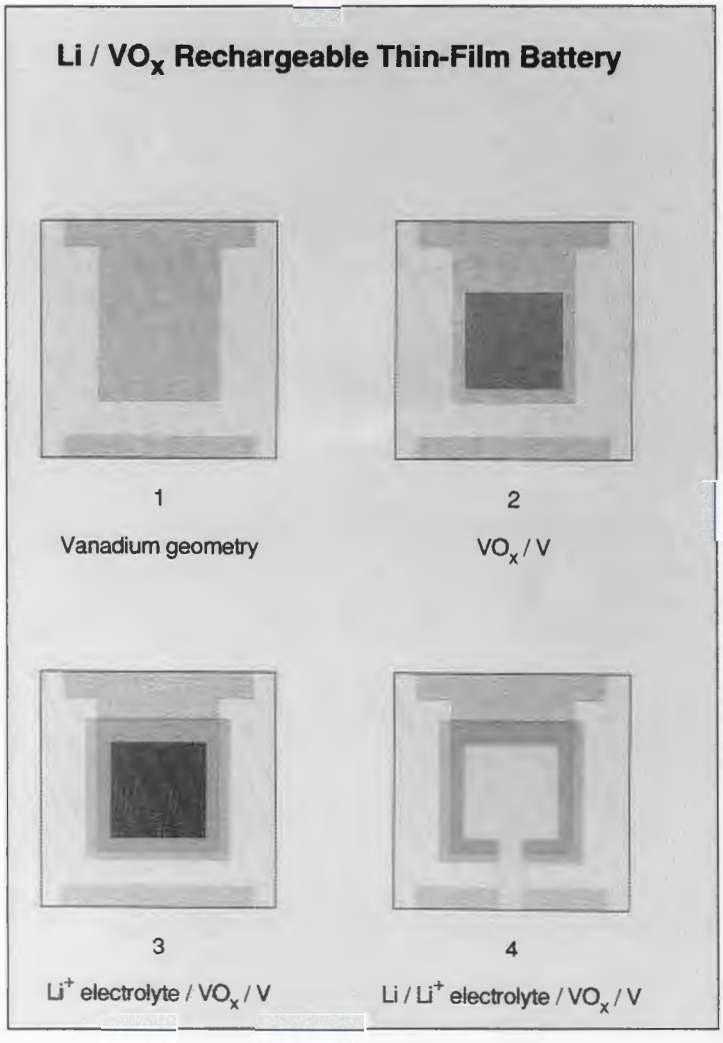
How ORNL's thin-film lithium battery works is shown here schematically on an atomic scale. The lithium oxidizes, diffuses through the electrolyte as an ion, and intercalates (inserts itself) into the reduced V_2O_5 cathode.

"Currently, the deposition rates are quite low because pushing for a more rapid rate of film growth would sacrifice the film's uniformity and quality," Bates says. "But this production problem should be considerably reduced when larger sputter sources are employed."

The final cell layer, the lithium anode, is deposited by thermal evaporation under vacuum.

CRADA with Eveready

The ORNL group has apparently solved the problem of lithium attack on the thin-film electrolyte. However, a remaining problem that



ORNL's rechargeable thin-film lithium–vanadium oxide battery is fabricated by deposition of three layers on the vanadium current collector—the cathode (amorphous vanadium oxide, or V_2O_5), the electrolyte (lithium phosphorus oxynitride, or LiPON), and the anode (lithium, or Li).

must be addressed is protecting the lithium from corrosion in air. Currently, thin-film batteries must be stored in a protective argon atmosphere. "We must find a way to seal up the battery and make it self-contained," says Bates.

The researchers are now working on a project to package thin-film batteries under a CRADA signed in March 1992 between Energy Systems and the Eveready Battery Company. Eveready had approached ORNL about a cooperative research effort because the company had not found a packaging solution and because the smaller-scale deposition equipment at ORNL allows researchers to try out ideas rapidly. The deposition system at Eveready is much larger because it is designed for small production runs, not research.

"We will work with Eveready on determining which material could best seal up the battery without altering the properties of our films," Bates says. "We are testing the results of depositing a variety of materials onto the lithium as a sealant film."

Bates predicts the group will develop a self-contained thin-film battery of more than 3.5 volts during 1992. Then he hopes the group may become involved in research on scaling up thin-film batteries for use as lightweight, energy-efficient sources of power for electric cars (see sidebar "From Chips to Cars").

Future of Thin-Film Battery Research

The use of LiPON in thin-film batteries will make possible higher voltage cells based on lithium cobalt oxide ($LiCoO_2$) or lithium manganese oxide ($Li_2Mn_2O_4$). Raising the voltage of these cells is important because it increases their energy density.

Another goal of the ORNL research is to enhance the current density and pulse capability of the thin-film cells. One problem in the ORNL cell is that the current appears to be limited by lithium ion transport in the vanadium oxide cathode.

The discovery of lithium phosphorus oxynitride and its excellent properties as an electrolyte has opened up a new area of research for thin-film materials, which will be explored in a Basic Energy Sciences program of the

Dudney, Bates, and Luck examine the digital watch powered by the thin-film lithium battery they developed. The electrometer shows that the battery voltage is 3.35 V while powering the watch.

Department of Energy. In addition, the new field of microionics could become a major target of research at ORNL.

"We hope to continue to focus our basic research on improving battery technology," Bates says. "Our work in microbatteries and our work with other groups on microelectronics could be extended to development of, for example, miniature radiofrequency transmitters and remote microsensors for environmental or biomedical applications."

In conclusion, the program started by Bates, Dudney, and others could expand to scale up microbatteries being developed for computer chips into macrobatteries that could be useful in many ways, including powering electric vehicles. Use of thin films for batteries to power everything from chips to cars may someday be seen as a classic example of getting more from less. ornl

Thin Films for Advanced Batteries

From Chips to Cars

"DOE has established an Advanced Battery Consortium in which national laboratories, universities, and other companies will collaborate on battery research with Ford, Chrysler, and General Motors."

In the fall of 1991, the U.S. government gave a jump start to the nation's battery research by combining its resources with those of the Big Three automakers in Detroit.

Because of renewed concerns about air pollution and future oil shortages, there has been a resurgence of interest in electric cars. But to be acceptable to the public, such vehicles will need batteries that are low in cost and able to keep the vehicle operating for many miles before a recharge is needed. In addition, the time to recharge the battery should be short.

DOE has established an Advanced Battery Consortium in which national laboratories, universities, and other companies will collaborate on battery research with Ford, Chrysler, and General Motors. The latter company is already developing electric vehicles that would use lead-acid batteries. One reason for this move by DOE is to make the United States more competitive in battery research and electric vehicle development; nations taking the lead in these areas are Great Britain, Germany, Japan, and Canada.

ORNL is expected to be named a lead laboratory for DOE and the consortium in at least one area of electric vehicle development: lightweight body materials. ORNL may also play a role in the development of electric vehicle battery materials.

The potential competitors for electric vehicle propulsion include lead-acid (Pb/acid) batteries, sodium-sulfur (Na/S) batteries, and lithium–iron sulfide (Li/FeS) batteries. The lithium–iron sulfide battery has higher specific energy and energy density than the other two. However, according to Bates, a scaled-up thin-film lithium battery would be an improvement over the lithium–iron sulfide battery by a factor of about 4 for specific energy and by a factor of about 5 for energy density (see table).

"Improved power density is achieved by using a lithium battery," Bates says. "By making a thin-film battery, we hope to increase the maximum discharge current and decrease the time required to recharge the battery."

	Specific energy (Wh/kg)	Energy density (Wh/L)
ORNL thin film	400	570
Li/FeS	83	110
Na/S	80	89
Pb/acid	34	82

Waste R&D At ORNL

By Diedre Falter

In the past few years efforts to clean up hazardous waste at sites across the country, including Department of Energy facilities, have increased dramatically. Vast economic and personnel resources are being devoted to environmental restoration. Sometimes problems can be solved quickly using available techniques; however, solving many old environmental problems requires new methods and technologies. Creating these new approaches is the task of the Office of Technology Development (OTD) within DOE's Office of Environmental Restoration and Waste Management.

The success of this task depends to a considerable degree on maintaining open lines of communication between OTD and its counterparts, the Office of Environmental Restoration and the Office of Waste Operations. These organizations are involved in the nuts and bolts work of restoration, remediation, and waste management, often responding to crisis situations. During the course of this work, some areas are found to have cleanup and waste management needs that cannot be met with existing technologies. OTD's mission is to be attentive to these areas, seek out possible solutions, and nurture their development so they can be implemented in the field.

At ORNL, innovative environmental restoration and waste management techniques for OTD are being developed in the following areas:

• **Characterization**—developing advanced models, field measurement and sensing methods, and data acquisition and analysis systems for mapping and determining the contents of a waste site;

• **Bioremediation**—developing microorganisms to "eat" or otherwise stabilize selected organic contaminants, such as trichloroethylene (TCE) and polychlorinated biphenyls (PCB), and inorganic species, such as uranium and lead, in situ (in place) or in process;

• **Treatability**—developing methods for treating soils contaminated with volatile organic compounds and low levels of radioactive substances;

• **Robotics**—developing robotic systems and remote technology to characterize and clean up waste without exposing workers to a hazardous environment;

• **D&D**—decontamination and decommissioning of metals and concrete to assist in disassembling old facilities and in replacing several major facilities in the Defense Programs Reconfiguration;

• **Transportation**—performing evaluations of transportation needs for on-site and off-site transfer of hazardous and mixed waste (hazardous and radioactive waste combined); and

• **Technology transfer**—promoting the transfer of technologies developed at ORNL that potentially could improve program effectiveness, reduce costs, and save time for federal agencies, industry, academia, and the international community.

All these activities involve developing new remediation and waste management methods or modifying existing techniques to create cost-effective, energy-efficient waste-minimization technologies.

ORNL is developing innovative environmental restoration and waste management technologies.

Characterization

Finding more economical ways to clean up soil and groundwater contaminated by radioactive and hazardous chemicals is a priority in environmental restoration and waste management. The first step toward reducing the cost of cleaning up sites is reducing the cost of collecting and analyzing soil and groundwater samples. The process of collecting and analyzing samples is not only costly, but it also delays cleanup efforts because of the time required to obtain results. The Office of Technology Development is currently supporting a number of projects at ORNL addressing these problems.

For example, ORNL researchers Marcus Wise, Cyril Thompson, and Mike Guerin, all of the Analytical Chemistry Division, have developed a portable, real-time, direct-sampling ion-trap mass spectrometer that can detect hazardous organic

Cyril Thompson operates the Analytical Chemistry Division's portable direct sampling ion-trap mass spectrometer, which can detect hazardous organic compounds at extremely low concentrations, reducing sample processing time by half.

compounds at extremely low concentrations. This device reduces sample processing time to less than half that required using conventional analytical methods (see sidebar on p. 80).

The improved Derivative Ultraviolet Absorption Spectrometer (DUVAS) system developed by John Haas of the Health and Safety Research Division measures groundwater contamination directly and, as a result, is able to more accurately characterize any such contamination. The system may have additional applications in the monitoring of manufacturing discharges and chemical process streams (see sidebar on p. 83).

The colloidal borescope previously developed by Tom Cronk and Pete Kearl, both of ORNL's Grand Junction, Colorado, office, is being adapted to measuring the velocity of groundwater flow. This instrument offers the potential for improved site characterization, design of faster and more cost-effective remediation strategies, and improved monitoring of the remediation process.

Meanwhile, nondestructive assay and nondestructive examination methods using a linear accelerator have been developed for characterizing remote-handled transuranic (RH-TRU) waste by Fred Schultz of the Office of Environmental and Health Protection Compliance.

Tuan Vo-Dinh of the Health and Safety Research Division is developing a luminescence spot test for rapid screening of soils to find out if they contain PCBs. In this technique, the presence and concentration of PCBs adsorbed on chemically treated filter paper and exposed to light are determined by detecting and measuring their resultant luminescence. Advantages of the technique are that the simple instrumentation can be easily set up and used in the field and that it can analyze samples more rapidly and at a lower cost than conventional methods.

Some effort at ORNL has been devoted to developing technologies for analyzing air, water, and soil in place, thus reducing considerably the cost, time, and hazards associated with extracting, transferring, and analyzing contaminated samples. Haas has been building a fiber-optic probe and monitoring system using DUVAS to provide fast, cost-effective in situ sampling of groundwater to identify its contaminants. At the same time, Roger Jenkins of the Analytical Chemistry Division is developing an arrayed multisorbent sampler—an array of tubes packed with layers of various materials that adsorb volatile organics—for in situ collection of volatile species at depths up to 38 m (125 ft). An example of such an organic pollutant

is TCE, a solvent that had been widely used to remove grease from metal. The samplers will provide temporally and spatially resolved chemical information concerning the impact, effectiveness, and zone of influence of candidate remediation technologies.

Considerable time and money can be saved by identifying the technologies already available and establishing procedures for their use. Wayne Griest, Gary Sega, and Bob Schenley, all of the Analytical Chemistry Division, are adapting analytical methods already approved by regulatory agencies to the characterization of mixed wastes and radioactive environmental samples.

By detecting and measuring the concentration of groundwater contaminants directly, rather than by "sniffing" the air above the water, the DUVAS system, displayed here by John Haas of the Health and Safety Research Division, is able to more accurately characterize groundwater contamination.

"Considerable time and money can be saved by identifying the technologies already available and establishing procedures for their use."

Bioremediation

A number of hard-to-degrade volatile organic compounds, such as TCE, have been identified as groundwater and soil contaminants at DOE sites. These contaminants are of particular concern not only because of their potential toxicity but also because of their movement through soils as vapors and in water. New technologies are needed to remove these contaminants from groundwater and soil and to safely dispose of them.

For example, the popular method of air stripping results either in the discharge of TCE to the atmosphere or its capture on activated carbon, which itself must then be disposed of. In either case, the TCE is not actually destroyed. A more viable solution seems to be bioremediation, which is based on the use of organisms to destroy the contaminant at the site, thus avoiding the risks to worker safety of handling, transporting, treating, or storing contaminated residuals.

Two types of contaminants, perchloroethylene (PCE) and PCB, are effectively nondegradable under aerobic (oxygen-rich) conditions, but they may be broken down into harmless substances in an anaerobic (oxygen-free) environment. At least two OTD projects at ORNL are focused on developing techniques to break down these chemicals in anaerobic environments. For instance, Terry Donaldson, Thomas Klasson, and Betty Evans, all of the Chemical Technology Division, are working to identify and cultivate naturally occurring anaerobic bacteria that break down PCB molecules by eating and digesting them (see sidebar on p. 65). Likewise, Steve Herbes and Mike Morissey, both of the Environmental Sciences Division, are exploring methods to assist cleanup at the Savannah River Site by anaerobically degrading PCE and other organic compounds resistant to biological treatment using existing commercial processes.

Remediation of TCE-contaminated water using bioreactors, such as that being operated by Chemical Technology Division engineers Hal Jennings and Andrew Lucero, relies on the use of naturally occurring organisms to destroy the contaminant at the site, eliminating the need for handling, transporting, treating, or storing contaminated residuals.

Because bioremediation approaches that exploit existing bacteria or green plants are more socially acceptable than using engineered microbes, Barbara Walton and Nelson Edwards, both of the Environmental Sciences Division, are studying the effects of vegetation on the bioremediation of soils contaminated with TCE and PCE. In particular, they will determine whether certain plant species and fertilizers speed up the rates at which TCE and PCE decompose in soil. Meanwhile, Tony Palumbo of the same division is coordinating a soil bioremediation team including scientists from both the University of Tennessee and the University of Minnesota. They are using innovative methods of monitoring microbial activity in the soil to measure the effectiveness of bioremediation of TCE- and PCE-contaminated soil and water deep underground at the Savannah River Site.

Treatability

Waste retrieval and waste processing currently constitute the largest segment of the mission of DOE's Office of Environmental Restoration and Waste Management. Current technologies for treating contaminated materials to eliminate their toxicity or removing them from sites and processing them into a suitable form for shipping or disposal are often inadequate and expensive. In situ vitrification is one promising technology that instantly destroys many hazardous components and immobilizes the remainder by trapping them in a block of glass or slag with minimal personnel exposure. Gary Jacobs and Brian Spalding, both of the Environmental Sciences Division, successfully demonstrated this technique on a trench containing radioactive materials (see a description of this demonstration on p. 78 of the Number Two, 1991, issue of the *Review*).

A Chemical Technology Division team consisting of Lloyd Youngblood, Jr., Zane Egan, Klasson, and Donaldson is adapting previously developed techniques for the chemical destruction of PCB-contaminated cooling oils and electrical transformer oils to the treatment of DOE's mixed wastes. Youngblood is also addressing the concern about the integrity of aging tanks containing mixed wastes by trying to determine the best method for removing the

sludge from these tanks before they begin to leak.

Mixed wastes offer plenty of tough problems for researchers to solve. For instance, many aqueous mixed waste streams contain concentrations of nitrate that exceed drinking water standards. Al Mattus of the Chemical Technology Division is searching for ways to chemically reduce the nitrates contained in these mixed waste streams, producing gaseous ammonia and achieving acceptable nitrate levels. At the same time, Chet Francis of the Environmental Sciences Division is hot on the trail of a method for selectively removing uranium from soils containing high concentrations of silt or clay. Selectively removing the uranium would be much less costly than transporting, storing, and monitoring of tons of contaminated earth.

Robotics

In the movies, robots are literally able to "boldly go where no one has gone before" and save human adventurers from risking life and limb. Real-life robots are being developed at ORNL and elsewhere to help reduce or eliminate the risks of exposing personnel to radioactive or hazardous wastes. Researchers are applying the principles of robotics to develop servomechanical devices that incorporate sensors, computer control, and human-machine interfaces for efficient remote operations under hazardous conditions and for improvements in productivity. Typically, a robot possesses sufficient autonomous control capability to perform many of its functions automatically, but more difficult tasks are supervised and guided by a human operator who is remotely located—out of harm's way.

ORNL researchers are focusing on developing a practical robotics technology to reduce the hazards and costs of cleaning up DOE sites. The work is being carried out by a research team headed by Bill Hamel, who also serves as one of the National Robotics Program coordinators. This team forms an important part of the Robotics Technology Development Program in OTD. This national robotics effort is addressing needs at many DOE laboratories and weapons and materials production sites.

The ORNL team seeks to develop robotic technology for applications involving underground storage tanks, buried wastes, waste minimization, contaminant analysis automation, waste facility operations, and decontamination and decommissioning associated with DOE facilities.

Research efforts in the characterization and remediation of underground storage tanks are led by Barry Burks of ORNL's Robotics and Process Systems Division. Recently, a team led by Burks achieved tremendous success in applying computer-based laser imaging techniques to mapping the surface topology of radon-emitting uranium ore residue stored in silos at what used to be the Fernald Feed Materials Production Center in Ohio. The accuracy of the surface maps has enabled workers to precisely apply a foot-thick contaminant barrier of low-permeability clay over the waste to reduce radon emissions, saving DOE millions of dollars in remedial action costs (see sidebar on p. 86).

ORNL's efforts in remote characterization of buried waste sites are being led by Brad Richardson and Mark Noakes, both of the Robotics and Process Systems Division. Previous collaborative work with the U.S. Army is now being extended toward development of a special low-ferromagnetic signature vehicle that will significantly improve the performance of subsurface mapping sensors, and a new ORNL-Army collaboration is seeking to adapt a military backhoe to remote excavation of buried waste trenches and contaminated soils.

Members of Hamel's team are working on robotics projects with researchers at other DOE sites who are supported by the Robotics Technology Development Program. These collaborations are expected to result in significant progress in applying robotics and remote technology to the cleanup of DOE sites.

Technology Transfer

The need to make the world a healthier, cleaner, and safer place to live in has motivated people everywhere to join together to solve a common problem—cleaning up the environment. Tom Gagnier, coordinator of the Office of Technology

Researchers are developing robotic devices that incorporate sensors, computer control, and human-machine interfaces to characterize waste under hazardous conditions.

Development environmental technology transfer efforts at ORNL, plays a key role in this effort by promoting the sharing of technologies among other federal agencies, industries, educational facilities, and international communities to improve efficiency, reduce costs, and save time in environmental cleanup.

Tom Mayfield of the Office of Technology Transfer of Martin Marietta Energy Systems, Inc., is already heavily involved in at least two projects at ORNL that do just that. For instance, ORNL scientists led by Brenda Faison of the Chemical Technology Division have identified biosorbents—biological tissue that will bind metal, removing it from solution—that significantly reduce levels of uranium, strontium, cesium, lead, silver, iron, cadmium, and copper in contaminated process fluids. The team is now putting together a cooperative research and development agreement (CRADA) with a U.S. firm to develop biosorbent technology for remediation of 14 German sites where uranium mining and milling operations were carried out from 1949 until they were closed in 1990. The technology employed may also be customized for use at other sites, including those in the United States.

The technical exchange goes both ways. ORNL has entered into a collaborative agreement with a laboratory in Germany and several other DOE facilities in which ORNL personnel led by Robert Siegrist will have the opportunity to study unique technologies developed at the University of Karlsruhe in Germany, including a groundwater well system used to manipulate and treat contaminated soil and groundwater and an in situ

biotechnology treatment system. In addition, the parties involved will study other approaches and technologies that have potential applications in both countries.

Integration

Somehow, all of these diverse activities have to be brought together. To make sure that important information does not fall through the cracks, the ORNL team must interact not only with our counterparts at the other Energy Systems sites but also with our colleagues throughout the DOE complex. In addition, someone must make sure that the research being conducted at ORNL is actually implemented in the field. These tasks all fall under the jurisdiction of the Office of Waste Research and Development Programs, directed by Tony Malinauskas with the aid of Norm Cutshall and Jan Pruett. The goal of this office is to ensure that ORNL becomes a valuable source of model technologies for improving the economics and effectiveness of DOE's waste management and environmental restoration efforts. ornl

Biographical Sketch

Diedre Falter is completing a year-long assignment in the Waste Research and Development Program Office at ORNL, where one of her first assignments was to write this article for the *Review*. After working as a laboratory supervisor at Transducer Research, Inc., of Naperville, Illinois, and receiving her B.S. degree in engineering physics from Murray State University in 1986, she joined ORNL's Instrumentation and Controls (I&C) Division. There she helped develop detectors for use in radiation detection, genome sequencing, radiometry, and high-temperature thermometry. She was project leader of a team that received a 1990 Martin Marietta Energy Systems Technical Achievement Award for development of a microminiature infrared transmitter. As a result of that work, she was awarded her first patent. She has spent several years coordinating precollege (K–12) activities and internships for the I&C Division. Her husband is an engineer in the I&C Division.

New Waste Technologies

By Jim Pearce

A growing national concern over contamination of the soil, the water supply, and even the air we breathe is one of the driving forces behind current efforts by government and industry to more aggressively address the problems associated with hazardous waste management.

Several factors have contributed to this increased concern over environmental contamination. Recent studies have shown that many commonly used compounds, previously thought to be harmless, are powerful pathogens, mutagens, and carcinogens. Also, as more is learned about the effects of chemical pollutants on the environment, researchers are finding that levels of contamination previously considered insignificant can have serious environmental consequences.

These findings both reveal a threat and present a challenge. The threat is obvious. We are inexorably tied to the environment—we cannot afford to kill it. The challenge is to stem the tide of waste and to develop ways of cleansing and reclaiming areas that have already been fouled.

To meet this challenge, ORNL researchers in a range of disciplines are developing the tools needed to determine the type and extent of environmental contamination, to remove those contaminants from the environment, and to monitor potential waste sources to prevent further releases. A number of these projects are described in the following pages.

Putting PCBs on the Microbial Menu

For years, polychlorinated biphenyls (PCBs) were considered ideal insulating fluids for transformers and other electrical equipment because they are nonconductive, inert, and chemically stable.

After years of widespread use, these chemicals were determined to be potential carcinogens, and their production was banned in 1977. By that time, PCB contamination of soil and water from the deterioration of discarded equipment and discharges from manufacturing processes had become an environmental concern.

Further evidence of the serious nature of the problem is DOE's $350-million phased plan to clean up PCB contamination at the K-25 Site in Oak Ridge and uranium enrichment plants in Paducah, Kentucky, and Portsmouth, Ohio.

Ironically, the properties that make PCBs good insulators—their stability and lack of reactivity—are also the properties that make them so long-lasting in the environment. Until recently, conventional wisdom was that PCBs were impossible to degrade biologically. However, in the last decade, research has shown that certain microbes can break down PCBs into harmless substances, but only slowly and selectively.

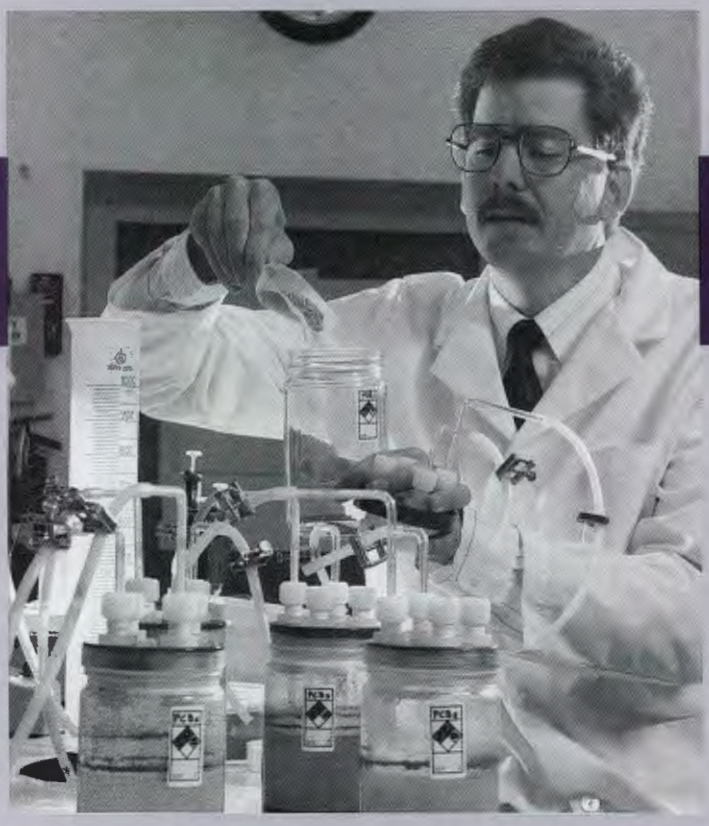
PCBs are a large class of chlorinated (chlorine-containing) biphenyl chemicals, known as congeners, that differ primarily in the number of chlorine atoms they contain. As a result, PCB contamination may involve several different congeners, each of which is treated differently by different microbes.

How Microbes Degrade PCBs. There are two pathways for microbial PCB degradation. In an aerobic, or oxygen-containing, environment, congeners containing fewer than five or six chlorine atoms can be degraded by aerobic microbes that use enzymes to add oxygen atoms to the congeners. Oxidation of these congeners breaks them down into carbon dioxide and water.

"The more chlorine atoms a molecule has, the more difficult it is to oxidize," says Terry Donaldson of the Chemical Technology Division (CTD). "Molecules with more than four or five chlorine atoms are very difficult to oxidize." The inability of aerobic organisms to degrade these highly chlorinated molecules may be partly the result of "steric hindrance"—the presence of so many chlorine atoms prevents the microbial enzymes from getting close enough to the biphenyl backbone of the molecule to oxidize it.

Fortunately, researchers have found that certain anaerobic microbes—organisms that exist in an oxygen-free environment—can remove chlorine atoms from highly chlorinated molecules. Once the molecules have been stripped down to fewer than

"Ironically, the same properties that make PCBs good insulators—their stability and lack of reactivity—are also the properties that make them so long-lasting in the environment."



The dechlorinating properties of anaerobic microbes are studied by placing the microbes in a soil-water slurry in 1-liter bioreactors, which are then spiked with a particular type of PCB. Periodic sampling allows researchers to measure the amount of dechlorination that takes place.

"Figuring out how to manipulate metabolism is an art."

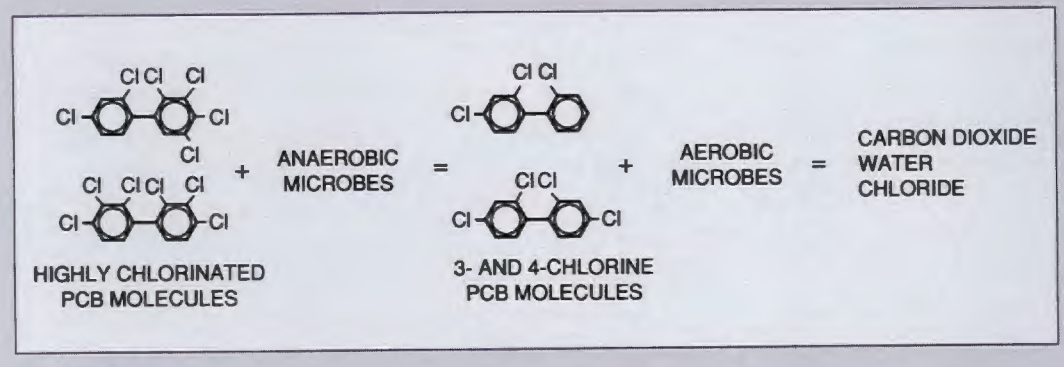
four or five chlorine atoms, they can be oxidized by aerobic organisms.

For the past several years, Mark Reeves and Betty Evans, also of CTD, have been working in the laboratory to isolate microorganisms that can degrade a broader range of congeners more efficiently and to find ways of enhancing their performance. They have searched PCB-contaminated soil on the Oak Ridge Reservation (ORR) for microorganisms with a particular talent for degrading PCBs and have found several likely candidates.

"Looking for these organisms in PCB-contaminated areas is a good strategy," says Donaldson. "The microorganisms at contaminated sites have had time to adapt to the presence of PCBs and are more likely to have the biological qualities we're looking for."

The microbial cultures found on the ORR consist of several types of organisms, but no attempt has yet been made to culture a pure strain of microbe. "The advantage of using a mixed culture," Donaldson says, "is that a mixed population of microbes can probably degrade a wider range of PCB compounds."

To obtain optimum performance from these microorganisms, Reeves and Evans studied the effects of various nutrients on microbial metabolism by varying their diet. As in humans, the type and amount of nutrients microbes receive affect their metabolic behavior. Most microbes require nitrogen, potassium, phosphorus, and trace levels of minerals, metals, vitamins, and other nutrients. "Figuring out how to manipulate metabolism is an art," says Donaldson.



ORNL researchers are using anaerobic microbes to break down highly chlorinated PCBs into molecules having only three or four chlorine atoms. These less-chlorinated molecules can then be degraded further by aerobic microbes, leaving only carbon dioxide (CO_2), water (H_2O), and chloride (Cl).

"The relationships between microbe metabolism and diet are not very well understood."

Working toward field tests. Before field testing begins at ORNL, small-scale bioreactor tests of remediation techniques are being used to investigate the dechlorinating effect of anaerobic microbes. The bioreactors are 1-L glass containers filled with a soil slurry—a mixture of soil, water, and microbes. These containers are generally spiked with a particular PCB congener, and samples are taken and analyzed every two to four weeks to measure the amount of dechlorination that has taken place. "The degradation process is slow," Donaldson says. "An experiment may take six to nine months." However, results from recent tests indicate it may be possible to accelerate the degradation rate.

The goal of this research is to accelerate the development and testing of new technologies for the biodegradation of PCBs to meet Martin Marietta Energy Systems cleanup standards, which are as low as 2 parts per million in solid materials.

"When we get this technology into the field, remediation techniques are likely to be site-specific," says Donaldson. "One approach to treatment would be to place the contaminated soil in a tank along with water, nutrients, and the microbial culture. This approach would let us control conditions closely, but it's cost-intensive. As we gain experience with the process, we want to be able to treat the soil in place."

"The goal of this research is to accelerate the development and testing of new technologies for the biodegradation of PCBs to meet Martin Marietta Energy Systems cleanup standards."

Battling PCBs in the South Pacific

"Conventional technologies can decontaminate oils with PCB concentrations of a few thousand parts per million or less. The BCD process can potentially handle oils containing concentrations of 100,000 parts per million or greater."

In 1944, the U.S. Army drove the Japanese from Kwajalein Atoll in the South Pacific. Nearly fifty years later, the Army is fighting a different kind of battle on Kwajalein—against potential environmental contamination resulting from its decades-long presence on the island.

One of several environmental concerns is a collection of 100 electrical transformers at the U.S. Army Kwajalein Atoll. This equipment is filled with about 15,000 gal of askarel, an insulating oil containing high levels of polychlorinated biphenyls (PCBs).

The Army is considering several options for destroying the contaminated oil, including shipping it back to the mainland for destruction in a specially designed incinerator, bringing a portable incinerator to Kwajalein, or using a noncombustion chemical technology, such as the base-catalyzed decomposition (BCD) process.

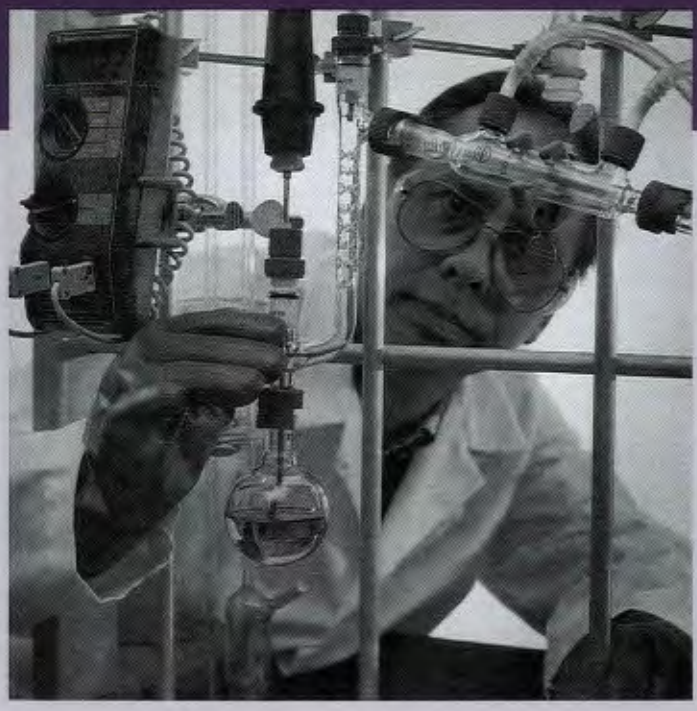
The BCD process is currently being developed under a set of agreements among ORNL; S. D. Myers, Inc.; DOE's Hazardous Waste Remedial Actions Program (HAZWRAP); and the Environmental Protection Agency (EPA).

Cliff Brown and Lloyd Youngblood, both of ORNL's Chemical Technology Division, are working under a cooperative research and development agreement (CRADA) between Martin Marietta Energy Systems, Inc., and S. D. Myers to refine the process so it can be scaled up and moved out of the laboratory. "Our goal," says Brown, "is to get this technology in the field and demonstrate it on Kwajalein."

S. D. Myers' staff have a wealth of experience in building and operating transformer oil decontamination systems, and they specialize in decontaminating and recycling old transformers. The CRADA combines this experience with ORNL's chemical engineering expertise and ability to select and conduct the development activities necessary to design a BCD system. After the technology has been successfully demonstrated on Kwajalein, S. D. Myers will be able to market it in the private sector. Several organizations have already expressed interest in a system capable of treating oils containing high levels of PCBs.

DOE also has a vested interest in seeing BCD technology through to its fruition because of its potential for treating the large quantities of PCB-contaminated mixed waste (containing both radioactive and hazardous chemical wastes) sludges, soils, and oils stored at Oak Ridge and other DOE sites.

The BCD process was originally developed by the EPA at its Risk Reduction Engineering Laboratory in



Researchers are currently conducting bench-scale studies of the effects of changes in temperature, reaction time, mixing, and other BCD process variables.

Cincinnati, Ohio. In this process the PCB-contaminated oil; an uncontaminated "donor" oil, used as a source of hydrogen atoms; sodium hydroxide; and a carbon catalyst are reacted together at high temperature. "As a result," says Youngblood, "hydrogen atoms from the donor oil take the place of the chlorine atoms on the PCB molecules, leaving environmentally manageable biphenyl molecules. The sodium then reacts with the displaced chlorine atoms to form salt." Plans are for waste oil from the process to be recycled and burned to provide the heat (approximately 300°C) required to sustain the reaction.

BCD processing potentially extends the range of noncombustive PCB decontamination technologies by several orders of magnitude. Conventional technologies can decontaminate oils with PCB concentrations of a few thousand parts per million or less. The BCD process, on the other hand, can potentially handle oils containing concentrations of 100,000 parts per million or greater.

The most obvious advantage to using the BCD process is that the destruction of the PCBs can be accomplished on-site, avoiding the risk involved in shipping thousands of gallons of hazardous material 6900 kilometers (4300 miles) to the mainland. Other factors to be considered by the Army before choosing a solution to its PCB problem are the efficiency of the process and its cost of implementation.

Current research at ORNL involves bench-scale studies of the effects of changes in temperature, reaction time, mixing, and other process variables. "Once these variables are understood," says Youngblood, "the next step will be to optimize the chemistry of the process and work out the details of transferring the process from the laboratory to the field."

Bioremediation of TCE Through Co-metabolism

"In a process known as co-metabolism, digestive enzymes produced by certain microorganisms are applied to the task of degrading contaminants, such as TCE."

Trichloroethylene (TCE), a potential carcinogen, was widely used as an industrial degreaser for cleaning metals and as a dry-cleaning agent until it was classified as a hazardous waste by the Resource Conservation and Recovery Act (RCRA) of 1976.

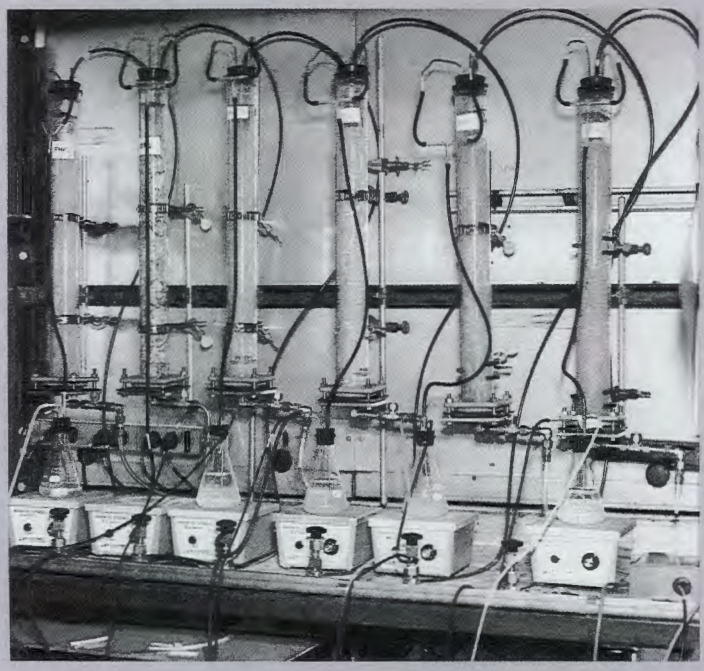
Because RCRA regulations greatly increased the costs of disposing of TCE, most uses of the chemical were discontinued in the United States by the early 1980s.

Up to that point, most TCE was disposed of in a fairly haphazard manner. "For years," says Steve Herbes of the Environmental Sciences Division, "practically every metal machining shop, automotive repair shop, and dry cleaner in the country used TCE, and many of them disposed of it improperly when they were done with it." As a result, TCE is now one of the most commonly found groundwater contaminants in the United States. It is also found at most DOE sites, including the Oak Ridge K-25 Site.

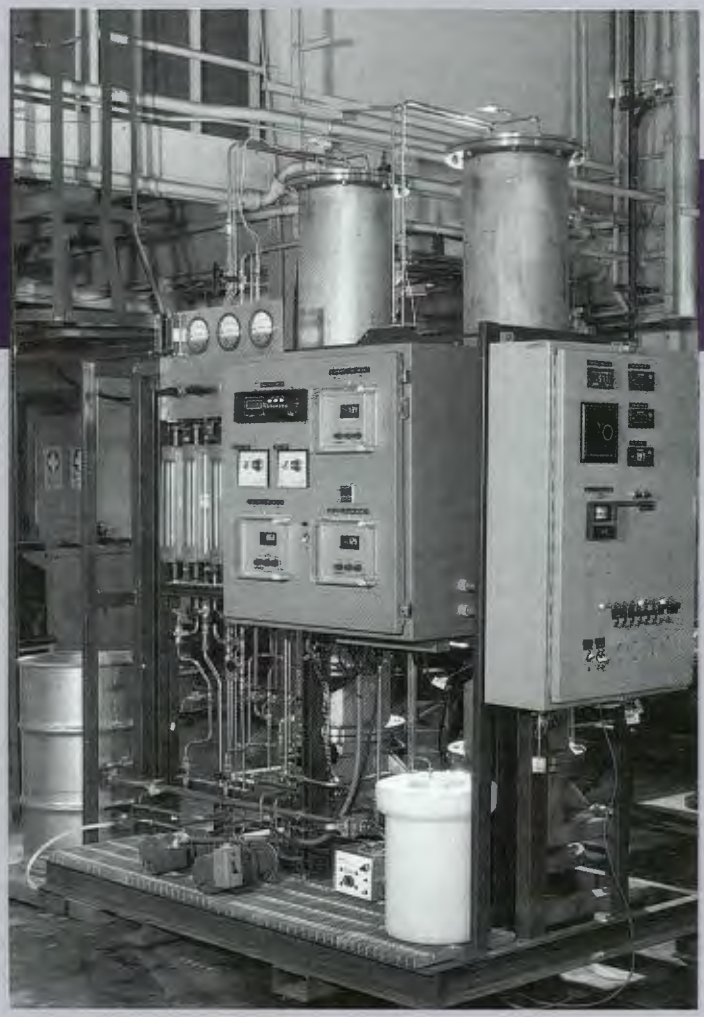
Researchers in ORNL's Environmental Sciences and Chemical Technology divisions are testing two innovative biological techniques for removing TCE from groundwater. In a process known as co-metabolism, digestive enzymes produced by certain microorganisms are applied to the task of degrading contaminants, such as TCE.

"Under natural anaerobic (oxygen-free) conditions, such as those found in groundwater, TCE degrades to vinyl chloride, an even more toxic compound," says Herbes. "Our goal for co-metabolic remediation is to encourage degradation of TCE along pathways that result in less harmful products."

Two basic groups of microorganisms are involved in co-metabolism of



Bench-scale bioreactors were used to demonstrate the feasibility of co-metabolism as a remediation technique and to evaluate various methanotrophs gathered from groundwater contaminated with TCE at the Oak Ridge K-25 Site and DOE's Kansas City Plant.



A co-metabolism demonstration project is currently under way at the Oak Ridge K-25 Site using a specially modified bioreactor on loan from the U. S. Air Force Civil Engineering Support Agency. The goal of the project is to treat seepage from a series of pits used in the 1980s for the disposal of a variety of organic compounds, including TCE.

groundwater contaminants. The first is methanotrophs—bacteria that live on methane. The enzymes these bacteria produce to digest methane can also metabolize TCE. When methane and TCE-contaminated water are added to a bioreactor containing methanotrophic bacteria, their digestive enzymes break down both the methane and the TCE. The TCE is first broken down into TCE epoxide and then into other products that can be further degraded by normal biological processes.

To prove the usefulness of this technology, the project team is demonstrating the co-metabolism process at the K-25 Site with the support of DOE's Environmental Restoration and Waste Management Program's Office of Technology Development. The heart of the project is a specially modified bioreactor, on loan from the U. S. Air Force Civil Engineering Support Agency, that houses methanotrophic bacteria cultures. The bioreactor consists of two reactor columns that are 2.13 m (7 ft) tall and 40 cm (16 in.) in diameter and are filled with polypropylene support material for the cultures to grow on. A control system is mounted with the columns on a portable platform, which is housed in a trailer at the K-25 Site. The goal of the project is to treat seepage from a series of pits used in the 1980s for the disposal of a variety of organic compounds, including TCE.

The drainage from these pits amounts to several liters per minute, a fraction of which is diverted for use in the demonstration project. Before the water can be pumped into the bioreactor, however, it must pass through an air oxidation system to decrease its iron content because the high level of iron in the seepage would eventually foul the bioreactor system. As the seepage passes through and out of the bioreactor, it is collected in a storage tank that is periodically emptied at K-25's Central Neutralization Facility.

Bench-scale bioreactors, developed by Terry Donaldson and Jerry Strandberg of ORNL's

"In initial bench-scale tests, this process removed up to 80% of the TCE from simulated groundwater."

Chemical Technology Division, were first used to demonstrate the feasibility of this technology and to evaluate various methanotrophs. The cultures selected for use in the K-25 demonstration project were evaluated on the basis of their stability and level of activity over time. Of the three cultures finally selected, one was from groundwater at the K-25 Site and two were from DOE's Kansas City Plant.

The second group of microorganisms involved in co-metabolic research is bacteria that consume toluene or phenol. Herbes and his project team have been working closely with a private biotechnology firm to develop a culturing and bioreactor system for determining the feasibility of employing these bacteria in a bioremediation system. Like their methanotrophic cousins, these bacteria produce enzymes that metabolize TCE as a side-effect of their normal metabolic processes.

In initial bench-scale tests, this process removed up to 80% of the TCE from simulated groundwater containing a mixture of organic contaminants similar to that at the K-25 Site.

A field test of this technology is planned for the K-25 Site for the summer of 1992. "At the end of this test," says Herbes, "we will have data that provide a head-to-head comparison of the two most promising techniques for the bioremediation of TCE in groundwater. There are many possible applications within the DOE system for this technology. It could be scaled up and used as the treatment of choice at K-25 or other DOE sites."

Bioluminescent Bacteria: Another Bright Idea

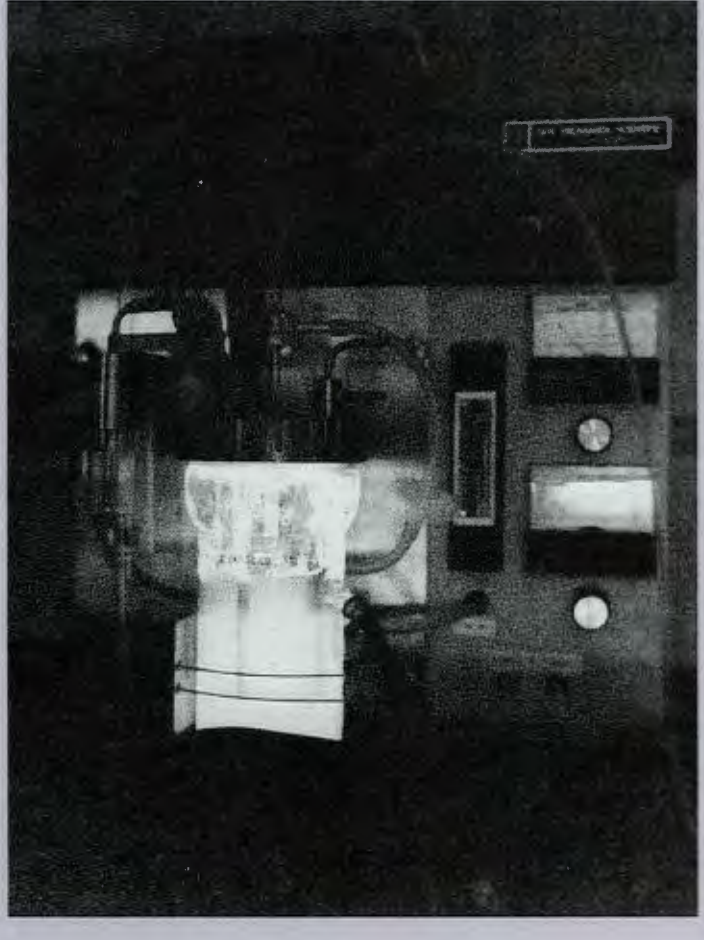
Since petroleum-eating microbes were used to help scour the beaches of Alaska's Prince William Sound in the aftermath of the Exxon Valdez oil spill, the world has gotten used to the idea of using microscopic "bugs" to clean up environmental contamination.

But do you ever wonder if there's a way to tell if these critters are eating or not? Or if they're undernourished? Or too hot to work? These are some of the questions that researchers at ORNL and the University of Tennessee are addressing as they develop a new technology to monitor the efficiency of microorganisms in cleaning up soil and groundwater.

In a project originally sponsored by the Laboratory Director's Research and Development Fund, ORNL researchers have been developing bioluminescent sensor technology to monitor bacteria as they digest soil and groundwater contaminants, converting them to relatively harmless substances, such as water and carbon dioxide. Bioluminescent sensor technology is a method for detecting the light emitted in the visible range by genetically engineered bacteria that luminesce during metabolism of certain types of chemicals.

Robert Burlage of the Environmental Sciences Division (ESD) started experimenting with the bioluminescent, or "lux," genes while working with

"ORNL researchers have been developing bioluminescent sensor technology to monitor bacteria as they digest soil and groundwater contaminants."



To determine the optimum diet for a colony of bioluminescent bacteria, nutrients are added or taken away, based on the colony's light level—the more light given off, the more nutrients the bacteria are metabolizing. This luminescence, which is too dim to be seen in normal room light, is measured by precision light-sensing equipment.

"Researchers are also developing strains of bacteria that light up when the culture is lacking a particular nutrient."

Gary Sayler in the University of Tennessee's Microbiology Department, where most of the initial work on the gene was done. Burlage and his collaborator Tony Palumbo, also of ESD, continue to collaborate with the university group with whom they share "constructs"—combinations of the lux genes.

The lux genes were originally taken from bioluminescent bacteria that live symbiotically with several species of deep-sea fish. It is theorized that, because the bacteria are also a food source for smaller fish, they are used by the larger fish as a sort of "bait" to lure the small fish into attack range. This type of bioluminescence is similar to that found in lightning bugs and other insects.

Once the lux gene was isolated, researchers incorporated it into genes from common soil and water bacteria that are activated in the presence of toluene, a component of gasoline and other solvents, and use it to indicate degradation of trichloroethylene (TCE), a common industrial degreaser. This combination of genes causes the genetically altered bacteria to light up when they metabolize toluene or TCE. As a result, researchers can monitor the rate at which the bacteria are metabolizing the TCE by measuring the amount of light they give off.

"It also gives us a way to control their activity," says Palumbo. "Depending on the light level, we add or withhold nutrients as necessary." To respond to the bacterial culture's specific nutritional needs, researchers are also developing strains of bacteria that light up when the culture is lacking a particular nutrient, such as nitrogen or phosphorus.

Almost all DOE sites have problems with toluene, TCE, or other types of contamination resulting from disposal or spills of gasoline and various chemicals used in research labs. A variety of bacteria will be needed to metabolize the potpourri of chemical wastes at some sites because each strain of bacteria eats only certain types of waste. Because these bacteria light up selectively, they can also be used to identify the types of

contamination present at the site.

"When we look at a site we ask two questions," Burlage says. "Does it have bacteria that can handle bioremediation? The answer is usually yes. Once the lux gene is added to these bacteria, the next question is, 'Are the genes that control the digestion of contaminants turned on?'" If the genes are not turned on, causing them to turn on may be as simple as adding nutrients or as difficult as identifying other environmental factors that adversely affect the bacteria. For example, one of the current challenges facing Palumbo and Burlage is developing a construct that remains active above 37°C, the temperature at which the current construct turns off.

"To determine the optimum conditions for a bacterial culture," says Palumbo, "you can either take all the nutrients away and add them back one at a time until you see an improvement or you can look at the soil chemistry and add things that you think are missing." The culture's response is determined by its light level—the more light, the more the bacteria are metabolizing. This luminescence, too dim to be seen in normal room light, is measured by precision light-sensing equipment.

Palumbo and Burlage's latest refinement of the system is a cooperative effort with Tuan Vo-Dinh of the Health and Safety Research Division to develop a fiber-optic containment system that will enable researchers to lower a bioluminescent bacteria culture into a well to monitor groundwater. To prevent release of genetically engineered bacteria into the environment, the system will include a container that admits groundwater without letting the bacteria escape.

This type of apparatus would be used primarily as a continuous monitor for waterborne contaminants; however, some of the same technology also could be used for soil sampling. They expect to have a prototype system working by the end of the summer of 1992.

"The applications of this technology are widespread," says Burlage. "The only things that limit us are our imagination and knowledge."

"The culture's response is determined by its light level—the more light, the more the bacteria are metabolizing."

New Waste Technologies

Screening Method Speeds Search for Waste Eaters

"This increase in efficiency has enabled ESD researchers to evaluate 10 times as many samples as would have been possible using standard methods."

So many bacteria and so little time. That was the problem faced by researchers in ORNL's Environmental Sciences Division (ESD) when asked to evaluate the ability of thousands of bacteria samples to metabolize environmental contaminants common to many DOE sites.

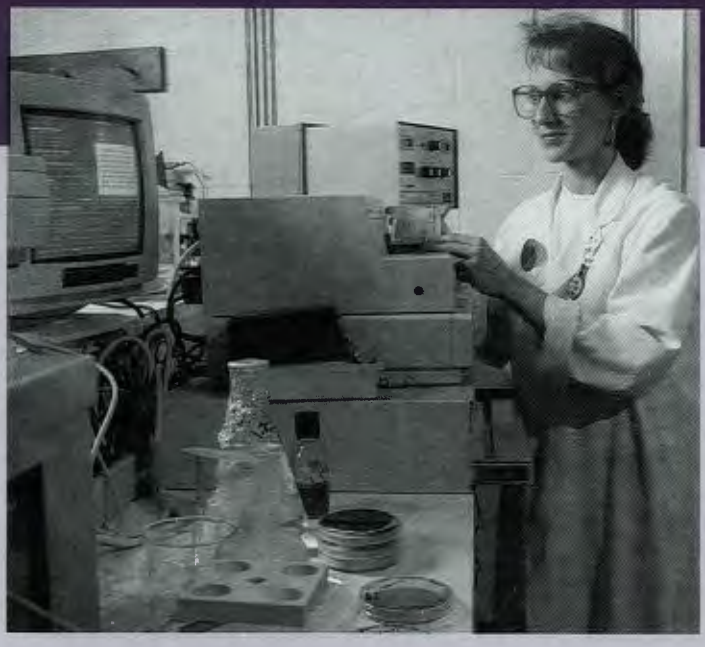
At the time, standard diagnostic tests involved culturing each strain of bacteria in a separate container, adding a contaminant, and measuring the breakdown of the contaminant with a gas chromatograph. This process was time-consuming and produced a fairly large amount of waste requiring special handling and disposal.

"The volume of testing requested by DOE's Subsurface Science Program was more than we could handle using standard methods," says ESD researcher Tony Palumbo. So—necessity being the mother of invention—Palumbo and his colleagues spent about three months developing and testing a new procedure for rapidly identifying waste-eating bacteria.

The procedure uses palm-size plates containing 96 cm-deep cells that are filled with bacteria, water, and a dye that is sensitive to the bacteria's metabolic processes. The plates, along with a beaker of a contaminant—usually toluene, xylene, or carbon tetrachloride—are place in a dessicator and allowed to incubate for 24 to 48 hours. The contaminant evaporates into the air inside the dessicator and is eventually absorbed by the water in the cells.

As the contaminant is absorbed, those bacteria that are able to metabolize it remove carbon from its atomic structure. This action frees hydrogen atoms, which react with the dye, changing its color from clear to purple. Because not all bacteria metabolize the contaminant equally well, many shades of purple may result—the more contaminant that is metabolized, the deeper the color. A "control" group of plates is incubated in ordinary air to ensure that any changes in the experimental plates are caused solely by the contaminants.

When the incubation is complete, the plates are placed in a spectrophotometer that shines a light through each cell, measuring its depth of color, or optical absorbance. These readings are then translated into computer data. Only the bacterial strains in those cell showing high levels of metabolic activity are required to undergo more definitive gas chromatography (GC) testing. "With the old method, every strain would undergo GC testing," says Palumbo. "Using the screening procedure, only one in 50 is tested." This increase in efficiency has enabled ESD researchers to evaluate 10 times as



A spectrophotometer is used to screen contaminant-enriched bacterial cultures. Only one in every 50 cultures exhibits enough metabolic activity to require more definitive gas chromatography testing.

many samples as would have been possible using standard methods. Also, the amount of waste generated by the screening process is 10 to 50 times less than that produced by standard methods.

Palumbo and his group are using this technique to study bacteria gathered through DOE's Subsurface Science Program from contaminated areas at the Savannah River Site, Idaho National Engineering Laboratory (INEL), and Pacific Northwest National Laboratory, as well as bacteria gathered at ORNL by ESD researchers. The bacteria received from the Subsurface Science Program are cultured on the surface of a substance known as agar, which provides the general types of nutrients needed to keep bacterial colonies alive. To increase the chances of isolating useful organisms, the ORNL bacteria are cultured in a contaminant-enriched environment, enabling contaminant-degrading organisms to thrive. "We're getting very good results using this process," Palumbo says.

Palumbo indicates that the Subsurface Science Program may be sampling bacteria sometime this year from ORNL's Melton Branch area as part of its ongoing study of diversity in bacterial communities.

ESD researchers are also working with INEL on a related project using many of the same techniques. This work, funded by DOE's Office of Technology Development, involves finding bacteria that metabolize chelators—compounds that attach themselves to radionuclides, preventing them from reacting with other elements in the environment and allowing them to move more freely through soil and groundwater. Because chelators are used to clean radionuclide-contaminated equipment, they have often been disposed of along with radionuclides. Chelator-metabolizing bacteria would be useful in slowing or stopping the migration of radioactive contaminants.

New Waste Technologies

Waste-fighting Consortium of Bacteria Found in Amoebas

While studying amoebas from a well on the Oak Ridge Reservation, researchers have found groups of microorganisms with a knack for bioremediation of hazardous wastes.

Researchers in ORNL's Health and Safety Research Division (HASRD) spend a fair amount of time studying the effect of amoebas living in ORNL's cooling towers and other warm water systems around the Lab.

The reason for all this attention is simple—in their travels, amoebas pick up a lot of bacterial hitchhikers, which can cause illnesses in humans ranging from minor infections to tuberculosis and Legionnaires disease. These bacteria are particularly hard to eliminate because they live *inside* the amoebas, an arrangement known as a consortium, giving the bacteria an extra layer of defense against environmental stresses, such as toxic compounds and changes in water temperature or pH.

While studying amoebas found in a well on the Oak Ridge Reservation, researchers have found consortia made up of microorganisms with a knack for bioremediation of hazardous wastes.

"The well was primarily contaminated with the industrial solvent trichloroethylene (TCE)" says Arpad Vass of HASRD, "so we looked for organisms in the well that could metabolize TCE. Because we knew that some methanotrophic bacteria—those that live on methane—degrade TCE, we took amoebas from the well and put them in a methane atmosphere. In this environment, 20 different bacteria were isolated from within the amoebas, one of which was able to degrade TCE. This is one of the most, if not *the* most, complex microbial consortium known in the world."

Vass says no one is sure why these consortia occur, but a high degree of interdependence apparently exists among the organisms. "The theory is," says Vass, "that one of the organisms metabolizes methane making methanol. In turn, another metabolizes the methanol, making formic acid, and so on. Most significantly, the consortia can be maintained on mineral salts in a methane and carbon dioxide atmosphere—an environment that will not support most of the bacteria individually."

In addition to the TCE-degrading bacteria, researchers have also identified bacteria that produce biodispersants (compounds that break up oil and other organic contaminants) as well as others that metabolize creosote and trinitrotoluene (TNT).

A number of applications have been proposed for members of this unusually versatile group of microorganisms. The first field test for the biodispersants will come this summer at DOE's Savannah River Site (SRS) where a large amount of creosote-contaminated lumber has been stockpiled over the years. Because creosote, a wood preservative used on railroad ties, telephone

Both of these test tubes contain gasoline and water. Biodispersants break up solvents, such as gasoline, into tiny droplets, known as a microemulsion (in the container on the right). This process dramatically increases the surface area of the solvents, allowing them to be more easily metabolized by bacteria.

poles, etc., is both a toxin and a mutagen, SRS personnel have been searching for an environmentally acceptable way to dispose of it. The ability of biodispersants to remove contaminants from substrates like wood, rock, or soil prior to biodegradation makes them ideal candidates for this job.

When mixed in relatively low concentrations (1–2%) with compounds such as creosote, oil, or solvents, the biodispersant breaks these substances into tiny droplets, known as a microemulsion, dramatically increasing their surface area. Once a compound is separated from its substrate in this manner, it can be more efficiently degraded by other microorganisms. Also, using microemulsions of solvents for various industrial processes could potentially decrease the amount of solvent needed, reducing the amount of waste produced.

Biodispersant-producing bacteria will be field tested in conjunction with creosote-eating bacteria from both ORNL and SRS. It is hoped that the results of these experiments will confirm laboratory results supporting the effectiveness of bioremediation of creosote contamination.

Other applications for biodispersant/bacteria combinations include secondary oil recovery. When an oil well has been pumped "dry" using conventional methods, it is often abandoned because of the high cost of retrieving the residual oil. It is hypothesized that pumping biodispersant-laden water into these wells could loosen the oil from its rock substrate and allow it to be economically recovered.

Another combination of biodispersant and bacteria has developed a taste for TNT, first removing the explosive from its soil or water substrate and then breaking it down into harmless components. This process has shown a potential for removing soil and water contamination around munitions plants and storage facilities—so much potential, in fact, that it has been licensed to Oak Ridge-based EODT Services, a company specializing in cleaning up sites contaminated with explosives-related waste.

"Historically, our interest in amoebas has been pathogenic—related to its ability to transmit disease," says Vass, "but since we found this consortium, we've been broadening our interests and, at the same time, helping the environment."

New Waste Technologies

Waste Identification: Building a Better Ion Trap

"Its immediate uses are screening for the presence or absence of certain chemicals in the environment—this avoids having to send samples off to be analyzed at $500 a shot—and repetitive monitoring of specific pollutants.

Normally, when soil, water, or air sampling is done in the field, samples are taken back to the lab, processed, and analyzed. Hours or even days later, toxins contained in the samples are identified. If other work depends on these test results, it waits, too.

Obviously, this is a problem begging for a cost-effective solution—a system that can be used in the field to provide rapid identification of specific toxins.

Enter ORNL's Analytical Chemistry Division (ACD). ACD researchers have developed a portable mass spectrometry system for identifying organic toxins in air, water, and soil samples in the field. It consistently outperforms conventional analytical methods, quantifying toxins in as little as two minutes down to the parts-per-billion level.

The system was originally developed to detect volatile organic solvents in soil and water, but its versatility has resulted in its use for several other purposes, including "sniffing" air samples to detect organic contaminants; detecting semivolatile pollutants, such as pesticides; and directly analyzing body fluids for commonly used drugs, such as cocaine, codeine, and nicotine.

"This technique is not expected to replace existing Environmental Protection Agency methods," says ACD's Mike Guerin. "Its immediate uses are screening for the presence or absence of certain chemicals in the environment—this avoids having to send samples off to be analyzed at $500 a shot—and repetitive monitoring of specific pollutants, as is done in remedial action programs."

Starting with a commercially available ion trap mass spectrometer, Guerin and his group have developed a system to introduce samples directly into the ion-trap and standardized procedures for analyzing samples. (For more information on this technique, see *Review*, No. 4, 1991, p. 54.)

"People are primarily interested in the speed of the system and the ability to do the analysis in the field," says Guerin. With this system, checking a soil sample for carcinogenic solvents such as benzene is as simple as mixing the soil with distilled water, bubbling helium through the mixture to remove the solvent, and routing the solvent-containing off-gases into the ion trap for analysis. All of this is accomplished in a matter of a few minutes.

Work on the system was originally funded by the Department of Defense as a method of quantifying organic compounds used as nerve gases. "During the course of this work, we observed that this technology might be applicable to environmental studies," says Guerin. Further research proved the system's environmental applications, and the cost of its continued development

The direct-sampling ion trap mass spectrometer's portability allows researchers to detect the presence or absence of certain chemicals in the field. Both time and money are saved by eliminating the need to send samples to a laboratory for analysis.

is now underwritten by both DOE's Office of Technology Development and the U.S. Army's Toxic and Hazardous Materials Agency.

In September 1991, the first field trial for the system was held at DOE's Volatile Organic Compounds in Non-arid Soils Integrated Demonstration test site at the Savannah River Site, a proving ground that has horizontal well setups to demonstrate gas extraction and bioremediation technologies. The trial was highly successful and led to a second trial in March. During the March trial, Marc Wise and Cyril Thompson, both of ACD, used a more portable version of the system to monitor volatile organic chemicals in the headspace of a groundwater well and in the waste stream of a soil remediation process known as steam stripping. Also, groundwater samples were analyzed in the field at a rate of 20 samples per hour.

As a result of their success at the test site, Guerin's group has received funding from DOE's Office of Technology Development to build another system for the Savannah River Site and train their people to use it. "We want to know whether people who have not been involved in the development of this technology can be trained to use it," says Guerin. "We also want to see what kind of problems the system will encounter if it is used intensively."

Guerin and his group are in the process of testing and calibrating the system using pure compounds to determine its sensitivity and durability. The current system is about the size of a two-drawer filing cabinet and is mounted on a shock-absorbing base, so up to two of the units can be transported into the field in a van. Also, an even smaller version of the system is in the works.

Guerin is encouraged by the success of a recent unplanned test of the system. In March 1992, an environmental remediation group was pulling a tank out of a waste burial ground at ORNL when their field monitor indicated a high level of organic contaminants. They also noticed a strong odor and a hole in the bottom of the tank.

"They brought us some air and soil samples to analyze," Guerin recalls, "and we had preliminary results for them within minutes—even before they were back in their office. They were pleased with that kind of response. Typically emergency response in this business takes from several hours to as much as a day."

New Waste Technologies

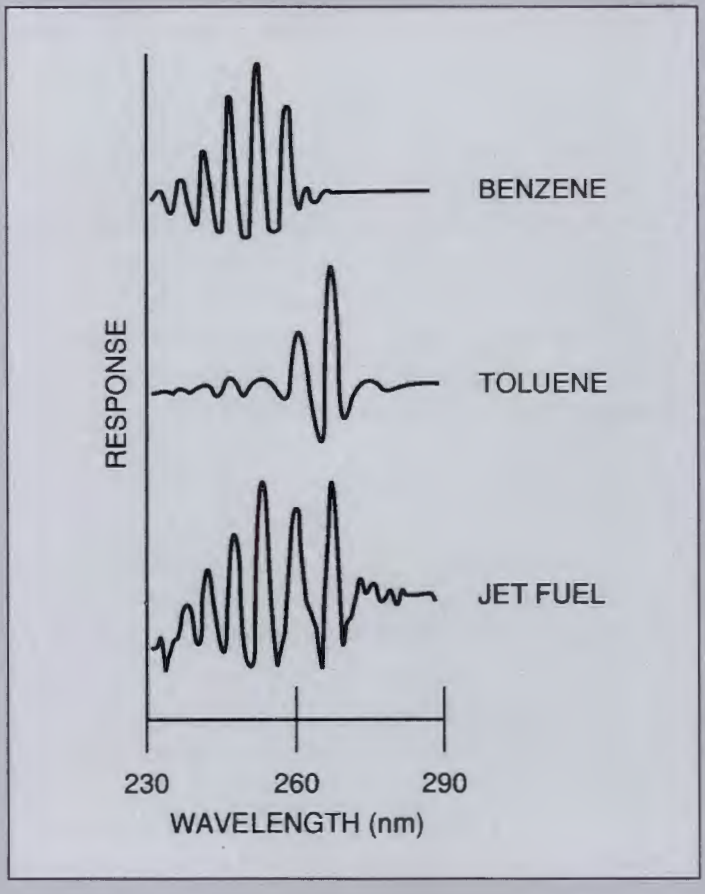
Fiber-Optic Probe Sheds New Light on Groundwater Contaminants

"To my knowledge," says Haas, "this is the first fiber-optic spectroscopic device designed to identify and measure volatile aromatic compounds directly in the groundwater."

One of the problems facing researchers interested in measuring groundwater contamination is a lack of accessibility.

Groundwater is usually sampled by either lowering a collection device down a well, taking a sample, and pulling it back up for analysis or by using equipment that "sniffs" the air in the well to identify the substances dissolved in the water.

The new and improved Derivative Ultraviolet Absorption Spectrometer (DUVAS) system, developed by John Haas of the Health and Safety Research Division, solves the accessibility problem and a few more problems besides. "To my knowledge," says Haas, "this is the first fiber-optic spectroscopic device designed to identify and measure volatile aromatic compounds directly in the groundwater."



The DUVAS system measures the amount of light absorbed by the sample across a range of wavelengths, producing an absorption spectrum. Individual compounds can be identified by their characteristic spectra. In this example, the spectra for benzene and toluene, the primary components of jet fuel, are combined in its absorption spectrum.

Why direct sampling?

By detecting and measuring the concentration of groundwater contaminants directly, rather than by "sniffing" the air above the water, the DUVAS system is able to more accurately characterize groundwater contamination and avoid problems posed by air sampling. "For example," says Haas, "because some chlorinated hydrocarbons are heavier than water, they could go undetected by air sampling above deep aquifers."

Direct sampling also enables researchers to use a technique known as depth profiling—analyzing groundwater samples from various depths. Depth profiling provides a more accurate assessment of contamination by

considering the possibility of varying concentrations at different depths, rather than relying on a single measurement.

Other advantages of using the DUVAS system for groundwater analysis are that it offers

- Rapid analysis of groundwater contaminants in the field. The system conducts a complete spectral analysis in less than a minute.
- Increased safety. Because groundwater samples are not removed from the well, workers are not exposed to chemical and radioactive contamination.
- No chain of custody for samples and no storage concerns.
- Direct measurement of groundwater contamination, making possible continuous monitoring.

New applications. DUVAS was originally developed in the early 1980s in response to the push in the United States to replace fuels refined from imported oil with coal- and shale-based alternatives. DUVAS was designed to "sniff" air samples at synthetic fuel production plants to detect carcinogenic vapors. The technology is now being applied to the detection of aromatic hydrocarbons in groundwater.

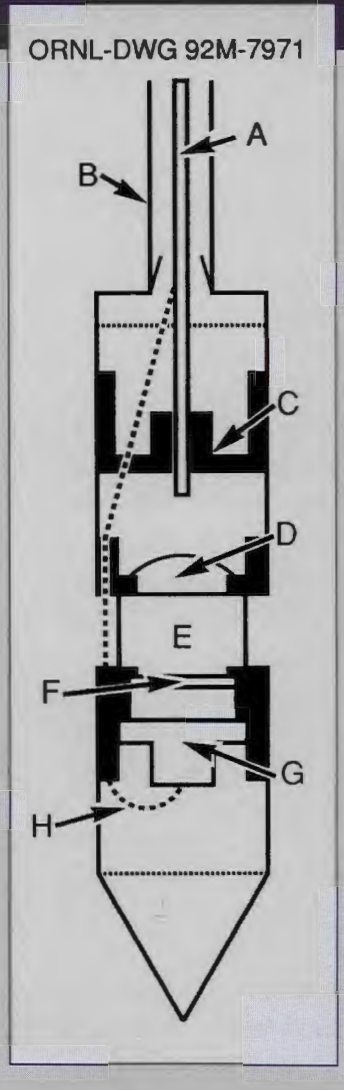
Aromatic compounds are a particularly important class of chemicals because of their presence in fuels (benzene and toluene) and their use in the manufacture of paper (phenol) and insulators (polychlorinated biphenyls, or PCBs). They are also widely used as solvents, dyes, and explosives. Topping the list of organic chemicals most commonly found at DOE sites, including ORNL, are volatile aromatics, such as benzene and toluene, which are among the most migratory components of fuels contaminating groundwater. As a result, they are usually found farthest from the source of contamination. DUVAS' sensitivity to these chemicals makes it especially adept at detecting the first signs of groundwater contamination.

The system is well suited for several applications, including monitoring groundwater around underground fuel storage tanks or disposal areas where solvents, such as benzene, are buried; monitoring manufacturing discharges or chemical spills in surface water; and monitoring reagent concentrations in chemical process streams.

Over the past three years, Haas has received funding to update the DUVAS system and to develop a new fiber-optic sampling probe. The updated system is computer controlled, battery powered, and, at about 9 kg (20 lb), it is completely portable.

Now that this phase of his research is complete, Haas is field testing the system at Lawrence Livermore National

"DUVAS was designed to 'sniff' air samples at synthetic fuel production plants to detect carcinogenic vapors."



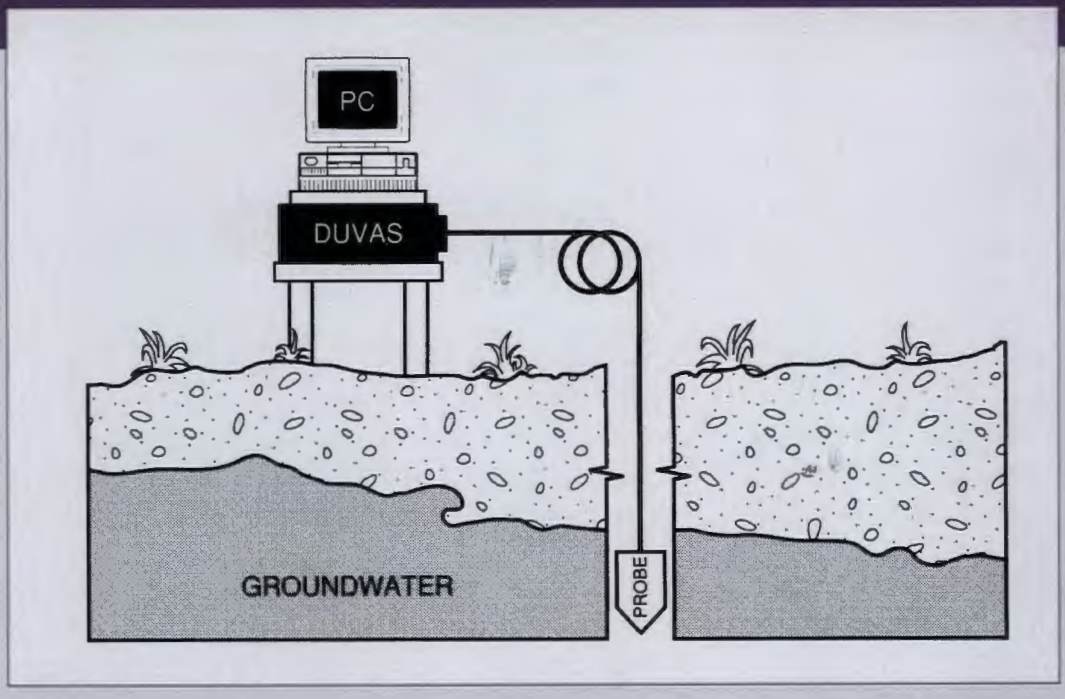
Probe components include an optical fiber (A), a garden hose used as a sheath for the fiber (B), an adjustable chuck to hold and position the fiber (C), a lens to focus light into the detector (D), a sampling region where the sample is collected (E), a quartz window between the sample and the detector (F), a photodiode detector (G), and a cable to provide power to the detector and carry data to the computer (H).

Laboratory's technology demonstration site where about 68,000 L (17,000 gal) of gasoline have been spilled. There DUVAS will be used to monitor the effectiveness of a remediation process known as dynamic underground stripping. This technique uses a combination of steam injection and electrodes to heat contaminated soil, turning water in the soil to steam that drives out volatile contaminants. The ability of the DUVAS system to provide continuous monitoring of the process in underground wells at the site will help researchers determine the effectiveness of the process and optimum conditions for "steam cleaning" gasoline contamination out of the soil.

How it works. DUVAS is a spectroscopic technique based on the principle that virtually all molecules absorb light. When light is shone on a groundwater sample, the difference between the amount of light that enters the sample and the light that passes through can be measured. That difference is attributed to absorbed light. Measuring the amount of absorbed light at many different wavelengths produces an absorption spectrum. Because individual compounds absorb light at characteristic wavelengths, the presence of each chemical is indicated by its absorption spectrum.

The system operates by generating ultraviolet light in the range from 230 nm to 350 nm and transmitting that light through an optical fiber to a submerged probe. Ultraviolet light is used because it is absorbed well by aromatic compounds.

When the light reaches the probe, it is focused through the groundwater sample onto the detector. The probe is fitted with a pump and a filter to ensure that water samples are free of dirt and other particulate matter. Because ultraviolet light is not conducted well



Typically, the DUVAS fiber-optic probe is lowered down a well, where it collects and analyzes a groundwater sample and transmits the resulting information to a computer on the surface.

by optical fiber, Haas incorporated a detector into the probe and added an electronic feedback loop, rather than using an optical fiber to transmit light from the probe back to a detector on the surface. As a result, the required length of the optic fiber is reduced by half, allowing the probe to be used in wells as deep as 50 m. The information gathered by the detector is then transmitted back to the surface where it is analyzed by a laptop computer.

Concentrations of chemicals that absorb ultraviolet light weakly, such as benzene, can be measured to as low as 100 parts per billion. Strong absorbers, such as polynuclear aromatics, some of which are potent carcinogens, can be detected at parts-per-trillion levels. The system's analysis of contaminant concentrations is typically accurate to within 1%.

Future enhancements of the DUVAS system include coupling the probe with a camera to examine phenomena such as high-velocity contaminant jets entering a well through small cracks in the well casing. Modifying the system to accommodate analysis of contaminant vapors in subsurface soil gas is also being considered.

New Waste Technologies

Laser System Sizes Up Fernald Waste Problem

The highly accurate data on the waste's surface features saved 15 to 25 million dollars.

DOE's Fernald Feed Materials Production Center had a problem. In 1951, four domed storage silos were built, and two of them were filled with radium-rich uranium ore residue, a by-product of uranium processing at the site.

The ore was originally stored in the four-story-tall silos for use in commercial processes, such as producing luminous paint for watch and instrument dials. However, before the radium could be recovered, its health hazards were discovered, and the ore was reclassified as waste.

Four decades later, this material is still sitting in aging silos 20 m (60 ft) above the largest aquifer in the Midwest, and the decaying radium continued to generate large amounts of radioactive radon gas.

Under terms of a 1990 agreement between DOE and the Environmental Protection Agency (EPA), the ore residue is scheduled to be removed from the silos beginning in 1995 as part of the Fernald Environmental Management Project. Until then DOE and EPA agreed to suppress radon emissions by putting foot-thick bentonite clay caps over the waste in the two silos. These caps contain the radioactive gas until it decays into non-gaseous elements that are trapped in the bentonite. The deadline for putting the cap in place was December 1991.

In December 1990, Barry Burks of ORNL's Robotics and Process Systems Division attended a meeting at Fernald on how robotic technology could be used to help meet remediation needs at the site. During a coffee break, Burks talked with a representative from Parsons Engineering, one of the contractors remediating the site. Parsons was looking for a way to ensure that the clay cap they were preparing to install was at least a foot thick over the entire surface of the waste.

ORNL engineers who had previously used laser range cameras to map three-dimensional robot environments saw that this technology could be used to build a three-dimensional surface map of the waste before and after the bentonite was applied. A comparison of these measurements would verify that the bentonite seal was at least a foot thick. Having accurate information about the surface of the waste would also keep the amount of bentonite used to a minimum. This was especially desirable given that the contents of the silos, both the ore residue and the bentonite, would be removed and treated prior to permanent storage, beginning in 1995.

Burks suggested the surface-mapping technique to the group, and in January 1991, this approach was officially adopted. Only 9 months were left for the system to be developed, tested, and used to map the surface of the wasteforms before the clay seal was scheduled to be applied in October. "By

The storage silos at DOE's Fernald Feed Materials Production Center were built in 1951 to temporarily store radium-rich uranium ore. Discovery of the health hazards associated with radium prolonged this stay by several decades.

the time we figured out what equipment we needed and began detailed design, it was May," says Burks, "and we had to have the system working by the end of July, so we could test it at Fernald in August."

Several ORNL groups helped Burks' group meet the deadline. "The Plant and Equipment Division helped us when we urgently needed fabrication work done," says Burks, "and the Finance and Materials Division gave us a warehouse where we roped off an area 24 m (80 ft) in diameter to use as a mock storage silo. Then we set our equipment up on stands to simulate conditions at Fernald."

Despite all the simulations, conditions at Fernald were not what Burks and his group were used to. Protective clothing was required, even in the control area, and when repairs had to be made, the task fell to the ORNL researchers. "One of our guys had to dress out completely, including wearing respiratory equipment and three pairs of gloves, before entering the restricted area around the silo. This kind of field work was a new experience for many of us who were used to laboratory conditions," says Burks. Other trying conditions included evacuations of the area several times a day because of high radon concentrations, poor weather, and high winds that prevented workers from reaching the access doors, called "manways," located on top of the silos.

In August 1991, Burks and colleagues John Rowe, Fred DePiero, and Marion Dinkins conducted a cold test (a test in a nonradioactive environment) of the system's performance in an empty silo at Fernald. It performed beyond requirements, measuring the height of a 0.3-m (1-ft) tall calibration target to within 0.64 cm (0.25 in.) of its actual height with a variation of less than 0.25 cm (0.10 in.) between repeated measurements. Also during the cold test, an alignment and calibration scheme was developed that was a major factor in the success of the measurements. "The tests demonstrated the superior

Workers installing the system in the silo access doors used protective clothing and respiratory equipment to guard against high concentrations of radon gas in and around the storage silos.

accuracy and reliability of the measurement system," says Burks. "Practicing installing the system in an empty silo also helped us determine the tools we needed to do the job. When you're working in a contaminated environment, you don't want to stop halfway through the installation and go get a tool."

Before the cold test, the project team had focused on system function and accuracy. The test successfully demonstrated the system's performance, but it also highlighted the need to increase its rate of gathering and processing data. In response, the group developed a piece of menu-driven software which enabled the user to calculate, set, and change system parameters as often as necessary. "This cut down on the time it took to gather data," says Burks. "It also allowed us to specify a series of lines for the system to scan and then leave the computer to run the system at night or when high radon levels forced evacuation of the control area."

To map the large, irregular waste surfaces inside the silos, Burks and his group used three camera-laser units (one was a backup) and rotated them among the silo's manways to obtain a complete surface map. Maps were built up a section at a time using an infrared laser equipped with a cylindrical lens to project a line on the surface of the waste. A high-resolution, black-and-white video camera was used to record an image of the line.

"In one image, you can get up to 50 to 60 data points on the surface being scanned, each several inches apart," says Burks. "Thousands of images were acquired and analyzed to map each silo." an image-processing system digitized each image and fed it into a computer that performed high-speed geometric transformations on the processed image to determine the location of the line in space. The results of these calculations were then fed to a workstation where they were displayed for the operator. From the workstation, the operator

could control system parameters, such as the starting and ending points of regions to be scanned and various image analysis parameters.

Mapping the entire surface of the waste required that it be surveyed from several different perspectives. Each silo has five manways, one in the center of the dome and four around the perimeter; data were gathered using the measurement unit in the center manway in conjunction with units located in each of the perimeter manways. A frame of reference was established by placing lights in sounding ports along the edges of the domes, several feet above the waste. As a result, maps of surface features before and after the application of the bentonite could be compared, verifying that the entire waste surface had been covered to the required depth.

The cold-test silo took two weeks to scan. Using the new software and techniques developed over the course of their work at Fernald, Burks' group scanned the final silo in only 47 hours, enabling them to finish taking data on October 11—one day ahead of schedule. The bentonite caps were applied by Thanksgiving, and mapping of those surfaces was finished in late December.

"The people at Fernald were happy to get the results," Burks says. "The surface features of the waste were different from what they expected, and that made a big difference in the amount of bentonite they applied and how they applied it. Various scenarios called for the application of up to 3000 m^3 (80,000 ft^3) of the clay sealant. Using our data on surface features, they met DOE-EPA requirements using only about 900 m^3 (24,000 ft^3)."

The highly accurate data on the waste's surface features resulted in considerable cost savings because it eliminated the need to buy and apply thousands of extra cubic feet of bentonite. It also made it unnecessary to retrieve and treat the excess radon-contaminated clay that would have been applied if Burks' surface data had not been available. "It cost about $700,000 to develop the system and about $300,000 to put it in place," says Burks, "The savings have been estimated at 15 to 25 million dollars. That's a good return on an investment by any measure."

Microwaves Chip Away at Contaminated Concrete Problem

"We expect the process to be faster than conventional technologies when it is fully developed."

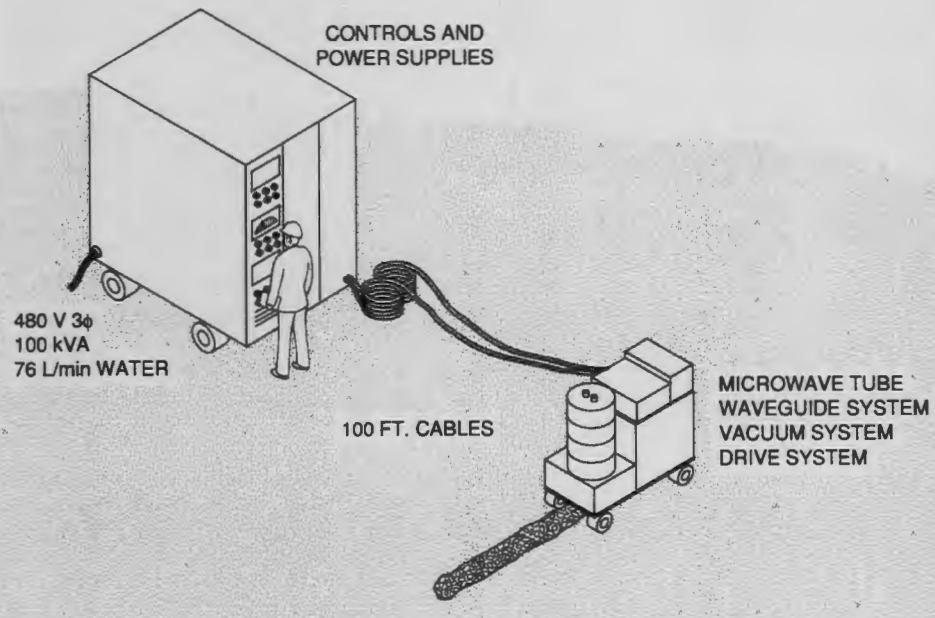
Why, you might ask, would anyone want to develop new ways to clean concrete?

Well, for starters, there are over 200 acres of radiation- and hazardous waste-contaminated concrete under roof at the Oak Ridge K-25 Site, and concrete tainted with contaminants, such as uranium or polychlorinated biphenyls, is a common problem at nearly every DOE laboratory or production plant. Before these areas can be used for other purposes or demolished, the contamination in the concrete must be reduced to safe levels.

Using a microwave generator originally developed for fusion energy research, Terry White of the Fusion Energy Division has developed a method of decontamination

Microwave heating of concrete avoids many of the problems of conventional decontamination methods. It creates chips that are small enough to be removed by a vacuum system, but too large to create an airborne contamination hazard; it is a dry process, eliminating problems with soluble contaminants; and, because no external impacts are required to remove the surface, contamination is not driven farther into the concrete.

Phase II Mobile Microwave Concrete Decontamination Prototype

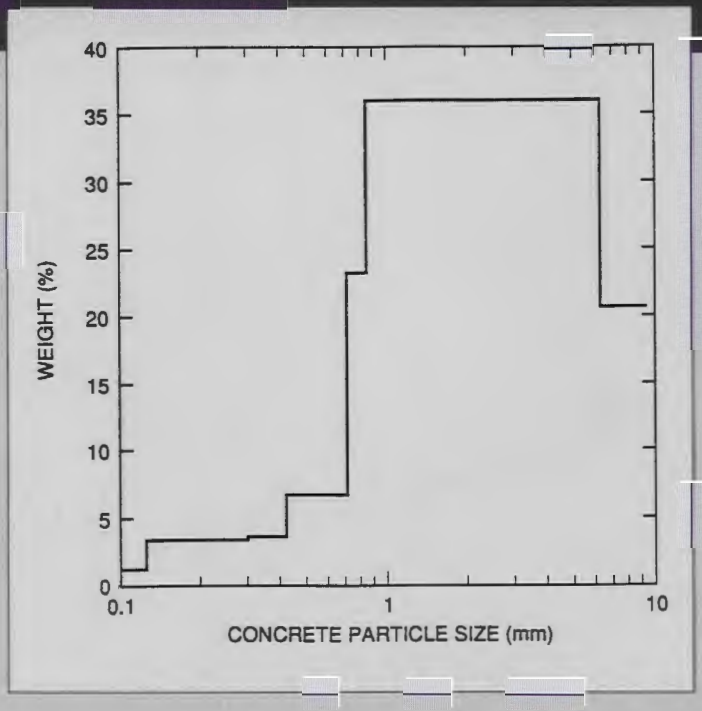


A more powerful mobile version of the microwave decontamination system is expected to be completed by the end of this year. The system will be designed to remove concrete faster and in thinner layers. Testing of the new system is scheduled to begin in 1993.

that uses microwaves to rapidly heat concrete surfaces. The heat causes water present in the concrete to turn into steam, generating internal pressure. This pressure combines with the thermal stresses produced by rapid microwave heating to break the surface layer of concrete into small chips. Because the vast majority of contamination is confined to the top several millimeters of the concrete, removing the concrete's surface is an effective form of decontamination.

Several methods are currently used to remove contamination from concrete surfaces, but they all have shortcomings. Pneumatic chisels are used to chip away contaminated surfaces, but this approach generates a lot of dust, creating an airborne contamination hazard. The dust can be minimized by working on a wet surface, but the water causes soluble forms of contamination, such as uranyl nitrate, to soak into the concrete. Also, the impact of the chisel can drive contamination farther into the concrete.

High-pressure water can be used to blast contamination free, but the waste water must be treated afterward to remove contaminants. High-pressure water cleaning also causes soluble contaminants to penetrate farther into the concrete.



Removal of contaminated concrete using microwave heating solves the problem of airborne contamination. Less than 1% of the debris created by this process is small enough to pose an airborne contamination hazard.

A third approach has been steel shot blasting, a surface-finishing technology that creates a uniform finish by removing and compacting surface material. Its shortcomings as a decontamination method are that it creates a lot of dust, it is relatively slow, and it also tends to pound contaminants back into the concrete.

Microwave heating, on the other hand, solves the dust problem by creating chips small enough to be removed by a vacuum system, but generally too large to create an airborne contamination hazard. As a result, the surface can be kept dry, eliminating problems with soluble contaminants. This approach also avoids the problem of driving contamination farther into the concrete because no external impacts are required to remove the surface.

In his initial research, White simulated a mobile microwave heating system by sliding a concrete slab under a stationary applicator. The applicator is designed to minimize reflected power so as not to damage the system. During the course of the experiments, detectors measure forward power, the amount of microwave power applied to the concrete; transmitted power, the power passing through the concrete; and scattered power, power that escapes around the applicator.

White's experimental setup consists of a stationary microwave generator, a waveguide system and applicator to channel the microwaves from the generator to the concrete, a concrete slab mounted on a roller system used to slide it along beneath the waveguide applicator, and a vacuum system to remove debris generated by the heating process.

Two different microwave generators have been used in White's research—a 6-kW, 2.45-GHz generator and a 10-kW, 10.6-GHz generator—allowing him to control the depth of concrete removal by

varying the frequency of the microwave source. Higher frequencies concentrate more of their energy near the surface of the concrete and remove a thinner layer of material. Lower frequencies are absorbed deeper in the concrete and, therefore, remove a thicker layer. "A lot of microwave design is based on intuition, experience, and trial and error," White says. "There aren't many standards in this kind of work."

The next step will be to construct a 15-kW, 18-GHz system designed to remove thinner layers of concrete more efficiently. The increases in frequency and power, combined with improvements in the applicator design to spread the microwaves over a larger area, are expected to result in considerably higher removal rates.

"We expect the process to be faster than conventional technologies when it is fully developed," says White. A mobile microwave heating prototype is expected to be completed by the end of this year, and testing will begin in 1993.

License Renewal for Commercial Nuclear Power Plants

By Claud E. Pugh

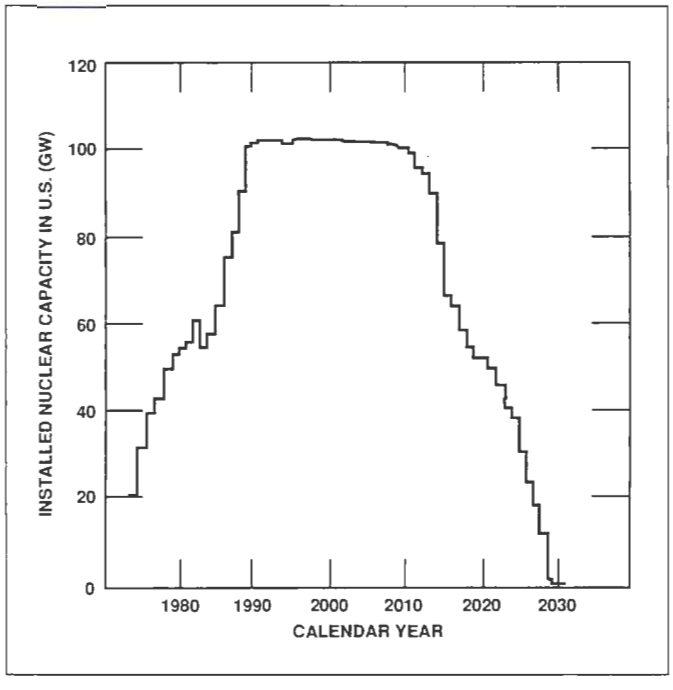
Since the 1973 oil embargo, demand for electricity in the United States has increased at a slower rate than historic-demand projections would have predicted for the economic growth of the past 18 years. Nonetheless, the demand has increased by 60% over this time. Commercial nuclear power plants, some of which have been operating since the 1960s, have met a significant portion of this increased demand. Today nuclear generating capacity in the United States totals over 100 gigawatts, representing over 20% of the nation's total capacity for generating electricity. In addition to their energy contribution, U.S. nuclear plants have offered several environmental advantages over plants fired by fossil fuels, including the absence of emissions of carbon dioxide (one of the greenhouse gases), sulfur dioxide (a possible cause of acid rain), and nitrogen oxides (contributors to urban smog and acid rain).

Although nuclear energy has played an important role over the past three decades, it is approaching a crossroads. One decision must be made concerning the feasibility of building future nuclear plants, and another must be made concerning the need to extend the operating life of existing nuclear plants.

Claud Pugh examines one of the many large-scale vessels that the Heavy-Section Steel Technology Program overpressurized until they fractured. These tests were done by ORNL for the federal government to confirm that the margins between allowable operating conditions and conditions that could lead to pressure vessel fracture were sufficiently large.

Although the most recent order for a commercial nuclear power plant in the United States was placed in 1978, the plants ordered before that year have continued to be completed and connected to the nation's electrical grid. Today five plants remain to be completed. It is recognized that electric utilities probably will not order additional nuclear plants unless regulatory requirements are restructured to reduce their complexity and the time required for license approval and

construction. Progress is being made; however, DOE, the electric utility industry, the Nuclear Regulatory Commission (NRC), and the Congress are taking major steps toward establishing designs, regulatory processes, and a legal framework for future nuclear plants. For example, in late May 1992 the U.S. House of Representatives passed legislation similar to a previously passed Senate bill and similar to new NRC procedures that will permit one-step licensing of nuclear power plants. Concurrently, the industry and DOE are working on designs for passive-water reactors and advanced reactor concepts to be certified by the NRC.



The capacity of nuclear power plants to generate electricity in the United States has reached its maximum and will decrease dramatically after the year 2010 unless the licenses for these plants are renewed.

Because licenses of the existing plants are for 40 years, they will begin to expire at the end of the century, before the advanced nuclear plants can be available, even under the license-reform rules. Nonetheless, the United States is on the verge of a significant increase in nuclear power production capability, an increase that will be vital until advanced plants take their place in power generation. This increase is to come from the renewal of the operating licenses for the existing nuclear plants. Instead of permanently shutting down dozens of nuclear plants and removing an important source of electricity, the NRC and utilities may extend their operating life 20 years. License renewal is the second most important decision that must be made at the nuclear energy crossroads.

The figure here shows the rapid loss of nuclear generating capacity that will occur after the year 2010 if no additional plants are built or licenses extended. However, it is anticipated that up to 75% of the 112 existing plants, or some 80 plants, will apply for license renewal. In addition to helping meet demand for electricity, renewal of licenses can lead to major economic savings. For example, it has been estimated that if the licenses were renewed for 20 years for all of the existing nuclear plants, a savings of up to $200 billion could be realized. The principal reason is that the utilities have amortized the capital cost of the plants over the initial 40-year license period. Increased operating and maintenance costs for an aging plant during a renewal period will be much less than the capital investment required to build new plants, nuclear or fossil. Additionally, the economic infrastructure of the utility industry would experience significant relief if replacement of these plants were deferred by up to 20 years.

Current federal regulations permit license renewal, but they do not give guidance on the

requirements. Anticipating that nuclear utilities would request renewal of plant licenses, the NRC began several years ago to establish regulatory policies, technical bases, and procedures appropriate to license renewal. The NRC is now completing that process, and the regulatory bases to approve these renewals and to oversee the plants during the renewal period are essentially all in place. For this effort, the NRC has drawn heavily on ORNL to conduct supporting research.

The regulatory requirements for license renewal fall into two categories—technical and environmental. The NRC places such requirements in the U.S. Code of Federal Regulations. Plants seeking license renewal must satisfy review requirements both at the time renewal is granted and during the renewal period. As in earlier phases of developing nuclear power, ORNL has contributed significantly to both areas by supplying data, analysis, and technical interpretations to the NRC. The NRC requirements and some of ORNL's contributions are presented below.

Technical Requirements

The technical requirements for license renewal are based on two key principles: (1) the existing current licensing basis (CLB) for each operating reactor provides an acceptable level of safety for operation during the renewal term, and (2) each plant's licensing basis must be maintained during the renewal period, using existing or new programs that focus on the management of age-related degradation of plant systems, structures, and components (SSCs). Evaluators of a renewal application will determine if the applicant has taken the required steps to

- document the CLB for that plant—that is, state all the codes, standards, and regulatory guides that apply to that specific plant;
- identify the SSCs—safety equipment plus those components that may affect the performance of safety equipment;
- complete an assessment of the plant to verify that it complies with the CLB at the beginning of the renewal period;
- establish a program that can identify and monitor age-related degradation of SSCs throughout the renewal period; and
- establish a program to demonstrate that the plant is in compliance with the CLB throughout the renewal period.

The CLB is composed of the original licensing requirements (e.g., codes, standards, regulatory guides) plus requirements that have been added for the plant during its current license period. Compliance with the CLB ensures that at least the current margins of safety are maintained throughout the renewal period. One major emphasis for the NRC has been to identify exactly which parts of the plant should be required in the SSCs to avoid or mitigate the consequences of hypothetical accidents.

ORNL has been a major participant in conducting research on the age-related degradation of many of these structures and components. This work has included identifying degradation mechanisms, developing methods for monitoring degradation, evaluating approaches (rules, criteria, and limits) for mitigating the effects of degradation, and establishing technical bases for rules limiting the effects of aging. In particular, ORNL researchers have addressed concrete structures, pressure vessels, and engineered safety systems components.

Concrete Structures Studied at ORNL

The containment building and the basemat, on which the reactor sits, are the two most important concrete structures in a nuclear power plant in terms of safety. Material and structural degradation resulting from aging and environmental influences must be understood and managed to ensure the integrity of these components and the associated defense against release of radiation to the environment.

ORNL addresses concrete structures in the NRC-sponsored Structural Aging Program, led by Dan Naus and Barry Oland, both of the Engineering Technology Division. The

program's chief goal is to establish technical bases for regulatory criteria, which will identify for license reviewers and licensees potential structural safety issues and provide acceptance criteria.

ORNL researchers are studying the aging and environmental influences on the properties of both concrete and steel-reinforcing materials, potential degradation mechanisms, structural inspection and monitoring techniques, repair methods, and procedures for structural evaluations, especially of the containment building and basemat.

The ORNL group has compiled extensive information from domestic and international sources for nuclear and non-nuclear civil structures and research activities. The information is being compiled into comprehensive data bases on long-term material properties, concrete aging mechanisms, inspection, repair, and structural integrity experience. One important part of this effort is ORNL's development of a Structural Materials Information Center, which makes these data bases available in handbook and electronic formats. It will be an important resource for assessing concrete structures during license renewal evaluation.

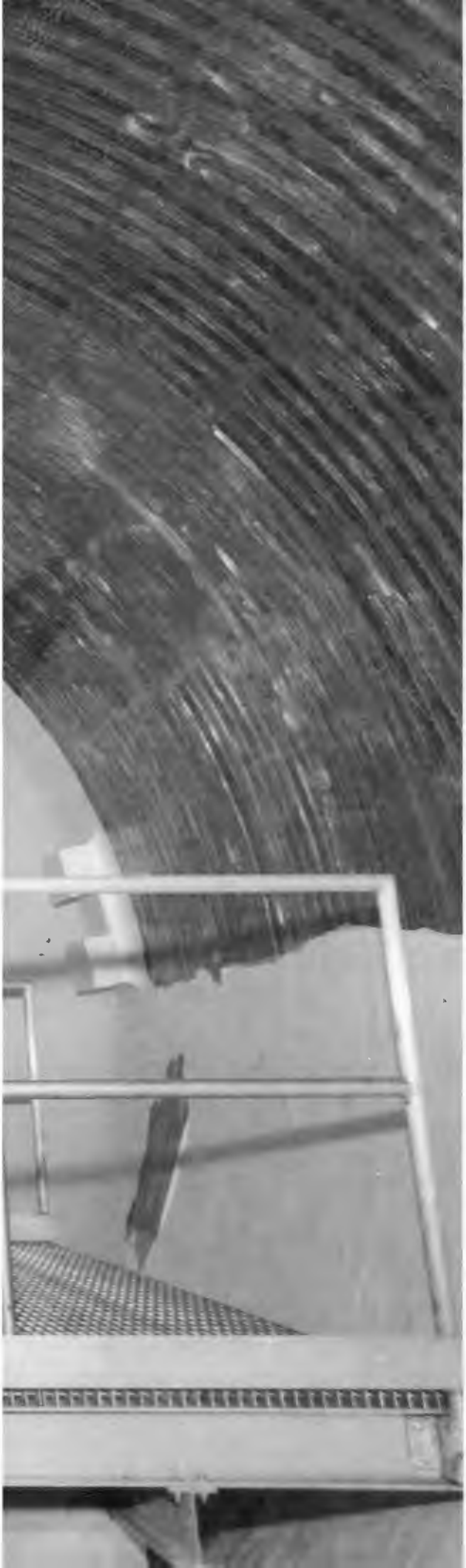
Other developments include (1) an aging assessment methodology, which can be used to rank concrete structures in terms of safety significance and resistance to environmental damage, and (2) a methodology to assess the current condition and predict the lifetime reliability of concrete structures. Other guidelines on inspection and repair will be issued by ORNL.

John Merkle of the Engineering Technology Division describes to former NRC Chairman Admiral Kenneth Carr some of the ORNL material specimen studies that have provided the bases for many of the rules and criteria for reactor pressure vessel safety assessment.

Reactor Pressure Vessel Research at ORNL

Reactor pressure vessel (RPV) research continues to receive high priority from the NRC because of its importance to safe plant operation and other factors. ORNL, through the Heavy-Section Steel Technology (HSST) Program, has been the lead laboratory for this research for more than 25 years. The principal factors of concern are that vessels are subjected to active aging mechanisms, such as increasing embrittlement caused by neutron radiation; can be potentially exposed to stresses, such as sudden decreases in temperatures and pressures, under accident conditions; contain fabrication flaws; and cannot be easily replaced to extend the plant's life.

Before the creation of the NRC, the Atomic Energy Commission (AEC) initiated research to obtain data and develop methods to ensure that adequate margins of safety existed for the thick-wall pressure vessels in commercial nuclear power plants. In 1966 ORNL was chosen to be the lead laboratory for that research and has provided continuous support to the AEC and NRC. The work has produced many of the methods that are

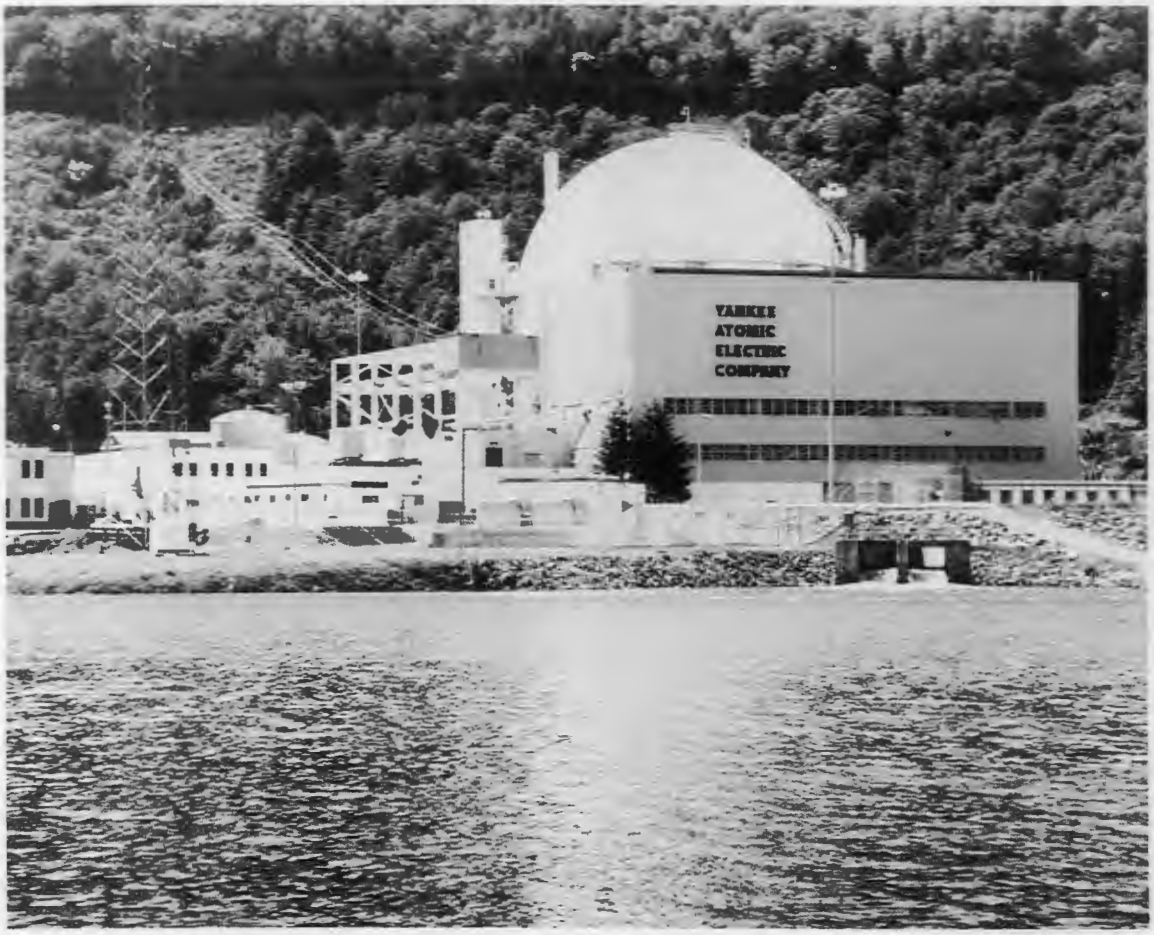


William Pennell observes the interior of a full-size commercial reactor pressure vessel whose walls are 20 cm (8 in.) thick.

incorporated in codes and standards used by the nuclear industry and the NRC, such as the reference fracture toughness procedures in the American Society of Mechanical Engineers (ASME) code and the NRC Regulatory Guide 1.154, which gives guidelines for evaluating RPV integrity under pressurized thermal-shock (PTS) scenarios in which a hot, pressurized, irradiated vessel is suddenly chilled by the introduction of cooling water.

Current work on RPVs at ORNL consists of three programs: the HSST Program, managed by Bill Pennell of the Engineering Technology Division; the Heavy-Section Steel Irradiation (HSSI) Program, managed by Bill Corwin of the Metals and Ceramics Division; and the Surveillance Data Bases, Analysis, and Standardization Program, managed by Frank Kam of the Computing and Telecommunications Division. ORNL's leadership in these areas is recognized worldwide, and the ORNL staff maintain strong relationships with their counterparts in many countries and at the International Atomic Energy Agency.

Don Casada examines a worn gate valve similar to valves used in nuclear power plants.



The Yankee Rowe Plant was the oldest operating commercial nuclear power plant in the United States, and its license was scheduled to expire in the year 2000. This plant, which has a pressurized-water reactor, has an electric generating capacity of 167 MW. It was to be the first to apply for license renewal, but the utility recently retired the plant for economic reasons.

The first sidebar to this article addresses the HSST Program and some of the issues it examines. The HSST goal is to provide the NRC with the best available technology to ensure margins of safety against fracture of the RPV under hypothetical scenarios. The PTS scenario has gained the most attention because it combines the elements of fracture-prevention analysis, material properties, fabrication factors, and aging effects resulting from irradiation.

Mechanisms responsible for age-related degradation of pressure vessels include prolonged radiation exposure, sustained pressure and thermal loadings, and transient pressure and thermal loadings. Understanding these mechanisms and the materials making up vessels is the key to ensuring that a vessel will not rupture under prescribed conditions. In this area, ORNL has developed a series of advanced data bases and computer codes for use in making fracture predictions.

ORNL researchers are continuing to conduct advanced studies of the fracture characteristics of the materials, fracture behavior of structures, and analytical methods applicable to complex structures. Careful performance of many large-scale fracture experiments and their supporting analyses have defined the validity of and margins for the current RPV assessment methods. These efforts now include a focus on conditions that would exist beyond the initial license period.

RPV life is based not exclusively on time, but rather mostly on the embrittlement of the RPV steels, which depends on the amount, rate, and

temperature of neutron radiation. In other words, the life-limiting conditions for a vessel depend on the neutron exposure and the conditions under which it is accumulated. Of course, during the approved period of extended operation, the accumulated radiation exposure will be greater than for the plant's initial 40 years. Current limits on allowable embrittlement are expected to apply in principle during renewal periods, and the current research is aimed at verifying that these limits will not be exceeded during a 20-year extension. With respect to monitoring RPV aging, one key need is in-reactor surveillance programs that give accurate data on the neutron exposure and vessel embrittlement during operation. Frank Kam and his project team are working closely with the NRC to improve surveillance programs by combining the best available dosimetry techniques with the periodic testing of tensile and fracture specimens made of the RPV steel and weld materials that are exposed to actual reactor operation. They also maintain for the NRC a carefully documented national surveillance data base on which regulatory guidance for embrittlement assessments is based.

If the calculated embrittlement for the vessel in a specific plant reaches the allowable limit, regulations permit the owner to thermally anneal the vessel to remove a portion of the accumulated embrittlement. In work for the HSSI program, Bill Corwin and Randy Nanstad are verifying the correct times and temperatures for annealing to achieve acceptable levels of recovery for vessel steel and welds that may be more than 20 cm (8 in.) thick. Their experiments on welds removed from the vessel of the cancelled Midland Nuclear Plant Unit No. 2 will determine the degree of recovery from annealing and reembrittlement rates during subsequent radiations for prototypically thick welds. The HSSI Program staff are carefully combining these results with those from earlier and smaller specimen studies to provide the NRC with the best available basis for establishing annealing standards. The NRC is completing development of a regulatory guide to permit utilities to anneal their RPVs and to continue operation after annealing even under license renewal.

Radiation-induced embrittlement is not the only age-related degradation mechanism affecting RPVs. Material damage caused by thermal and mechanical stress cycles over time results in degradation that must be factored into the allowable life assessments. By knowing the plant's operating history, the owner can compute accumulated damage resulting from thermal aging, fatigue, and other factors to determine the remaining allowable life for the vessel, as defined by the code criteria in the CLB. Thus, accurate records of a plant's operating and maintenance histories are recognized by utilities as important for license renewal. Nanstad's group also continues to study the aging of these steels under long-term thermal exposure conditions.

Engineered Safety Systems Components Studied at ORNL

ORNL researchers are studying aging of nuclear reactor plant components, such as valves, pumps, steam generators, and vessel internals. Because the condition of these aging SSCs must be considered throughout license renewal periods, the research is focused on (1) developing guidelines for assessing the condition of components at the end of the current license period, (2) devising methods for monitoring age-related degradation during the license renewal period, and (3) where possible, identifying approaches to mitigate age-related degradation effects.

For the past eight years, ORNL has been a lead laboratory for the NRC in this area and has made some major breakthroughs, especially in developing techniques for nonintrusive monitoring of valves. This work has led to patented techniques and substantial technology transfer to industry. Don Casada, the manager of this research, describes these developments in the second sidebar to this article on p. 95. The research at ORNL is part of the NRC's overall Nuclear Plant Aging Research Program.

"ORNL researchers are studying aging of nuclear reactor plant components, such as valves, pumps, steam generators, and vessel internals."

Environmental Effects

A proposed NRC rule will cover environmental effects that should be addressed during the process of license renewal. Over the past few years, a multidisciplinary team led by Rich McLean, Lance

McCold, and Johnnie Cannon, all of the Energy Division, has intensively studied the potential environmental impacts of extended nuclear plant operation (see the interview on p. 114). The study identified more than 100 issues, made detailed assessments of potential environmental impacts, and examined the relationships of the issues to the National Environmental Policy Act (NEPA). The final goal was to identify the many issues that can be treated on a generic basis and the remaining few that must be handled on a plant-by-plant basis.

The results of the study were published for public comment in late 1991. The public-comment period recently ended, and ORNL is helping the NRC formulate responses. After the NRC makes its final responses, this part of the license extension rule will be complete. The NRC will document the final rule as a modification to Part 51 of Element 10 of the U.S. Code of Federal Regulations (10 CFR 51).

Implementing the License Renewal Process

Upon completion of the generic environmental impact statement for extending nuclear plant operation, all the regulatory instruments will be in place to allow applications for license renewal. The first license renewal application was expected to be for the pressurized-water reactor of the Yankee Atomic Electric Company's (YAEC) Yankee Nuclear Power Station in Rowe, Massachusetts (see photo on p. 88). Commonly called Yankee Rowe, it was the oldest operating nuclear power plant in the United States, and its license was scheduled to expire in 2000. However, YAEC recently decided to retire this plant because of economic considerations, including the cost of the extensive efforts that would have been required to qualify its embrittled reactor vessel for continued service.

The first application to renew a license for a boiling-water reactor is expected to come from the Northern States Power Company (NSPC) for its Monticello Nuclear Power Plant, whose license is scheduled to expire in 2010. Both of these plants have in recent years been the focus of advanced studies by DOE and the Electric Power Research Institute to assess the issues of aging and potential procedures for license renewal. The NSPC is expected to submit its application for license renewal in early 1993.

The lead time between submittal of a renewal application and expiration of the initial license period is expected to be about 15 years. About 5 years will be required to obtain approval for all aspects of the application, and the other 10 years are allowed for the plant owner to provide an alternative source of electricity should the application be denied or if the owner decides not to extend the plant's operation. The license renewal is to become active when the approval is granted and to extend through the renewal period. For example, if the renewal is approved 10 years before expiration of the initial 40-year license, the renewal will cover the remaining 10 years plus the approved renewal period.

In conclusion, meeting the growth in demand for electricity in the next several decades in the United States can be easier and less costly if the operating licenses of existing nuclear power plants are renewed for another 20 years. ORNL has played an important role by providing the NRC with technical expertise, data, and analyses on which to base regulatory criteria and guidelines for license renewal. The development of the regulatory procedures is now essentially complete. It is expected that ORNL will continue to contribute to the development of nuclear power technologies, including the advanced reactors that will be certified by the NRC for the next generation of nuclear power plants.

Biographical Sketch

Claud E. Pugh has been director of the Nuclear Regulatory Commission (NRC) Programs Office of ORNL since 1989. Since joining the ORNL staff in 1968, he has spent most of his career with the Engineering Technology Division, where he had served as head of the Pressure Vessel Technology Section (1986–1989), manager of the NRC Heavy-Section Steel Technology Program (1982–1987), and manager of Structural Design Technology in DOE's Liquid Metal Fast Breeder Reactor Materials and Structures Technology Management Center (1978–1982). The chief focus of his technical work has been structural materials technology for nuclear and non-nuclear applications. His models of the behavior of inelastic structural materials have influenced the analysis of high-temperature structural designs in Europe, Japan, and the United States.

A native of North Carolina, he received his Ph.D. degree in engineering mechanics from North Carolina State University. He has served on that university's faculty and as a part-time professor of engineering science and mechanics at the University of Tennessee. Pugh is a fellow of the American Society of Mechanical Engineers and a member of the American Nuclear Society. He is the U.S. member on the International Atomic Energy Agency's International Working Group on Life Management of Nuclear Power Plants and coordinates activities with the Fracture Assessment Group of the Committee on Safety of Nuclear Installations within the Nuclear Energy Agency of the Organization for Economic and Cooperative Development in Europe.

Nuclear Plant Life Extension

Aging and Safety in Reactor Pressure Vessels

"The rate of embrittlement in each reactor vessel is monitored with the aid of surveillance programs, and limits are imposed by NRC regulations and regulatory guides that ORNL has helped to establish."

Reactor pressure vessels in nuclear power plants must remain structurally sound to prevent loss of water used for cooling the nuclear fuel. Overheated fuel could result in localized melting of the vessel wall and thus in the escape of radioactivity into the containment building.

The thick steel walls of new reactor pressure vessels possess sufficient strength and ductility—the ability to accommodate stresses and strains caused by pressurization, heating, and cooling—to prevent vessel failure. Over many years, however, as the vessel interior is bombarded by neutrons from nuclear reactions in the fuel, the walls tend to lose their ductility. This tendency is greater for those vessels that have relatively high concentrations of copper (an impurity) and nickel (an alloying element). Such radiation-induced embrittlement can occur in older pressurized-water reactors and, to a lesser extent, in boiling-water reactors.

Embrittlement and thermal shock. Radiation-induced damage, or embrittlement, is the aging mechanism of dominant concern in reactor pressure vessels. Long-term exposure of vessel walls to neutron radiation causes dislocations of atoms in the steel's crystalline structure,

At the K-25 Site, Bill Pennell inspects the full-size reactor pressure vessel that ORNL obtained from Combustion Engineering 5 years ago for research purposes. ORNL and Pacific Northwest Laboratory are planning to use ultrasound to nondestructively detect tiny flaws introduced into the steel wall plates of the vessel during manufacturing. Such vessels are no longer being built in the United States.

Nuclear Plant Life Extension

"Nuclear plant operators can reduce the embrittlement rates of their reactor pressure vessels by minimizing neutron bombardment of the vessel."

increasing its strength but decreasing its ductility and fracture toughness.

During manufacture of steel plates for vessel walls, crack-like flaws may develop. Welding of the plates and forgings is another potential source of flaws. As the walls become embrittled, these flaws could propagate under severe loading conditions. One such condition is thermal shock, which may occur when the hot walls of a vessel are suddenly subjected to cold water as a result of loss of pressure and the operation of safety injection systems to cool the nuclear fuel. In the 1980s, ORNL researchers demonstrated that thermal shock, combined with repressurization (which can result from activation of the safety injection system), could (for postulated severe conditions) drive a crack through the vessel wall, which could result in a loss of essential core cooling water. This combination of thermal and pressure loading is known as pressurized thermal shock (PTS).

For older nuclear power plants, radiation-induced embrittlement is clearly an aging-related issue that must be addressed if plant operating licenses are to be renewed. ORNL is providing guidance to the Nuclear Regulatory Commission on this issue by estimating the probability of failure for reactor vessels as a function of operating time. The rate of embrittlement in each reactor vessel is monitored with the aid of surveillance programs, and limits are imposed by NRC regulations and regulatory guides that ORNL has helped to establish.

Nuclear plant operators can reduce the embrittlement rates of their reactor pressure vessels by minimizing neutron bombardment of the vessel. Recommended approaches include (1) rearranging the nuclear fuel core so that used nuclear fuel assemblies are nearest to vessel walls and (2) adding shielding between the nuclear core and the vessel walls.

A potential method for restoring ductility and toughness to an embrittled vessel is a heat treatment called thermal annealing. The technique has never been used on a commercial U.S. nuclear power plant, but American researchers have conducted irradiation-annealing-reirradiation experiments to establish the necessary data base and have studied Soviet experience in annealing nine of their reactor pressure vessels. The annealing procedure involves heating the embrittled portion of the vessel to a temperature substantially above the operating temperature (288°C) for about one week. A partial anneal is achieved at 343°C (the maximum temperature permitted when water is in the vessel), and a "full" anneal is achieved at 454°C (using electric heaters on a vessel after the water has been

removed) to raise the temperature of the vessel beltline weld metal to 454°C for about six days. Soviet vessels differ, however, from those in the United States in that their welds run in one rather than two directions. This difference permits them to avoid introducing high, potentially damaging temperature gradients in the nozzle region of the vessel during annealing. These temperature gradients may be unavoidable during the annealing of a U.S. reactor vessel.

Fracture-prevention margins. ORNL researchers calculate fracture-prevention margins for reactor pressure vessels for the NRC and compare them with the margins required throughout the vessel's operating life. Fracture-prevention margins are calculated using fracture-mechanics technology in conjunction with fracture toughness, a measure of the ability of a material containing sharp-edged cracks to sustain stress. Fracture-prevention margins will progressively decrease as the vessel material absorbs increasing amounts of radiation-induced damage throughout its operating life.

Limits to such damage are set to maintain required fracture-prevention margins throughout a nuclear plant's licensed operating period. Regulatory requirements are based on fracture-mechanics technology and use materials-aging data gathered from test reactors and from mandatory surveillance programs for operating power reactors. The surveillance programs use steel specimens placed in the reactor pressure vessel, which are withdrawn and inspected for radiation-induced damage and the extent of embrittlement. These requirements address both normal operation of the reactor system and potential accident loading—that is, pressure and temperature changes that could drive a crack through an embrittled vessel wall.

For normal operation, the regulatory requirements call for plant technical specifications to be periodically adjusted to preclude operating conditions that could reduce the fracture-prevention margins below acceptable levels. For accident loading, they set regulatory limits on the acceptable level of radiation-induced damage in the vessel material. They also define the scope and acceptance criteria for fracture margin assessments, which must be performed to support any proposal for continued operation of the plant once the regulatory limits on radiation-induced damage have been exceeded.

HSST Program. ORNL has long been at the forefront of developing and validating technology for assessing fracture-prevention margins in aging reactor pressure vessels.

"ORNL has long been at the forefront of developing and validating technology for assessing fracture-prevention margins in aging reactor pressure vessels."

Nuclear Plant Life Extension

"In the 1970s ORNL researchers focused on validating the newly developed fracture margin assessment technology."

Research that enabled development of this technology has been performed in the Heavy-Section Steel Technology (HSST) Program in ORNL's Engineering Technology Division. The HSST Program at ORNL has been supported by the U.S. Nuclear Regulatory Commission and its predecessor, the Atomic Energy Commission, for more than 25 years.

In the late 1960s the HSST Program initiated the development of the fracture toughness data base for reactor vessel materials, which is essential to all fracture margin assessments for reactor pressure vessels. Large plates of thick reactor pressure vessel steel were purchased and used by HSST researchers to fabricate test specimens, some of which weighed over a ton. John Merkle of ORNL played a leading role in developing the fracture-mechanics technology required to interpret and apply the test results to assessments of vessel fracture margins.

In the 1970s ORNL researchers focused on validating the newly developed fracture margin assessment technology. They ran large-scale experiments to verify fracture margin predictions for a broad range of pressure vessel loading and operating conditions. Large, thick-walled pressure vessels containing cracks were pressurized to destruction in these tests, sometimes with spectacular results. These tests involved a broad spectrum of past and present ORNL personnel under the leadership of senior scientists and engineers such as Richard Bass, Bob Bryan, John Bryson, Dick Cheverton, Bill Corwin, Shaffih Iskander, John Merkle, Randy Nanstad, Claud Pugh, Grover Robinson, and Grady Whitman.

The researchers proved the vessels are safe by overpressurizing several scaled-down, deliberately flawed pressure vessels until they leaked or ruptured. They found that the vessels failed only after being subjected to pressures about three times the design pressure even when large flaws were present. They concluded that flaws too small to be detected would not pose a safety problem under normal operating conditions and that the fracture-mechanics-based fracture margin assessment technology provided an adequately conservative assessment of pressure vessel integrity.

In 1978 an incident at the Rancho Seco nuclear power plant in California focused attention on PTS. In 1981 the NRC declared PTS an unresolved safety issue. An ORNL team was charged with developing and testing technology for assessing the ability of aging reactor pressure vessels to withstand PTS events without failure. Results from their work were later used as the basis for regulatory

requirements that assess the suitability for service of aging reactor pressure vessels.

The recent decision by the operating utility to retire the Yankee Rowe nuclear plant in Massachusetts was based partly on results generated using ORNL's technology for analyzing a vessel's ability to survive PTS. A preliminary ORNL report concluded that, based on such factors as uncertainty about the amounts of copper in the vessel welds, the probability of vessel failure exceeded the NRC's acceptance guideline.

Current research in the HSST Program (managed by William E. Pennell) is focused on resolving issues identified in earlier research programs and refining the fracture margin assessment process. For example, in light of University of Kansas studies of enhanced fracture toughness for shallow flaws in two structural steels, ORNL researchers are generating a shallow-flaw data base and developing technology to apply this data base to the analysis of reactor vessel response to PTS events. They are modeling the distribution of stresses in vessel walls during PTS events and trying to determine their impact on fracture toughness. ORNL researchers are also trying to better understand the factors that start and stop crack growth in vessel walls.

The need for these developments becomes acute as operating reactor pressure vessels approach their currently authorized limit for radiation-induced embrittlement and as managers of older nuclear power plants exercise the option of applying for a license renewal. The HSST Program at ORNL intends to continue the tradition established over the past 25 years of providing the NRC with research results that enable it to address new challenges as they arise.—*William E. Pennell*

Biographical Sketch

William E. Pennell has been manager of ORNL's Heavy-Section Steel Technology Program since shortly after joining the Laboratory staff in 1987. He has an M.Sc. degree in mechanical engineering from the Cranfield Institute of Technology in England. He has 29 years of reactor engineering experience, much of it gained at Westinghouse Electric Corporation's Advanced Reactors Division, where he was manager of Reactor Engineering for the Clinch River Breeder Reactor Project. In 1986 when the U.S. fast breeder reactor development program was cancelled, he joined the Tennessee Valley Authority (TVA) for one year as manager of Engineering and Technical Services in the nuclear power recovery program. At TVA he was responsible for a staff of 1700 engineers, managers, and branch chiefs providing engineering support to TVA's four active nuclear power sites. He holds nine U.S. patents in fast breeder reactor technology.

Nuclear Plant Life Extension

Component Aging Research

"ORNL researchers have identified improved monitoring techniques that detect early signs of age-related degradation in power plant components."

In 1985 several check valves failed during operation of the San Onofre nuclear power plant in California (shown here), which was permanently closed in 1992. Since this incident, check valves and other power plant components have received increased attention from the NRC and the nuclear power industry, and ORNL has developed nonintrusive methods for monitoring age-related degradation in valves.

In 1985 several check valves failed during operation of the San Onofre nuclear power plant in California, resulting in extensive, costly damage to valves and pipes.

The valves failed as a result of service-induced wear, or aging. Since then check valves and other power plant components have received increased attention from the Nuclear Regulatory Commission (NRC) and the nuclear power industry, and ORNL has helped develop technologies to address these concerns.

Check valves and other components of nuclear power plants are subject to age-related stressors, including wear, corrosion, oxidation, and fatigue. Over time, these stressors lead to degradation and, in some cases, failure. Safety-related components affected by aging include valves, valve operators, pipes, pumps, instrumentation, motors, turbines, diesel generators, and heat exchangers.

These and other components have been the objects of study by ORNL

and other national laboratories since the mid-1980s under the NRC's Nuclear Plant Aging Research (NPAR) program. The NPAR program was chartered to identify and address safety issues related to aging of electrical and mechanical components in commercial nuclear power plants.

The program goal calls for the NRC, its contractors, and utility licensees to better understand the effects of aging on nuclear power plants and to identify ways to manage and mitigate these effects. Although the results of current studies apply to plants during their initial license periods, the insights acquired are especially important to extended plant operation under license renewal.

ORNL's Engineering Technology and Instrumentation and Controls divisions and the Engineering Division of Martin Marietta Energy Systems, Inc., have played a key role in the NPAR program, especially through studies of electrical and mechanical components and safety systems. The local program was initiated under the management of David Eissenberg, who retired last year; Don Casada is the current manager of the program. The NPAR program has begun or completed studies on a broad spectrum of equipment and systems, including centrifugal pumps, motor-operated valves, air-operated valves, check valves, solenoid-operated valves, relief valves, safety-related pump turbine governors, heat exchangers, auxiliary feedwater systems, control rod drive systems, instrumentation and control

Howard Haynes (left) and Don Casada observe the performance of a check valve installed in a test loop in the Engineering Technology Division using methods ORNL developed to unintrusively monitor valve performance and degradation. A prototypical magnetic field concentrator device is located on top of the valve.

"These studies provide the information needed to understand *aging problems."*

systems, and other internal parts of reactors.

The ORNL studies identify the causes of age-related degradation, failure mechanisms and modes, historical operating experience, and existing inspection and surveillance techniques for each component or system. These studies provide the information needed to *understand* aging problems.

For some of the components and systems studied, the current monitoring techniques were found to be unable to detect or adequately characterize some sources of age-related degradation. To help solve this problem, ORNL researchers have identified improved monitoring techniques that detect early signs of age-related degradation in power plant components in time to take corrective actions to *manage* the aging. For example, if degradation of a valve's motor is recognized by monitoring appropriate parameters over time (to look for trends), the motor can be replaced or rebuilt before it fails to work as designed.

By participating in industry standards and code groups, such as the American Society of Mechanical Engineers and the Institute of Electrical and Electronics Engineers, ORNL researchers can help ensure that the aging of nuclear plant components and systems is properly managed by using improved monitoring practices. The results of NPAR program research at ORNL have influenced the development of several in-service testing codes and standards, ensuring that age-related degradation mechanisms will be recognized and addressed.

In some cases, however, the NPAR program studies have identified potential age-related failure mechanisms that could not be identified by existing monitoring techniques, even if codes and standards were optimized. In several such cases, ORNL researchers have invented new monitoring techniques.

For example, after recognizing that it was not possible to adequately diagnose the condition of motor-operated valves without taking them apart, Howard Haynes and David Eissenberg, both of the Engineering Technology Division, invented a motor-current signature analysis technique. Motor currents, which can be measured during motor operation, carry characteristic signatures; when a motor is operating normally, the signature is different from that of a motor operating abnormally. By monitoring motor currents and comparing new signatures with known ones, abnormal motor operation can be identified. Haynes and Bob Kryter, both of whom have played important roles in ORNL's NPAR program, have successfully

demonstrated the ability of this nonintrusive technique to detect a variety of age-related degradations in motor-operated valves and other motorized equipment. A patent on this invention has been issued to Martin Marietta Energy Systems, Inc., and the process has been licensed for use by Performance Technologies, Inc., Spectrum Technologies USA, and Predictive Maintenance Inspection, Inc. Additional licenses are anticipated.

In much the same way, Haynes, Eissenberg, and Casada identified deficiencies in check valve monitoring methods and conceived of improved methods. Under the auspices of ORNL's Advanced Diagnostics Engineering Center, we developed nonintrusive techniques for determining the position and condition of the internal parts of valves. In these techniques, a magnetic field is applied externally to the valve and electronically monitored for changes in field strength resulting from changes in the internal position of the valve's obturator—the part that blocks or permits flow of water in power plants. Patent applications for these techniques have been filed by Energy Systems, which has licensed these techniques to MOVATS, Inc., and Valvision, Inc.

ORNL has played a vital role in supporting the NPAR program, whose results are being used in the license renewal rule-making process and its implementation. ORNL researchers have also developed novel techniques that will be useful to electric utility personnel for routine monitoring of equipment for age-related degradation. These contributions will help ensure that the aging of nuclear power plant components is not only well understood but also managed so that plants can continue to operate safely.—*Donald A. Casada*

Biographical Sketch

Don Casada is manager of ORNL's Nuclear Plant Aging Research program and leader of the Reactor Research Group in the Engineering Technology Division. He manages aging research performed for the Nuclear Regulatory Commission. A native of Bryson City, North Carolina, he holds an M.S. degree in mechanical engineering from North Carolina State University. He came to ORNL in 1988 from Carolina Power & Light Company. Since then he has worked for the Engineering Technology Division, studying auxiliary feedwater systems, valve-body erosion, and low-flow degradation of pumps in nuclear power plants and managing research. He is co-inventor of nonintrusive monitoring methods for check valves and is secretary of the American Society of Mechanical Engineers Working Group on Check Valves.

Nuclear Plant Life Extension

Environmental and Socioeconomic Impacts

An interview with Rich McLean
by Carolyn Krause

"We identified the issues that utilities individually must address for each of the 118 reactors at 74 different sites across the United States."

Extending the operating life of most of the 118 nuclear power plants operating or expected to be operating in the United States when their 40-year licenses expire is more cost effective than replacing these facilities with plants that operate on coal, biomass, or some other fuel. This was one conclusion of the Draft Generic Environmental Impact Statement that a team of 25 ORNL researchers prepared in 1990–91 for the Nuclear Regulatory Commission (NRC).

The 1500-page, two-volume document examines the environmental and socioeconomic impacts of refurbishing and relicensing aging nuclear power plants for continued operation for another 20 years. It was released by the NRC in August 1991 for comments by the electric utilities, government, regulatory and resource agencies, special interest groups, and members of the public.

Rich McLean of the Energy Division spearheaded the preparation of the document, which involved researchers, editors, and secretaries from six ORNL divisions—Energy, Health and Safety Research, Environmental Sciences, Engineering Technology, Research Reactors, and Engineering Physics and Mathematics divisions—and the Publications Division of Energy Systems. In the following interview with the *Review* editor, he discusses the document.

What are the purposes of the generic environmental impact statement (GEIS)?

One purpose of the document is to help the NRC make informed decisions about renewing the licenses of commercial nuclear power plants. The NRC will use the document when writing regulations pertaining to relicensing. Another purpose is to evaluate the environmental and socioeconomic impacts of extending nuclear plant operation. The utility industry will be affected financially because the NRC will require it to alter the power plants to meet the criteria for license renewal. My feeling is that the utilities are most concerned about economics—the costs of refurbishment and the financial benefits of extending a nuclear power plant's operating life. The public will be affected by the environmental and socioeconomic effects of refurbishing these facilities as well as the impacts of operating them for another 20 years.

How did the ORNL effort contribute to this final rule on renewing licenses of nuclear power plants that the NRC is expected to issue later this year?

In addition to drafting the GEIS, we participated in a public workshop on it November 4 and 5, 1991,

This West Indian manatee and her calf enjoy the environment at Homosassa Springs State Wildlife Park in South Florida. Manatees are rare and endangered marine mammals for whom nuclear power plants make good neighbors. In the winter, many manatees seek out and thrive in the heated water discharged from the Crystal River nuclear power plant, which is 12 miles from the state park. *Photograph by Doug Perrine.*

in Washington, D. C. The purpose of the workshop was to help the public and industry make more informed comments on the document by reviewing all the issues and subject matter. The comment period, which began in August, lasted for 90 days, and the workshop was held midway through this period. About 200 people from state and federal agencies and utilities as well as a few members of the public attended. In general, the document was well received and, as expected, the utilities wanted even more issues dismissed, the state governments expressed concern about on-site waste issues, and the public urged a more vigorous pursuit of alternatives to nuclear power.

In this document, we made recommendations on the level of analysis that should be performed for 104 issues. We identified the issues that utilities individually must address for each of the 118 reactors at 74 different sites across the United States. These recommendations are to be codified in a license renewal rule that the NRC is to issue. Effectively, the NRC will tell each utility which issues it should address and which ones do not need attention at particular plants. Those issues that are dismissed by this rule cannot easily be challenged during the license renewal process.

What are some examples of issues?

An issue is a potential impact, such as the effects of nuclear power plants on fish and other life in lakes and rivers. Issues were categorized as aesthetic effects, human health impacts, socioeconomic impacts, ecological effects, and accidents in which radionuclides are released.

We identified a number of plant-specific issues that need to be addressed. For example, water heated up in the process of cooling a nuclear reactor is discharged to a river and may adversely affect a fishery. The release of thermal effluent by another plant may restrict the recreational use of a cooling impoundment. At another site, power lines from a nuclear power plant could kill an unacceptable

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"Another human health impact not usually mentioned is the possibility of the growth of disease organisms in the warm water of cooling ponds at power plants."

number of birds. The data have not been definitive on the issue of electromagnetic field effects around transmission lines, so we addressed the issue by summarizing these data.

Another more general issue was that license renewal for another 20 years could result in greater impacts when the plant is decommissioned than if it ceases to operate and is decommissioned at the end of the original 40-year license.

What are the aesthetic issues?

Aesthetic issues go beyond the color of the paint on the nuclear power plant. They have to do with perceptions of the nuclear power plant. Some people look at the plant in terms of its potential to hurt them. They worry about an accident that would endanger their families. The plant may arouse feelings of fear or distress. If the plant is a good neighbor with no hint of an accident, employs many people in the community, and provides a tax base that results in good schools and public services, then many people in the community may say, "I like the looks of that plant." The document addresses these types of issues.

What are the most important human health issues of extending the operating life of 40-year-old nuclear power plants?

The normal releases from the currently operating nuclear power plants will not change. We know of no studies that show that these plants pose unacceptable human health risks from normal operation. Evaluations have been done by the NRC on the probability of an accident occurring at each plant. This accident probability is assumed to be the same during the license renewal period. If you assume that an accident will happen, the consequences may be unacceptable. However, the risk associated with the accident may be low. To illustrate this point, if you assume that you will be hit by a car when crossing the street, you would consider that situation unacceptable because you will probably die. But if you couple the likelihood of death from an accident with the probability that an accident will happen, then you will say that crossing the street when a car is approaching at a distance is an acceptable risk. If you look at the risk of a nuclear power plant accident coupled with the probability of a death from it, the risk is usually within society's acceptable range.

Another human health impact not usually mentioned is the possibility of the growth of disease organisms in the warm water of cooling ponds at power plants. These organisms, which are found naturally in shallow ponds and lakes that get quite warm during the summer,

pose a small risk to people who may use cooling ponds for recreational purposes.

What are some socioeconomic issues associated with preparing a nuclear power plant for license renewal?

To be relicensed, a nuclear power plant probably needs to be refurbished. Its worn-out components would be replaced with new ones. In our analysis, we assumed that refurbishment will be accomplished in a series of 3- or 4-month outages starting about 8 years before expiration of the original license. Near the time of license renewal, each plant would have a 9-month outage so that the utility can replace or repair pressure vessels, pumps, valves, controls, turbines, and other system components and refurbish the facility.

The final 9-month refurbishment outage could require about 1000 on-site workers. At the same time, plant refueling and maintenance activities requiring as many as 800 additional workers will be undertaken to prepare for continued plant operation during the license renewal term. The question that must be addressed is whether the presence of these 1800 workers would have unacceptable socioeconomic impacts on the community. Although the workers will bring in money to spend on consumer goods and will pay local taxes, the community will have the burden of providing transportation and public services, such as education and police and fire protection, for inmoving workers and their families. Based on past experiences, host communities will be able to absorb additional project-induced demands for most public services. However, demands for housing and impacts on local transportation networks could be significant at some sites.

How would the environmental impacts of a relicensed nuclear power plant differ from those of the original plant?

The relicensed plants may be safer or at least no less safe because of the refurbishment of the plant and replacement of the parts. New environmental impacts would come from the additional waste storage on-site and construction to provide for it. But, for the most part, the environmental impacts of the relicensed, refurbished plant would be pretty much the same as those of the original facility.

The Draft Generic Environmental Impact Statement says that two issues must be considered at every reactor site. One is the impact on the community of the daily transportation of workers, equipment, and plant components during a year of plant refurbishment. The other is the effect of the nuclear power station on rare and endangered species. Could you give more details on the second issue?

Rare and endangered species are important for many reasons, one of which is that it is a legal issue. Each time a federal action is taken, the effect on rare and endangered species must be addressed. A species at a plant site may have been declared threatened or endangered, or a new species, such as the bald eagle, may move into the area of a nuclear power plant.

For the most part, nuclear facilities have proved to be good neighbors to rare and endangered species. In south Florida, the manatee—a rare and endangered marine mammal—is found at the

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"It is more cost effective to relicense a nuclear power plant than to build a new coal plant."

Crystal River nuclear power plant (see photograph on p. 115). The manatees reside at the plant in the wintertime because of the heated water discharged from it. For the same reason, the Turkey Point nuclear power plant near Miami has become a home for the endangered crocodile.

A negative impact of nuclear power plants on endangered species is the destruction of sea turtles, which drown after being trapped by the water intake screens. The NRC works with utilities to minimize such impacts.

What other issues must be addressed by nuclear power plants?

We categorized the issues as 1, 2, or 3. Of the 104 issues we looked at, we defined 80 as too insignificant to have to be addressed for each site at the time of relicensing. These issues were not of sufficient importance to keep any of the plants from being relicensed. An example of such a category 1 issue is the need for generating capacity. Studies show that nuclear power will be needed by the turn of the century regardless of increases in the use of renewable energy and conservation. Most of the surface water, hydrology, aquatic ecology, and water use issues were category 1.

We identified 22 issues in category 2. These issues, which must be addressed at every reactor site to determine if the impacts fall within acceptable bounds defined in the GEIS, involve small, moderate, or large impacts that may require mitigation. An example in the aquatic ecology area is entrainment and impingement. Two other aquatic ecology issues that must be addressed deal with discharge from plants using either once-through cooling water or cooling ponds. Other category 2 issues include the cost-benefit ratio, conflicting water use, groundwater use and quality (four issues dealing with power plant use of groundwater that could conflict with agricultural use during droughts), use of terrestrial resources, human health concerns (two issues, including disease organisms in cooling ponds), socio-economics (two issues), and solid waste management (two issues).

Category 3 issues include rare and endangered species and transportation during plant refurbishment. Because we couldn't reach a generic conclusion on these issues, we recommended that the NRC and utilities examine them on a site-specific basis.

In what ways is relicensing nuclear power plants more cost effective than building a new coal plant or developing some other energy source? Can you give specific cost comparisons?

It is more cost effective to relicense a nuclear power plant than to build a new

coal plant because the need to pay the large capital cost for a new facility is avoided or at least delayed. Other existing energy sources may cost less than relicensing nuclear plants in specific cases. However, sufficient cost-effective alternatives are not currently available to displace existing nuclear plants as well as supply the additional energy that will be required in the future. Therefore, a cost-effective mix of energy sources must include relicensed nuclear plants.

We have developed many specific cost estimates comparing the relicensing of nuclear plants with other alternatives for producing electricity. We found that the capital cost of refurbishing a nuclear plant so that it can legally operate another 20 years may be only about $600/kW of capacity compared with the capital cost of about $1500/kW for a new coal plant. The fuel and nonfuel operating costs of a relicensed nuclear plant are expected to be very similar to those of a new coal plant. In terms of capital costs, relicensing a nuclear plant would cost more than a conventional oil-fired or gas-fired plant but would have significantly lower fuel costs. In general, of the traditional technologies used to generate electricity, only coal and nuclear energy would have the long-term fuel resources to be viable sources of baseload generation.

Many energy technologies are being studied at ORNL and elsewhere to determine their potential for commercialization. They include wind, solar, and geothermal generation, as well as coal gasification, combined cycle, and fossil-powered fuel cells. The costs of some of these new technologies will tend to decrease as they become commercialized. However, except in the very long term, they are not projected to replace much of the generating capacity expected to be provided by new fossil-fired power plants.

Biographical Sketch

Richard McLean is program manager for the National Environmental Policy Act (NEPA) projects in the Integrated Analysis and Assessment Section of ORNL's Energy Division. He joined the ORNL research staff in 1974, shortly before receiving his Ph.D. degree in marine biology from Florida State University. His work has centered on environmental impact assessment for energy-related technologies, and he is helping to transfer this approach to Third World countries. He was chairman of the NEPA Working Group of the National Association of Environmental Professionals (NAEP) and represents NAEP to the President's Council of Environmental Quality in a national awards program for NEPA excellence. He was recently elected a member of the NAEP's board of directors. He is a founding member of the International Design for Extreme Environments Association, which addresses engineering and environmental problems in polar regions, the deep sea, mines, and space.

What Edwin Abbott Did Not Know about Flatland

By Alan D. Solomon

Imagine living in a world of two, rather than three, dimensions. Edwin Abbott (1838–1926)—a prominent schoolmaster, scholar, and theologian who lived in England—anonymously published a book on this fantasy in 1880. It's called *Flatland, A Romance of Many Dimensions.*

From our three-dimensional perspective, the inhabitants of Flatland appear in a variety of flat geometric shapes, including triangles, circles, and squares. Viewed from their perspective, Flatland was populated by lines of varying lengths and points for very slender people. The book focuses on the impact of a major event in Flatland's history in which a three-dimensional sphere slowly passes through the country, first driving the Flatlanders away from its expanding circular intersection with their world, then slowly retreating back to a point, and finally disappearing. The Flatlanders would view this event as time-related. Abbott seeks to broaden our conception of time by using this physical analogy.

According to Abbott, Flatland was a difficult and dangerous place in which to live. Some of its inhabitants were so thin that, when angry, they could actually run through others, breaking them up into little pieces. Moreover, the Flatland government was highly intolerant of dissenting opinions, jailing the hero of the story for believing that the universe was not really flat.

Thanks to insights by the Dutch mathematician, physicist, and astronomer Christian Huygens (1629–1695), however, we may better understand the intolerance and difficult personalities of Flatland's people. In a series of works, Huygens showed that sound waves in our three-dimensional world move "sharply" through space and time. That is, if we are standing at a distance from the source of a gunshot, for a time we hear nothing. Then we hear a rapid report followed again by silence. Not so in Flatland. Here there would also be silence until the sound of the shot reached us. But forever after that time, we would continue to hear sound arising from the shot—a kind of eternal reverberation. Because our world is full of sound, the result would be a constant background noise of varying volume—perhaps resembling the world of a parent who has bought a very powerful stereo system for his or her teenager—and lasting forever!

Abbott's Flatland *was published in paperback in its fifth edition by Barnes & Noble Books in 1983.*

Further support for the assertion that sound propagation is not "sharp" in two dimensions, as it is in three, arises from the analysis of a particular partial differential equation, the so-called "wave equation," by a number of applied mathematicians over the past 300 years. More generally, for spaces having an even number of dimensions (2, 4, 6,...) sound propagation would not be sharp, while in spaces having an odd number of dimensions (1, 3, 5,...), it would be. Knowing this, perhaps a future visitor to an "Evenland" of an even number of dimensions will find many more interesting things to tell us.

Abbott's *Flatland* was published in paperback in its fifth edition by Barnes & Noble Books in 1983. Those interested in learning more about Huygens' Principle, or sound propagation in general, can turn to the book *Methods of Mathematical Physics*, Vol. II, by R. Courant and D. Hilbert (Interscience Publishers, 1962) or to me for more information. ornl

RE: Awards & Appointments

Stan David

Everett Bloom

John Hayter

Stan David has been appointed a corporate fellow by Martin Marietta Energy Systems, Inc. He has also been named an honorary member of the American Welding Society and the recipient of its 1993 Comfort A. Adams Lecture Award.

Jim Stiegler, former director of the Metals and Ceramics Division, has been named ORNL associate director for Nuclear Technologies, replacing **Alex Zucker,** who has been named special advisor to Martin Marietta Energy Systems, Inc., president Clyde Hopkins.

Douglas F. Craig has been named director of the Metals and Ceramics Division.

Vince Mei was one of 27 international energy experts to participate in a national development seminar in Taiwan to improve the country's power plants, energy conservation technology, transportation, communications, housing, social security, and health benefits.

Everett E. Bloom has been elected a fellow of the American Nuclear Society.

Annetta Watson was presented with the "Outstanding Leader and Advocate Award" by the East Tennessee Chapter of the Association for Women in Science.

Virginia Dale has been named an associate editor of *Environmental Reviews*, a journal of the National Research Council of Canada.

Owen Hoffman has received a letter of commendation from the Colorado Department of Health for his ongoing contributions to the national Health Advisory Panel overseeing the Rocky Flats Toxicologic Review and Dose Reconstruction study.

John Hayter, J. N. Leboeuf, and **Steve Pennycook** have been elected fellows of the American Physical Society.

The **Carbon Dioxide Information Analysis Center** has been named the Data Archive for the Atmospheric Radiation Measurement (ARM) program, DOE's premier global change research effort.

Thomas J. Wilbanks was invited to serve on the Geography Task Force of the National Council on Education Standards and Testing.

Donald Lee has been appointed chairman of the Air and Radiation Management Committee of the Environmental Engineering Division of the American Society of Civil Engineers.

Tom Ashwood has been invited to serve on a Local Government Oversight Committee to provide local input to programs relating to DOE Operations on the Oak Ridge Reservation.

Joseph Herndon has been named DOE's Office of Space representative to the Space Technology Interdependency Group (STIG) for robotics and artificial intelligence.

Bob Lauf, Barbara Hoffheins, Igor Alexeff (ORNL consultant), V. K. Sikka, and **D. O. Hobson** were inducted into the International Hall of Fame of the Inventors Clubs of America.

Allen Croff has been appointed to the newly formed National Academy of Sciences/National Research Council Panel on Separations Technology and Transmutation Systems.

John McCarthy has been appointed to the Scientific Advisory Committee of the United Nations Environmental Program's (UNEP) Marine Mammal Action Program.

Anthony Palumbo coordinated a short course at the 92d general meeting of the American Society for Microbiology.

Steve Lindberg was elected a fellow of the American Association for the Advancement of Science and appointed associate editor of *Environmental Reviews*, a publication of the National Research Council.

J. C. Holloway, Donna Griffith, Marilyn Brown, Ingrid Busch, Patricia Hu, Barbara Hoffheins, Claudette McKamey, Joan Muecke, Elizabeth Dagley, and **Katie Vandergriff** were selected as corporate honorees in the Knoxville YWCA's 1991 YWCA Tribute to Women.

Robert Compton was awarded the Jesse W. Beams Medal by the American Physical Society.

Gloria Mei was named a diplomate of the American Board of Health Physics.

Fran Sharples was named head of the Environmental Analyses Section of ORNL's Environmental Sciences Division.

ORNL's **Graphite Reactor** was recognized as a Nuclear Historic Landmark by the American Nuclear Society. In 1966, it was recognized as a Registered National Historic Landmark.

Emily Copenhaver, Scott Taylor, and **Janet Westbrook** have received TR-3 awards from DOE's Training Resources and Data Exchange (TRADE), an organization dedicated to promoting training techniques.

Norman H. Cutshall has been appointed deputy director of ORNL's Office of Waste Research and Development Programs (OWRDP) and manager of the OWRDP's Office of Technology Development Programs.

Richard McLean has been designated a founding member of the International Design for Extreme Environment Association.

Robert Young and **Po-Yung Lu** have received a letter of commendation from the U.S. Air Force for their work on the *U. S. Air Force Installation Restoration Program Toxicology Guide.*

William Painter has joined the Office of Guest and User Interactions to facilitate and support the cooperative research and development agreement (CRADA) process.

Stephen G. Hildebrand has been appointed associate director of the Environmental Sciences Division.

E. Ward Plummer, an internationally known physicist and professor of physics at the University of Pennsylvania, will be the first Visiting Distinguished Scientist at ORNL and will collaborate with researchers in the Solid State Division.

Mark Reeves has accepted a two-year appointment as manager of the Laboratory-Directed Research and Development Program.

Eric Hirst has been appointed to two committees dealing with energy matters: the Technical Advisory Committee to the Demand-Side Management Training Institute and the Committee on Energy Statistics of the American Statistical Association.

Patrick J. Mulholland received ORNL's 1991 Scientific Achievement Award for his research on the ecology of streams. He has also been appointed by the National Science Foundation to serve on its Special Advisory Panel for Long-Term Ecosystem Research.

Barbara T. Walton was elected secretary of the American Board of Toxicology.

Todd A. Anderson received a Student Presentation Award from the Society of Environmental Toxicology and Chemistry for his presentation entitled "Bioremediation of Surface Soils: A Novel Use of Vegetation."

Tuan Vo-Dinh has been invited to serve as an associate editor of *ANALUSIS*, an international journal of analytical chemistry. He was also selected to chair an international conference in Berlin that addressed toxic chemical monitoring and the human health effects of human exposure to toxic chemicals.

Keith F. Eckerman has been appointed co-chairman of Scientific Committee 57 on the Dosimetry and Metabolism of Radionuclides for the National Council on Radiation Protection and Measurements.

Larry Hawk has been presented the International Hall of Fame's Advanced Technology award by the Inventors Clubs of America for his and co-worker Joe Turner's invention of the Direct Braille Slate, a writing tool for the blind.

Mary Uziel has been presented a Distinguished Service Award by the East Tennessee Chapter of the American Society for Information Science.

Martin L. Grossbeck has been elected a fellow of the American Nuclear Society.

Jacqueline M. Grebmeier has been appointed to serve as a member of the Division of Polar Programs Advisory

Fran Sharples

Norman Cutshall

Steve Hildebrand

Patrick Mulholland

Wilbur Shults

Committee of the National Science Foundation.

Gerald A. Tuskan has been named guest editor for a special issue of the Canadian *Journal of Forest Research*, dedicated to the use of molecular markers in forest tree breeding research.

John S. Wassom has been appointed to a special task group of the International Commission for Protection Against Environmental Mutagens and Carcinogens, which will draft a document on genetic toxicology risk assessment guidelines.

Loucas G. Christophorou and **Lal A. Pinnaduwage** have been presented the Excellence in Research award by the Health and Safety Research Division for their electron attachment research.

Robert L. Atchley has been appointed manager of Fire Protection Operations.

A preliminary report from the U. S. Environmental Protection Agency gives high ratings to the **Environmental Sciences Division's Toxicology Laboratory** for the quality of its toxicity data.

Wilbur D. Shults has been appointed by University of Tennessee Dean Larry Ratner to the Board of Visitors in the university's College of Arts and Sciences.

William C. McWhorter and **Richard E. Ziegler** have been promoted to associate division director and manager of program development, respectively, in ORNL's Applied Technology Division.

Arvid E. Pasto has been promoted to leader of the Ceramics Processing Group in the Metals and Ceramics Division.

Lynn A. Boatner, Brian C. Sales, and **Brian Chakoumakos** won a second-place award in the optical micrographs category at the 94th Annual Meeting of the American Ceramic Society.

Donald R. Stallions has been appointed manager of the Emergency Management Department of the Laboratory Protection Division.

Tammy Prandini McKenzie has been presented with the 1991 Environmental Sciences Division Distinguished Achievement Award for Administrative Support.

Scott McLuckey was named head of the Analytical Spectroscopy Section of the Analytical Chemistry Division.

F. Owen Hoffman has been elected to the National Council on Radiation Protection and Measurement.

James C. Nook has been appointed head of the Research Services East Department within the Plant and Equipment Division.

Steve Sims has been named director of ORNL's Office of Radiation Protection.

Helga Van Miegroet has received the 1992 Distinguished Scientific Achievement Award from the East Tennessee Chapter of American Women in Science.

Curtis Travis directed a North Atlantic Treaty Organization (NATO) workshop on the "Use of Biomarkers in Assessing Health and Impacts of Chemical Pollutants."

Seven Energy Systems entries received awards in the 1992 International Publications Competition of the Society for Technical Communication (STC). **David Feldman** and his colleagues from the University of Tennessee received an award of merit in the category of whole periodicals for *Forum for Applied Research and Public Policy*; **S. Marshall Adams** and **James E. Beck** received an award of distinction in the category of scholarly/professional articles for "Methods for Fish Biology—Chapter 12. Bioenergetics"; **Virginia Dale** received an award of merit in the category of trade/news articles for "Revegetation of Mount St. Helens Debris Avalanche 10 Years Posteruptive"; **Elizabeth S. Martin, Larry H. Bohanan, John Waggoner, Melanie D. Conger, Mike A. Darnell, Ray M. Evans,** and **Ed Aebischer** received an award of excellence in the category of mechanical illustration, line art, black and white, for *3-D Map of the Oak Ridge National Laboratory Facility*; **Anna Fraser, Bert Longmire,** and **Jan Hickman** received an award of achievement in the category of design graphics, posters, for *K-25 Tiger Team*

Activities; **Robert James Zerby** and **Charles Douglas Hochanadel** received an award of achievement in the category of design graphics, presentations, for the *Martin Marietta Energy Systems, Inc., Back School* slide presentation; and **Richard Booker** and **Mitchell Williamson** received an award of achievement in the category of design graphics, exhibits/displays, for *Environmental Sciences Division Monolith.*

Numerous ORNL publications won awards in the Technical Publications and Art Competition sponsored by STC's East Tennessee Chapter. In brochures, an award of merit was given to **Wanda Jackson** and **Mark Spann;** in newsletters, award of excellence, **Charles Reeves, Jr. , Susan E. Hughes, Linda E. Battle, Allyn Zerby,** and **Frances Littleton;** award of merit, **Bill Cabage;** award of achievement, **Carbon Dioxide Information Center, Frederick M. O'Hara, Jr., Frederick W. Stoss, David Fields, Marilyn E. Langston, Information Technology Group, Cheryl A. Koski, Ken Davis, Gloria Glandon, Anne E. Freels, Shelia E. Poligone, Margaret L. Givens,** and **Sandra R. Schwartz;** in organization manuals, award of distinction, **Laura J. Morris, Gay Marie Logsdon, Linda S. Cooper, John Holbrook, Rosemary Adams, Dami Rich,** and **Robert T. Russell;** award of merit, **Gay Marie Logsdon, Waltina L. Lyons, Tina M. Thomas, Joe Rich, John Holbrook, Dami Rich,** and **Rosemary Adams;** in house organs, award of merit, **Judy Wyrick, Gloria Caton, Ceramic Technology for Advanced Heat Engines Program Staff, Tim Ellege,** and **Marilyn E. Langston;** in promotional materials, award of excellence, **Wanda G. Jackson, Berta Swain, Robert A. Eldridge,** and **Lynn Freeny;** award of merit, **Michael R. Aaron, Regina Stinnett,** and **Larry W. Davis;** in periodic activity reports, award of excellence, **Amy L. Harkey, Marsha K. Savage, Lydia S. Corrill, Gay Marie Logsdon, Delores H. Ogle, Karen N. Gibson, Jon Jefferson, Deborah Barnes,** and **Vickie Conner;** award of merit, **Wanda G. Jackson, Walter S. Konsinski, Jr. , Larry W. Davis, Vicky Rolfe, Sandi Lyttle, Darrell C. West, Ann Wilson, Deborah Counce-Brown, Ronald A. Evans, Steve Goodpasture, Richard Grant, Toni G. Jett, Frank Kornegay, Gary W. Snyder, Mark F. Tardiff, Linda Jeffers, Sandi Lyttle, James Mason, Nancy Smith, Thomas Tallant, Vickie Conner, Carol Hodge, Jamie Payne,** and **Leon Smith;** in whole periodicals, award of distinction, **David L. Feldman;** award of merit, **ORNL Editing and Graphics Staff;** in scholarly and professional journals, award of distinction, **S. Marshall Adams** and **James E. Breck;** award of merit, **Barbara T. Walton** and **Todd A. Anderson;** award of achievement, **Charles D. Scott, John E. Mrochek, Martha G. Stewart, Timothy C. Scott, Gordon E. Michaels, Eugene Newman,** and **Milicia Petek;** in trade/news articles, award of distinction, **Virginia H. Dale**; award of excellence, **Janet H. Cushman, Lynn Wright,** and **Linda K. Shaw;** award of merit, **Jon Jefferson, Deborah Barnes, Vickie Conner, Richard B. Gammage, Carolyn Krause, Michael R. Aaron,** and **Cindy Robinson;** in books, award of excellence, **S. Marshall Adams**; in technical reports, award of distinction, **Robert S. Turner, Robert B. Cook, Helga Van Miegroet, Dale W. Johnson, Jerry W. Elwood, Owen P. Bricker, Steven E. Lindberg, George Hornberger, David S. Shriner, Samuel B. McLaughlin, Margaret K. Lyday, W. W. Heck, D. W. Johnson, J. D. Joslin, C. E. Peterson,** and **P. M. Irving;** award of excellence, **Larry Dresner, Sandra Vaughn, ET/FE Publications Office, Brenda Smith, Margaret Boone Nestor, Judy Neely, Phyllis Sumner,** and **Cindy Johnson;** award of merit, **D. K. M. Shum, ET/FE Publications Office, Brenda Smith, Darcus Johnson, Cynthia Southmayd, Evelyn Carver, Cindy Johnson, Margaret Eckerd, Judy Neely, Jane Parrott,** and **Phyllis Sumner;** award of achievement, **Laura M. Yust, Anne E. Adamson, Human Genome Management Information System;** in mechanical illustration, line art, black and white, award of distinction, **Elizabeth S. Martin, Larry H. Bohanan, John Waggoner, Melanie D. Conger, Mike A. Darnell, Ray M. Evans, and Ed Aebischer;** in interpretive illustration, line art, color, award of achievement, **Mark Robbins** and **M. B. Lewis;** interpretative illustration, tone art, color, award of achievement, **Mitchell Williamson** and **Michael Farrell;** in design graphics, brochures, award of merit, **Sandra M. Schwartz**; in design graphics, covers, color, award of excellence, **Vickie Conner, Wanda G. Jackson,** and **Beverly Wilkes;** award of achievement, **Sandra Schwartz** and **Ken S. Davis;** in design graphics, posters, award of distinction, **Anna Fraser, Bert Longmire,** and **Jan Hickman;** award of merit, **Sandra R. Schwartz;** award of achievement, **Sandra R. Schwartz;** in design graphics, presentations, award of excellence, **Robert James Zerby** and **Charles Douglas Hochanadel;** award of achievement, **Mitchell Williamson** and **Uegang Wu;** in design graphics, exhibits/

Tuan Vo-Dinh

Steve Pennycook

displays, award of distinction, **Richard Booker** and **Mitchell Williamson**.

The following ORNL researchers were honored for receiving patents for their innovative developments: **C. V. Thompson** (first patent), **T. N. Tiegs, T. B. Lindemer, C. D. Scott** (fifteenth patent), **C. A. Woodward, C. H. Byers, T. L. White** (first patent), **R. A. Hawsey** (first patent), **T. Vo-Dinh, M. R. Cates, C. T. Liu, V. K. Sikka, L. Maya, K. H. Valentine** (tenth patent), **D. D. Falter** (first patent), **K. G. Falter** (first patent), **T. N. Tiegs, G. F. Dorsey, V. K. Sikka, T. N. Tiegs, T. B. Lindemer, T. L. Ferrell** (first patent), **R. J. Warmack** (first patent), **R. N. Compton, L. Maya** (fifth patent), **R. T. Jubin, J. D. Randolph** (first patent), **M. R. Cates, M. A. Janney, O. O. Omatete** (first patent), **C. C. Tsai** (first patent), **S. M. Gorbatkin** (first patent), **L. A. Berry** (first patent), **W. D. Arnold, Jr., W. D. Bond, R. J. Lauf** (fifth patent), **R. L. Beatty** (tenth patent), **D. P. Stinton, J. C. McLaughlin** (first patent), **R. A. Lowden, C. W. Forsberg,** and **J. W. T. Dabbs.**

Numerous ORNL employees were honored for outstanding accomplishments in research, management, and operational support activities at the annual Martin Marietta Energy Systems Awards Night, held May 29, 1992, in Knoxville. Two ORNL employees singled out for top awards who later received the Jefferson Cup Award at Martin Marietta Honors Night Ceremonies were Inventor of the Year **Tuan Vo-Dinh,** for inventing "the Surface-Enhanced Raman Optical Data Storage System that offers 100 times greater storage density than current compact disk technology and has wide-ranging application in the fields of computing, health care, government, banking, finances, and entertainment"; and Author of the Year **Steve Pennycook,** for detailing "the first comprehensive analysis of Z-contrast electron microscope imaging conditions which demonstrates that 'incoherent' imaging conditions can be obtained by using a high-angle detector."

The top team award went to leader **Ronald D. Kraemer** and team members **Ingrid K. Busch, Susan W. Diegel, Kahra G. Gilley, Ivor Glen Harrison, Michael R. Hilliard, Alton Huntley, Ronald W. Lee, Cheng Liu, Stephen Margle, Irene R. Moisson, Angela K. Sexton, Rajendra S. Solanki, Cynthia L. Terry,** and **Ed P. Tinnel,** for outstanding performance in developing the Airlift Deployment Analysis System (ADANS), which became the exclusive scheduling system used by the Military Airlift Command in Operations Desert Shield and Desert Storm in what has been called the largest airlift in history.

The following ORNL employees received a Technical Achievement Award for excellence of technical contributions involving research, development, engineering, publication, or invention including a development that makes a significant contribution to a mainstream activity of the company; an invention with realized or potential value to Energy Systems, the government, or other commercial clients; and a significant contribution as the author of a publication appearing in periodicals, proceedings, or books: **Barbara R. Beatty,** for notable contributions to the development of one of the most efficient and productive transgenic research facilities in the world; **Henry D. Cochran,** for developing a fundamental theoretical understanding of the structure and properties of solutions in supercritical fluids and creating useful models; **Brian Davison** and **James E. Thompson,** for innovative research leading to the development of the biparticle fluidized-bed bioreactor; **Lawrence Dresner,** for sustained contributions as a leading theorist in applied superconductivity with emphasis on the stability of

superconductors, protection of magnets, and development of cable-in-conduit superconductors; **Brendlyn D. Faison** and **Susan N. Lewis,** for publication of direction-setting research in the biotreatment of waste containing low-level radiation and heavy metals by a novel sorption technique; **G. A. Geist** and **Jack J. Dongarra,** for development of the parallel virtual machine (PVM), a software package that enables distributed computing across heterogeneous networks; **Virginia L. Godfrey, Eugene Rinchik,** and **Liane B. Russell,** for demonstrating the role of the thymus in "educating" T lymphocytes and providing a genetic mouse model for autoimmune diseases; **John A. Harvey,** for leading the team that measured the first non-zero value for the electric polarizability of the neutron; **Michael G. Jenkins, Matt Ferber,** and **Ted Nolan,** for significant materials characterization and analysis contributions to the development and commercialization of a high-performance silicon nitride ceramic; **L. Curt Maxey,** for developing a novel technique for aligning off-axis paraboloid mirrors that dramatically reduces optical component test costs; **Jim A. McEvers, Hugh M. Costello, Karen F. Cutshaw, Shaun S. Gleason, James S. Goddard Jr., Paul H. Hight, David E. McMillan, R. H. Miles, Robert N. Nodine, Paul Rathke, Marc L. Simpson, David H. Thompson, Dale A. Treece, John C. Turner,** and **Kenneth S. Weaver,** for development of a modular, on-line web quality inspection system capable of assessing color registration, color fidelity, presence and size of flaws, image registration, print width, and web width; **Herbert Mook, Jr., Bryan C. Chakoumakos, John A. Harvey, Mark Mostoller,** and **Brian C. Sales,** for observing phonon softening in a high-temperature superconductor through the innovative use of neutron resonant absorption spectroscopy; **Pedro J. Otaduy, C. R. Brittain, N. B. Gove,** and **Luis Rovere,** for development of an expert system–based automatic control system that allows a single operator to manage a three-reactor power block of the Advanced Liquid Metal Reactor; **Steven H. Overbury, Charles C. Havener, Fred W. Meyer,** and **David M. Zehner,** for explaining the extremely fast neutralization that is observed when highly charged ions interact with a solid surface; **Steven J. Pennycook** and **D. E. Jesson,** for establishing the incoherent nature of atomic resolution Z-contrast electron microscope images, thus ensuring direct, interference-free structure determinations; **Larry A. Pierce,** for superior technical support of the Active/Passive Neutron Examination and Assay system; **Lal A. Pinnaduwage** and **Loucas G. Christophorou,** for developing a method for studying and observing the first photoenhanced electron attachment to short-lived excited electronic states of molecules; **Dan Shapira, J. Gomez del Campo** and **Hee Kim,** for developing new techniques to determine the lifetime and volume of the nuclear source of particle emission during nuclear reactions; **Vinod K. Sikka,** for outstanding effort in the development of nickel and iron aluminides and in the identification of commercial applications for them; **Warren G. Sisson,** for exceptional service in the design, fabrication, and implementation of four critical experiments while serving as section quality assurance officer in exemplary fashion; **Audrey Stevens** and **Frank Larimer,** for cloning and sequencing the gene for a growth-regulating enzyme and demonstrating that its integrity is essential for normal cell growth; **Tuan Vo-Dinh,** for inventing the Surface-Enhanced Raman Optical Data Storage System, offering wide-ranging applications in areas demanding greatly enhanced storage capabilities; **Angela B. Walker,** for superior initiative, independence, and technical skills in evaluating ORNL environmental restoration and

Ron Kraemer

waste management needs; **Jack L. Yarber,** for technical support through outstanding, sustained contributions to the operation of plasma-confinement experiments.

ORNL employees who received an Operations and Support Award, which recognizes significant improvements to efficiency, major cost avoidance or cost-reduction efforts, innovations that enhance programmatic operations, and extraordinary personal effort in support of major projects and goals, are **Robert L. Atchley,** for innovative leadership resulting in the most cost-effective fire department with the lowest fire loss ratio in Energy Systems; **Virginia M. Cannon,** for unsurpassed expertise in Energy Systems' policies relating to hiring, termination, and internal payroll status changes; **Aurelia Carter,** for distinguished service to the staff of the Metals and Ceramics Division through enthusiastic cooperation and assistance in division financial planning, internal timekeeping, and cost reporting; **Edward D. Aebischer, Syd Ball, Christopher Bottcher, John Bownds, Bob Dory, David Giles, K. Bruce Jacobson, G. Malcolm Stocks, Michael R. Strayer,** and **Kibbee D. Streetman,** for development of the Saturday Academy of Computing and Mathematics; **Elizabeth L. Dagley, Linda Amburn, Charlene M. Horak,** and **Alan Scott Icenhour,** for superlative leadership in interpreting, developing, and implementing an effective self-assessment program at Oak Ridge National Laboratory; **Nancy Dailey, J. Ken Greer Jr.,** and **David D. Skipper,** for significant achievement in the preparation of Resource Conservation and Recovery Act permit applications and closure plans; **Norma Jean Hensley,** for superior performance as section secretary and for promoting continuity of section business voluntarily during her supervisor's absence; **Robert Mason, Thomas H. Monk, Mark R. Peet, Sharon M. Robinson, Gil W. Sherrill, Warren T. Thompson,** and **John R. Trabalka,** for exceptional commitment in preparing for application of Federal Facilities Agreement requirements to the active Liquid Low-Level Waste System at ORNL; **Donald R. Miller,** for innovative leadership in greatly increasing the quality and efficiency of Instrumentation and Controls Division maintenance at ORNL and in enhancing career development opportunities for a diverse staff; **Mary Anne Sedlmeier,** for outstanding administrative implementation of the new DOE order on occurrence reporting; **Randy M. Walker,** for achieving a turnaround in the effectiveness of the ORNL transportation and packaging function for radioactive waste and other hazardous materials; **Allison Baldwin, Charles R. Boston, Johnnie B. Cannon, Tina C. Curry, Charles W. Hagan, Anthony B. Hopwood,** and **Carolyn H. Krause,** for significant contributions in the preparation of the proposal to site Complex 21 on the Oak Ridge Reservation; **Paula F. Wright,** for administrative support and dedication to Research Reactors Division staff and to the division's missions and goals; **S. D. Wright,** for excellence in administrative support for ORNL and the Analytical Chemistry Division.

The following ORNL managers received a Management Achievement Award for contributions characterized by exemplary performance in leadership, planning, organization, staffing and control functions; achievements in dealing effectively with resource limitations and other constraints, meeting or exceeding schedules, attaining mission goals, training and motivating people, and demonstrating support for company values; or specific accomplishments during the award period or over a long period: **Robert I. Van Hook,** for exemplary achievements in leading ORNL's Environmental Sciences Division in research and operations activities; and **Colin D. West,** for exceptional service as manager of the Advanced Neutron Source Project.

A Community Service Award, which recognizes outstanding and noteworthy performance in voluntary activities of benefit to the community and involving considerable personal time, demonstrated dedication and continuous long-term service, significant contribution to quality of life in the community, demonstrated and recognized leadership abilities or considerable creativity in the initiation and implementation community projects, was given to **G. C. Robinson, Jr.,** for leadership in community service that has opened the doors for many children and families to experience a more meaningful life. ornl

ORNL's SMAC Facility: Improving on Mother Nature

Nature provides us with materials of varying hardness, durability, conductivity, and a range of other traits. When these materials don't meet our needs, we can take advantage of natural chemical interactions to create substances with more desirable characteristics. However, some specialized technical applications require materials having combinations of characteristics that don't occur naturally and can't be created using standard chemical techniques.

Researchers at ORNL's Surface Modification and Characterization Collaborative Research Center (SMAC) specialize in circumventing these limitations by firing beams of ions into or onto the surfaces of a range of targets, altering their physical properties and creating materials that Mother Nature never imagined.

Ion-beam processing is calculated to produce or enhance particular surface characteristics of materials, such as hardness, conductivity, adhesion, or optical properties. "SMAC is concerned with surface modifications, not bulk properties" says Steve Withrow of the Solid State Division. "This type of research enables us to determine which combination of ion species and target material to use to tailor a surface having a particular set of characteristics."

"For instance," says Withrow, "we might want to investigate ways to prevent unwanted chemical reactions, such as corrosion, or improve the ability of a material to speed up a chemical reaction, known as catalysis. Because corrosion and catalysis occur on the surface of materials, they can be influenced by ion-beam processing. Similarly, we could try to reduce the friction between a metal ball bearing and a race (the track the bearing rides in) because friction depends on the surface characteristics of the bearing and the race. These are the kinds of problems we can attack."

SMAC researchers rely on a variety of techniques to achieve surface and near-surface modification of materials. Several of these are described here.

Ion implantation doping is the process of firing charged atoms, or ions, of carefully selected masses and energies at a target, with the goal of embedding these ions in the near-surface layers of the target material. The higher the energy of the ions, the deeper they penetrate, disrupting the normal structure of the target material.

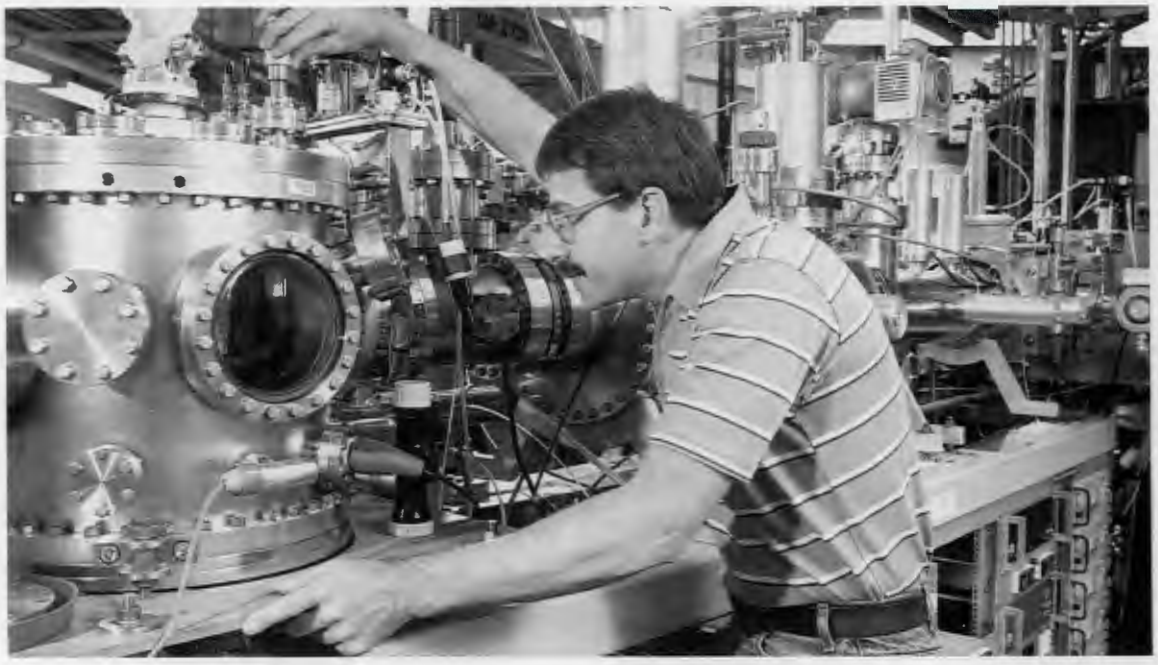
Implantation research at SMAC has resulted in a number of beneficial developments, including a method of increasing the durability of the wear surface of a titanium alloy artificial hip joint. Nitrogen-doping of the wear surfaces of the prosthetic joint reduced corrosion and abrasion by a factor of 1000, extending its life and presumably reducing the likelihood of subsequent hip replacement operations. One project this technique is currently being used for is a study of the structural and electrical properties of implanted diamond, a material which may have applications as a thin-film semiconductor.

Ion beam deposition provides a means of building up layers of isotopically pure thin films on selected surfaces. These films can be used as research samples to study, for example, the migration of one isotope into another during heating. These layered films may ultimately find applications in X-ray optics, semiconductors, and materials requiring high thermal conductivity.

Ion beam mixing involves bombarding a thin film of material deposited on a substrate with ions that deposit most of their energy near the interface between the two materials, causing them to mix. This results in an intermediate layer of material possessing new and often desirable properties. This technique may be used, for instance, to attach a thin metallic film to a semiconducting or ceramic substrate. Mixing the two materials at their interface improves their adherence to one another. Such films could be used for electrical contacts, wear protection, etc.

Ion beam annealing may be used in conjunction with ion implantation doping to undo structural damage in irradiated materials. Annealing is achieved by heating the sample with

"Ion-beam processing is calculated to produce or enhance particular surface characteristics of materials."



Darrell Thomas attaches an electrical connector to the target chamber of SMAC's newest accelerator. Ion-beam processing conducted at SMAC enables researchers to tailor surface characteristics of materials, such as hardness, conductivity, adhesion, or optical properties, to meet specific needs.

a beam of energetic ions, thereby allowing internal stresses built up by the implantation process to be released.

Developing surface modification techniques, however, is only half of SMAC's mission. The other half is the analysis of modified surfaces. The results of ion-beam processing done at SMAC or of other processes that produce near-surface changes in materials can be studied at SMAC using a range of ion beam and surface analytical techniques.

Ion scattering analysis provides a nondestructive, depth-sensitive method of determining the near-surface composition of materials. This technique involves firing hydrogen or helium ions at a target and precisely measuring the angles and energies at which they collide and scatter. The information gained from these collisions enables researchers to construct a picture of the distribution of elements in the surface layer before ion-beam processing and to measure changes in these distributions as a result of processing.

Nuclear reaction analysis is another ion-scattering technique used at SMAC. By selecting an ion species that will undergo a nuclear resonance or possibly a nuclear reaction as a result of a near-head-on collision with an atom in the target, researchers can greatly increase the amount of information gathered from the ion scattering. This technique is useful when normal scattering techniques do not provide enough quantitative information about a particular component of the target because, for example, its concentration is small.

Positive ion channeling, the steering of charged particles between rows of atoms in a crystalline solid, can be used to gauge the perfection of crystal structure, determine the extent of damage to crystal lattice structure caused by ion implantation, locate impurities, and provide a number of other types of information about crystalline samples.

Surface analysis techniques employed at SMAC include several varieties of electron spectroscopy, including low energy electron diffraction and Auger electron spectroscopy. These techniques are primarily used for studying reordered surfaces and crystal growth and for monitoring surface cleanliness.

Computer analysis is also employed to model ion beam interactions with materials, simulate ion scattering, and predict other particle-solid interactions.

Withrow encourages outside users, including industrial, academic, government, or foreign researchers interested in pursuing projects at the SMAC/RC facility to submit research proposals describing the scientific problem to be addressed and estimating the time and support they would require. Nonproprietary use of the facility is free of charge.

"The SMAC facility is highly versatile," says Withrow. "We can implant ions of just about every element on the periodic table at energies from 10 keV to 1 MeV or higher. If there's an element you want to implant, we can probably do it."

Mother would be so proud. ornl

ORNL and ORAU: Partners in Education

As the effectiveness of the country's educational system is regularly being called into question, the Oak Ridge area is emerging as a proving ground for innovative educational strategies and programs. One of the driving forces behind this educational renaissance is the long-standing partnership between ORNL and Oak Ridge Associated Universities (ORAU), which operates the Oak Ridge Institute for Science and Education (ORISE). This partnership can claim a share of the credit for developing in Oak Ridge the largest set of educational programs at a DOE site.

The long-standing science education partnership between ORNL and Oak Ridge Associated Universities has helped establish the Oak Ridge area as a proving ground for innovative educational strategies and programs.

The relationship between these two organizations dates back to the1946 debate over what to do with the Clinton Engineering Laboratories (the forerunner of ORNL), which was built in Oak Ridge for the Manhattan Project. A result of this debate was the formation of the Oak Ridge Institute of Nuclear Studies (ORINS), a consortium of colleges and universities that was to become Oak Ridge Associated Universities. This consortium was formed to promote access to the unique research facilities at Clinton Engineering Laboratories for students and faculty of universities in the region.

Seamless organization. Nearly 50 years later, this ongoing relationship provides a uniquely rich environment for the development of educational programs; however, maintaining this environment requires a high level of cooperation between the two organizations.

"Communication is the key to the relationship," says Wayne Stevenson of ORISE's Science/Engineering Education Division. "Because ORAU is a university consortium, we handle the recruitment and processing of program participants. ORNL is a laboratory, so its staff handles anything related to research. Our staff works with Ed Aebischer's staff in ORNL's Office of Science Education on a daily basis. When Ed and I go to Washington to make presentations to DOE's Office of University and Science Education, we represent a seamless organization—it's not just two groups showing up at the same place and the same time."

"This arrangement is unique in the DOE system," says Aebischer. "We work hard with ORISE to minimize any appearance to partners or participants that we are two different organizations."

The success achieved by this close cooperation has paid off for Oak Ridge as a whole. DOE contractors in Oak Ridge have the largest set of educational programs at any DOE site. "What's happening here is happening throughout DOE," says Chester R. Richmond, director of ORNL's Office of Science Education and External Relations. "Secretary of Energy Watkins has provided strong support for educational activities

"The ORNL research divisions have strongly supported the growth and development of all these educational programs."

and has emphasized education as a primary mission of the department. The reason DOE has looked to Oak Ridge is the combination of resources at ORNL and ORISE and the links that exist between these organizations and other regional institutions, such as the University of Tennessee and the Tennessee Valley Authority."

The partnership between ORNL and ORAU has produced thousands of undergraduate, graduate, postgraduate, and faculty research appointments and internships at ORNL over the years and has greatly enhanced the research base of colleges and universities throughout both the region and the nation. "ORAU is an avenue into the lab largely because of its extensive network into the academic world," says Al Wohlpart, head of ORISE's Science/Engineering Education Division.

DOE's multilevel University-Laboratory Cooperative Science Education Program and two newer national initiatives, the Science and Engineering Research Semester and the Teacher Research Associates Program, are mainstays of DOE's educational effort in Oak Ridge. More recently, increasing emphasis has been placed on the wide range of undergraduate and graduate internship opportunities and on development of a new ORNL Postgraduate Research Program designed to strengthen the vital contribution that postdoctoral appointments make at ORNL. These varied programs provide research and training opportunities at ORNL in disciplines ranging from environmental science to analytical chemistry to genetics research. "The ORNL research divisions have strongly supported the growth and development of all these educational programs," says Aebischer. "The things we do in this office could not happen without the cooperation of the divisions in matching the research interests of the participants with the research needs of the Lab."

These programs give participants the type of research experience that's not available on campus, providing them access to state-of-the-art equipment and enabling them to collaborate with world-class researchers.

Joint projects. The latest trend in joint ORNL-ORAU educational projects has been to broaden their scope to include programs for precollege students and their teachers—from kindergarten through high school. "We're doing a lot more at the beginning stages of the pipeline that ultimately produces scientists and engineers," says Aebischer. "We have more programs at the elementary and secondary levels, both for students and for teachers." Some of these programs are described below.

- The Science and Mathematics Action for Revitalized Teaching (SMART) program was implemented to combine the resources of ORNL, ORAU, and schools in Chattanooga, Roane County, and Harriman to enhance science and mathematics education. These school systems represent very different urban and rural environments and diverse student populations.

  Established in 1989, the SMART program brings teachers together with scientists and technical specialists from ORNL to develop new instructional materials and implement new teaching strategies. To maximize the impact of teacher development activities, a communication network has been established, linking teacher liaisons at each school with each other and with program administrators at ORAU and ORNL. Meetings for teachers in each system are held on a regular basis to allow them to share information and stay informed about SMART activities.

  Over 200 teachers have participated in SMART workshops and training to assess the needs of their education programs over the two years of the program's existence. This ongoing involvement has resulted in system-wide improvements in science and mathematics programs in participating school districts.

- Like SMART, the Teachers Research Associates Program, formerly known as STRIVE, emphasizes helping teachers develop innovative methods of communicating the importance of scientific research to their students. This program gives junior and senior high teachers the opportunity to spend part of their summers as members of research teams at ORNL, ORISE, or one of six other DOE research facilities. A portion of each week is spent exploring ways to incorporate their

research experiences into their teaching activities.

- The Minority Challenge Program promotes interest in science and engineering among junior high and high school students in five counties surrounding Oak Ridge. The program includes career awareness workshops, visits to college and university campuses, summer internships, and a summer science camp where students participate in classes and laboratory experiments.
- Last year's East Tennessee Regional Science Bowl, cosponsored by ORNL, ORAU, and Pellissippi State Technical Community College, drew 26 high school teams from Tennessee and Georgia to vie for the privilege of competing in the National Science Bowl in Washington, D.C.
- Area high school students joined hundreds of college students and faculty members at the third annual Women in Science and Technology Conference. The conference highlighted expanding scientific career opportunities for women in government, medicine, academia, and private industry through lectures and discussions.

These programs and a host of others are a sign of the continually expanding commitment on the part of DOE, ORNL, and ORAU to meet the challenge of providing today's students with the kind of high-quality science education that will allow them to compete and succeed in the world of tomorrow.—*Jim Pearce*

"Adventures in Supercomputing" Program at ORNL

DOE has funded a program to introduce supercomputing concepts into the high school classroom in Tennessee, Iowa, and New Mexico. The new program, "Adventures in Supercomputing" (AiS), is being offered by ORNL; Ames Laboratory, Ames, Iowa; and Sandia National Laboratories, Albuquerque, New Mexico.

Richard Hicks, AiS coordinator for ORNL, said that the response to the program in Tennessee has been tremendous. "We had more than 40 schools across the state apply," Hicks said. "I was pleased with the enthusiasm that all of the teachers expressed about the need for this type of program in Tennessee." A committee composed of Tennessee state officials, educators, and ORNL personnel selected seven high schools from the applicant pool.

AiS is based on a teaching curriculum first developed and tested in Alabama schools. In this successful program, high school students produced computer simulations to study heredity, the aerodynamics of a wind tunnel, the progression of the AIDS virus in a human body, and the thought patterns of a schizophrenic person.

Under the AiS program, participating schools received free loans from DOE of four Macintosh computers, which are networked to a supercomputer manufactured by nCUBE Corporation. The nCUBE supercomputer, which is a multiple-processor, massively parallel supercomputer, is being loaned by nCUBE Corporation of Foster City, California, at no cost to ORNL to implement the AiS program. Bobbi Hazard, vice president of sales for nCUBE Corporation, stressed nCUBE's commitment to education.

"Today's students are the researchers and engineers of tomorrow," Hazard said. "Exposing students to leading-edge technology, which normally is available only to the elite in scientific research and commercial industries, will significantly improve the students' education, and in the long term, the computer industry as a whole."—*Anne E. Armstrong* ornl

Laser Technique Detects Pollutants in Fish

Samuel McKenzie, a physicist in the Health and Safety Research Division, inspects a fish scale before inserting it in the sample chamber for pollutant analysis using two lasers.

Using a laser and a mass spectrometer, ORNL researchers can detect trace pollutants in fish and determine when and where the fish were most exposed to these pollutants. The technique permits scientists to map sources of contamination inexpensively and determine the contamination history of a fish without harming it.

ORNL researchers led by Ed Arakawa, leader of the Physics of Solids and Macromolecules Group in the Health and Safety Research Division, have demonstrated the technique using fish scales from striped bass. They believe they have detected polychlorinated biphenyls (PCBs) in the scales of fish three years old or younger.

"The scales of a fish have annual growth regions like tree rings," says Arakawa. "Thus, we can determine in which seasons and in which years it was exposed to certain pollutants, such as pesticides, mercury and other heavy metals, and PCBs.

"Because we know the local striped bass spend the summer in the Clinch River and the winter in Watts Bar Reservoir and because we can pinpoint when the fish were exposed to certain pollutants, we should be able to determine where contaminants are most concentrated. The fish scales we examined indicated that the fish were exposed to less pollution in the Clinch River than in the Watts Bar Reservoir."

The technique includes the use of laser ablation to vaporize different regions of a fish scale, which is composed of calcium and magnesium. An ultraviolet light from an excimer laser knocks off a few atoms from the fish scale and removes electrons from these atoms, making them positively charged ions. These ions form a beam that is pulled by an electric field into a time-of-flight mass spectrometer.

Because of the different masses of the ions, they slow down at different rates and are detected at different times, permitting identification of the different elements in the fish scale. One of the "peaks" on the mass spectrometer readouts for recent ORNL experiments indicated the strong presence of chlorine. The source of the chlorine, Arakawa says, is probably PCBs.

Chuck Coutant, an expert on the effects of water temperature on fish, proposed the idea of applying the technique to detecting pollutants in the scales of local fish. Coutant and Marshall Adams, both of the Environmental Sciences Division, remove a few scales from striped bass, which are then returned alive to the river, and supply them to Arakawa's

group for study. The original analysis was done by Ida Lee, a postdoctoral scientist; physicist Samuel McKenzie; and Arakawa.

If additional funding can be obtained, McKenzie and his colleagues will use two ultraviolet lasers to extend the technique to detecting pesticides and heavy metals and measuring pollutant concentrations in fish scales. To determine the accuracy of their technique, they will compare their measurements of pollutants in the outer edge of scales of dead fish from the Savannah River Site with the results of analyses of the total content of each fish.—*Carolyn Krause*

New Bioprocessing R&D Center at ORNL

A Bioprocessing Research and Development Center has been established at ORNL in recognition of the increasing importance of biotechnology to the nation's long-term security and economic prosperity. Bioprocessing uses living organisms to produce new products. Results from ORNL's expanded bioprocessing research and development effort will be transferred to the industrial sector to help make the United States more competitive in the marketplace.

Under the new initiative, scientists from ORNL's Chemical Technology Division, supported by the Biology and Environmental Sciences divisions, will develop bioprocesses for energy-related programs and environmental control and will produce a variety of commodity and specialty chemicals.

"The hallmark of our efforts, supported by some 25 years of past experience in bioprocessing research, will be to expand interactions with academia, other national laboratories, and industry," says Chuck Scott, senior corporate fellow and newly appointed director of the center. "Transferring bioprocessing technologies to industry will be the ultimate goal of most of our research and development work."

ORNL scientists will concentrate on bioprocessing systems that can economically produce fuels and chemicals from fossil materials and renewable feedstocks, including recycled waste material such as paper. Researchers also will develop bioprocessing systems to remove and degrade pollutants.

Funding for the center comes from the Department of Energy. Other government agencies benefiting from ORNL's contributions will include the Department of Defense and the Environmental Protection Agency, which need advanced techniques for environmental control technology and waste recycling; the National Institutes of Health, which can use advanced processing techniques to produce therapeutic agents; and the Department of Agriculture, which seeks processes for the small-scale conversion of surplus and waste agricultural products.

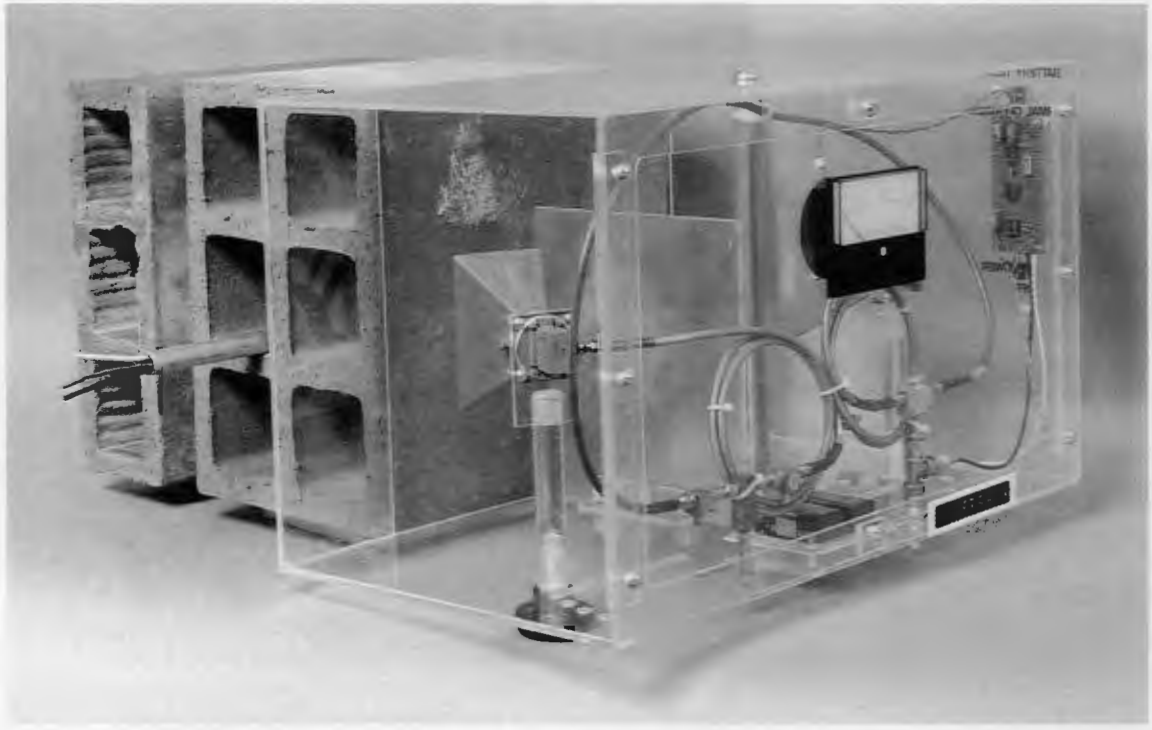
ORNL has established an interlaboratory initiative for bioprocessing research and development with Argonne National Laboratory in Argonne, Illinois; the Idaho National Engineering Laboratory in Idaho Falls, Idaho; and the National Renewable Energy Laboratory in Golden, Colorado. Laboratory scientists will also collaborate with several university laboratories, including the Center for Environmental Biotechnology at the University of Tennessee in Knoxville.

ORNL's achievements in biotechnology over the years include (1) creating advanced techniques for producing liquid and gaseous biofuels to provide alternatives for meeting future energy demands, (2) developing bioreactor systems for producing ethanol and other chemicals, (3) removing nitrates and phenols from industrial wastewaters using microorganisms, and (4) using biological agents to remove hazardous material from polluted soil and groundwater.

Funding for programs within the Bioprocessing Research and Development Center is being provided by several DOE offices, including the Office of Energy Research, the Office of Technical Coordination, the Office of Fossil Energy, and the Office of Industrial Technologies.—*Brian Daly*

"Transferring bioprocessing technologies to industry will be the ultimate goal of most of our research and development work."

"ORNL's wall probe can also be used for inspection of building foundations, concrete walls, bridge pillars, and road surfaces."



The portable microwave wall probe (shown here mounted on a mock wall section) provides a nondestructive method of locating irregularities in walls, such as cracks or variations in internal structures.

Off-the-Wall Idea for Structural Evaluation

Nondestructive evaluation (NDE) of structures, such as walls, bridges, and overpasses, is used to determine how much they deteriorate as they age. Traditionally, techniques such as ultrasonics or radiography have been employed for NDE; however, the limitations of these techniques make them unsuitable for many situations.

Ultrasonic systems can measure the depth or thickness of some materials with high precision, but they require a smooth surface through which to pass sound waves. Radiography using X rays or isotope sources is slow, requires the structure to be unoccupied, and requires access to both sides of the wall. Infrared thermography and ground-penetrating radar have also been applied to NDE, but their drawbacks are low resolution and high cost.

When a group at the Oak Ridge Y-12 Plant began looking for an NDE technique to examine the condition of the hollow clay tile block walls of some of Y-12's older buildings, Don Bible, Carl Sohns, Richard Crutcher, and Randal Maddox, all of ORNL's Instrumentation and Controls Division, came up with the idea of using a low-power microwave probe to do the job.

"DOE officials were concerned about the potential effect of an earthquake on these walls," Bible says. "They knew how the walls were supposed to have been built, and they knew they weren't always built that way. They needed a nondestructive way of getting an internal picture of the walls to locate irregularities. As a result, we began to develop a portable microwave diagnostic probe.

"At first, we tested mockup walls with sophisticated lab equipment and various

microwave frequencies. Then we came up with the idea of transmitting a simple reference signal into the wall at an angle and comparing the wave characteristics of the signal going in with those of the reflected signal coming out."

The microwave signal transmitted into the structure is partially reflected by different layers of materials or irregularities, giving a composite reflection that contains information about each internal layer. This composite signal is considered the "signature" of the structure under test. "Standard" signatures are obtained from structures of known composition that are in good condition.

When the signature of the test structure matches the standard signature, the structure is considered normal. A test signature that differs significantly from the standard may indicate irregularities in composition or it may be a sign of structural deterioration. By varying system parameters, such as the frequency of the microwaves or the separation between transmitting and receiving horns, the system can be customized for a wide variety of structures.

A more rigorous challenge for the microwave probe was a test wall built at the K-25 Site. "The K-25 wall incorporated a lot of irregularities," Bible says. "They filled some blocks with mortar and stuffed paper or rubber gloves into others—anything they could think of that workers might have done while building the walls at Y-12. That's when we decided to use a computer to compare test signatures with an entire set of standard signatures representing a range of possible wall characteristics."

Once tuned for a particular structure, the simple readout eliminates problems of interpretation and allows large areas of a structure to be rapidly examined. Eventually, Bible hopes to incorporate the entire system into a simple, hand-held unit that can be used by individuals with a minimum of training and will display the results of its analysis on a liquid crystal display screen.

The probe can also be used for inspection of building foundations, concrete walls, bridge pillars, and road surfaces and for the location of hidden polyvinylchloride pipes that elude metal detectors. Bible expects that this inexpensive, easy-to-use probe would benefit agencies charged with inspecting and maintaining the nation's infrastructure, allowing limited funds to be used on structures most in need of repair.

—Jim Pearce

Studying Snails and Stream Health

A type of snail that is abundant in most streams in east Tennessee is noticeably absent in contaminated Oak Ridge streams, indicating a significant level of pollution. Such a snail could serve as a sensitive indicator of and contributor to improved water quality in Oak Ridge streams as remediation programs take effect.

These are two conclusions of a recent study by Walter Hill, a research associate in the University of Tennessee's Graduate Program in Ecology, and Arthur Stewart of ORNL's Environmental Sciences Division. These stream ecologists have focused on snails of the family Pleuroceridae and of the genus *Elimia*, which are present in large numbers in freshwater habitats. Such snails are particularly useful as indicators of the presence of contamination.

Elimia snail studies have been funded by Oak Ridge biological monitoring and abatement programs set up to assess the impacts of pollutants on stream life. These programs are required by the National Pollution Discharge Elimination System permits issued to Department of Energy facilities, including those on the Oak Ridge Reservation.

In their paper "Grazers, Periphyton and Toxicant Movement in Streams," Hill and Stewart report that *Elimia* have probably been eliminated from Oak Ridge streams because of pollutants such as polychlorinated biphenyls (PCBs), heavy metals (mercury, cadmium, and chromium), chlorinated drinking water, and once-through cooling water discharges. The absence of *Elimia*, the scientists add, not only makes it difficult to study the indirect biological effects of contamination but may also lead to an increased accumulation of contaminants in fish and other animals higher in the food web.

"Elimia *snails have probably been eliminated from Oak Ridge streams because of pollutants.*"

"In addition to helping scientists monitor stream health, the snail also may help preserve it."

Elimia are individually tagged for mark-release-recapture studies.

The ecologists have used *Elimia* to study growth rates in three streams near ORNL and plan to transfer individually tagged snails to polluted ORNL streams to determine whether decontamination efforts have been successful.

"*Elimia* is the dominant invertebrate in many uncontaminated streams in eastern Tennessee," says Hill. "Several thousand snails can be found per square meter. This snail owes its dominance partly to its thick shell, which protects it from scouring floods and predators such as crayfish and fish."

This type of snail, Stewart says, is well suited for studying the biological effects of toxic materials in streams. It can live in a stream as long as 10 years, permitting extended studies of aquatic conditions. It is sensitive to various toxic substances, and its response can be measured. For example, it responds to toxicants by eating less (reduced feeding rate) and by dispersing in a certain pattern.

"*Elimia* tend to move upstream when water quality is good," Stewart says, "and downstream when water quality is degraded. Because of the large size of the snail, we can determine its rate and direction of movement remotely with a video time-lapse recording."

In addition to helping scientists monitor stream health, the snail also may help preserve it. *Elimia* feed mainly on masses of algae, bacteria, and other organic material that form a slimy film called periphyton. High populations of the snail graze periphyton down to a thin layer, preventing nuisance blooms. Other invertebrate species do not control algal biomass as well as this snail.

"By feeding on periphyton," Hill says, "the snails increase the movement of toxic substances downstream. If periphyton is allowed to flourish, the sticky film will take up many toxicants, slowing their net movement downstream. As a result, biologically available concentrations of toxicants in streams with low populations of *Elimia* snails can remain high, and the toxicants enter the food web more easily."

A recent study showed that the concentrations of mercury, cadmium, and chromium in East Fork Poplar Creek are many times higher in the creek's periphyton than in the water itself. The creek receives discharges from the Y-12 Plant, a nuclear weapons production facility in Oak Ridge.

"The absence of this snail in Oak Ridge streams," Hill says, "probably increases the movement of toxicants into stream food webs. This effect results from the expansion of the periphyton biomass, which accumulates contaminants in greater quantities the more it grows. Soft-bodied grazers that feed on periphyton become more abundant and further concentrate the pollutants, which move into the food web because these species make a good food for fish."

Hill and Stewart see the *Elimia* snail as an example of a sensitive key species whose removal will amplify pollution effects. "As ecotoxicologists," Hill says, "our challenge is to understand and predict the ecological consequences of both direct and indirect effects of pollution."—*Carolyn Krause*

ORNL Contributes to Wetland Management

To help the nation monitor gains and losses in its wetlands, ORNL is playing an important role in designing a program to measure changes in coastal land cover—marshes, swamps, forests, farms, and urban areas—and to provide reliable data on these changes. Two researchers in the Computing and Telecommunications Division at ORNL are working with the National Marine Fisheries Service to develop the CoastWatch Change Analysis Program (C-CAP). Since the early 1980s Jerome Dobson, a senior research staff member, and Edward Bright, a geographic information analyst, have been developing the program, which is supported by the National Oceanic and Atmospheric Administration (NOAA).

A recent proposal to change federal policy to open once-protected wetlands to development angered some environmentalists. The controversy hinged on questions on the definition of wetlands, the role they play in the environment, and the wetland area lost to development or natural changes.

Wetlands are those areas of the landscape where land and water meet. They help to control flooding, purify water, and provide an important habitat for fish and wildlife.

"The pressure to protect wetlands has been growing in concert with the environmental movement," Dobson said. "As a result, several agencies are supporting a national effort to map land cover and detect wetland gains and losses." Mapping will be done with the aid of geographic information systems, satellite and aerial data, and various ground-based data bases.

Dobson said the greatest challenge lies in the sheer size of the effort. "Detecting changes in small areas can be accomplished by making image-to-image comparisons, but detecting changes for areas that cover hundreds or thousands of square kilometers is more difficult," he said. To obtain accurate comparisons, C-CAP researchers first had to develop a consistent method of categorizing land cover (e.g., agree where marshes end and grasslands begin). In September, NOAA, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, and the Environmental Protection Agency agreed on a standardized classification scheme for defining categories of land cover.

For each area being monitored, current and earlier satellite scenes must be selected, and careful attention must be given to cloud cover, tidal stage, and vegetative season. Training samples containing areas of known land cover are selected with the help of wetlands ecologists and regional specialists and are then matched with patterns of light reflected from the known area, as identified through remote sensing by satellites.

Satellite images consist of 30-m^2 rectangles called pixels; data for each pixel indicate the amounts and wavelengths of light reflected from the surface. The type of land cover in each pixel can be determined through statistical analysis comparing unknown pixels with the training samples, Dobson said. "This way we can detect, for example, whether we're looking at an urban area or an agricultural area." He explained that multiple samples of each area are selected to represent each land-cover classification. Then the classified land cover is graphically overlaid on a map.

After initial classifications have been made, the researchers begin tests for reasonableness and consistency. These are accomplished by comparing selected areas with other wetlands data sources and by investigating the appearance of unlikely pixels, such as urban pixels showing up in areas where cities are not known to exist, he explained. "Once we're satisfied with the results for each current scene, we add adjacent scenes to create a single regional data base," Dobson said. "Then we repeat the entire process for the earlier time period based on the same ground control points." He said the process of detecting changes between the two scenes consists of a pixel-by-pixel comparison and the creation of a matrix for recording the changes.

Dobson said no literature previously existed on how to assess error levels for changes from one time period to another. "We brought in the top error-estimation specialists, who came up with a new and clever solution that involved focusing first on the area and then on the classification," he said.

"To help the nation monitor its wetlands, ORNL is helping to design a program to measure changes in coastal land cover and to provide reliable data on these changes."

Although national in scope, C-CAP will be administered as a series of regional efforts with help from state governments and universities. Candidates include Chesapeake Bay, Galveston Bay, Tampa Bay, coastal South Carolina, North Carolina, and Rhode Island. "Selected regions will be monitored every five years, except for areas that have experienced environmental disasters or rapid population growth," he said. "Those will be monitored more frequently."

Dobson believes the methods and technology developed for C-CAP are the same as those needed for global environmental monitoring and modeling. "The same protocols developed for C-CAP
and the care taken in its development are needed for monitoring such problems as deforestation and desertification. The consistent land-cover classifications are especially important to global monitoring, where we encounter very subtle gradients from temperate to tropical vegetative species," Dobson said. "Also, if sea levels begin to rise, the most sensitive indication of these changes will be differences in coastal vegetation."

Accuracy assessments for C-CAP will soon be completed, and Dobson said initial results have been encouraging. "If the results are as good as we expect them to be, C-CAP will provide more than just an effective measurement of changes in coastal wetlands. It will also be an effective tool for analyzing public policy and practices to ensure valuable U.S. wetlands are protected, and it could provide environmental analysts with the means to monitor changes in global environmental conditions."—*Karen Bowdle*

Wireless Robots in Hot Cells

Robots can now move freely in a highly radioactive environment too hazardous for humans, thanks to a new method of wireless communication developed at ORNL. With this invention, engineers in ORNL's Instrumentation and Controls Division have made it possible for untethered robots to operate freely in hot cells used for reprocessing nuclear fuel.

Until recently, wireless communication in large-volume hot cells had been considered impossible because the metal walls of the cell cause electromagnetic echoes, or reflections, that confuse robots. The new method employs directional radio waves of very high frequency to reduce the reflections to an acceptable level. It also eliminates damaged and tangled robot wires.

ORNL engineers have tested the new concept by constructing a Transportable Reflecting Environment Communication System (TRECS). The radio computer system sends signals to the robot's computer, enabling it to perform duties within a cell about the size of a football field.

TRECS' electronics are designed to withstand temperatures up to 60°C (140°F) and doses of gamma radiation up to one million rads (200 rads is considered lethal to humans). Although relatively maintenance-free, the system is designed modularly to facilitate any needed remote maintenance.

Use of this system will eliminate the large cable bundles that would otherwise be required between the walls of the cells and the operating robots. "TRECS has been fully developed and tested and is ready for commercialization," says Steve Schrock of ORNL's Robotics and Process Systems Division. "We expect the system could be adopted for use in hot cells toward the end of this decade."

As part of a DOE cooperative agreement with the French Commissariat a l'Energie Atomique (CEA), French researchers recently tested the TRECS on robotic equipment installed in metal-lined facilities in France. Shrock said the testing was "very successful."—*Brian Daly*

ORNL Produces a New Batch of Research Isotopes

A campaign to produce isotopes of transuranic elements for use in research at DOE laboratories and at other scientific facilities has been successfully completed at ORNL's Radiochemical Engineering Development Center (REDC). This was the first group of such target isotopes

processed since operations resumed in early 1990 at the Laboratory's High Flux Isotope Reactor (HFIR) following a three-year shutdown for procedural reviews.

The REDC is the production, storage, and distribution center for DOE's heavy-element research program. "It is the world's premier facility for such work and the only outlet for many of the heavy elements," said Bob Wham, REDC manager. "To continue advancing our knowledge of heavy elements, there must be basic research. And this center is the ground floor for that basic research."

By manipulating telerobotic arms in a hot cell, Ben Smith remotely works on separating transuranium elements, such as berkelium, californium, einsteinium, and fermium.

Transuranic elements, which are called heavy elements because of their high atomic weight, do not occur naturally on the earth. They are artificially produced by bombarding the nuclei of elements such as americium and curium with neutrons. At ORNL, such radioactive isotopes are produced in the HFIR.

"We have an abundance of requests from the research community for these ORNL-produced elements," Wham said, adding that the temporary shutdown of the HFIR had created somewhat of a backlog. "Laboratories and other facilities that depend on us to supply the material for their research were anxious for us to be back in business."

However, the interim period of the HFIR shutdown was not a time of idleness for the REDC, according to Wham. "The HFIR shutdown actually allowed us time to upgrade our system and to hone our operation so that we can continue to accomplish the goals of our campaigns safely and in compliance with regulations."

Uses for the heavy elements produced during the latest ORNL campaign range from studies in nuclear physics to cancer research. One transuranic element that has multiple applications is californium. The Food and Drug Administration proposes using californium-252 for determining the presence and concentration of sodium in food. The isotope can be used for the simultaneous detection in food of toxic heavy metals, such as arsenic or mercury.

Californium is also part of a technique now being used at several major airports in the United States and Europe to detect hidden explosives in air passengers' luggage. Because it fissions spontaneously and emits neutrons, californium is used by universities as a "substitute reactor." Wham said that students using the element learn how to develop reactor instrumentation and to analyze the spectrum associated with fission without requiring an actual nuclear reactor.

The REDC is operated for production 24 hours a day by members of ORNL's Chemical Technology Division and support personnel from other divisions.—*Wayne Scarbrough*

Global CO_2 Emissions Rise at a Lower Rate

Global carbon dioxide (CO_2) emissions from industrial sources continue to rise but at a lower growth rate than in recent years. According to a special issue of *CDIAC Communications* commemorating the 10th anniversary of ORNL's Carbon Dioxide Information and Analysis Center

(CDIAC), the 1989 estimate for global emissions of carbon represents a 1.2% growth over the 1988 value, "a notable drop from growth rates of the past several years."

The 1989 value for global CO_2 emissions from fossil-fuel consumption, cement manufacturing, and gas flaring is 5.97 gigatons (thousand million metric tons), compared with 5.90 gigatons for 1988. Emissions from the use of natural gas and other gas fuels and from cement production contributed less than 4% to the total carbon emissions for 1989, which was the sixth consecutive year that global CO_2 emissions have increased.

"Issues in data management are now recognized as equally important in understanding global change as the research that produces the data."

In commenting on CDIAC's 10th anniversary, Mike Farrell, former director of the center, writes that, in 1982, he believed that "climate change research was going to be highly theoretical and an area that would never draw much attention from the public." Ten years later, Farrell notes, "global change is the environmental problem of the 1990s and beyond." In fact, Farrell, Paul Kanciruk, and David Reichle, all of ORNL, presented papers at the world's largest conference, the United Nations Conference on Environment and Development (the so-called Earth Summit) in June 1992 in Rio de Janeiro, Brazil.

CDIAC is a data management and distribution center. It develops, collates, and provides extensive quality-assurance audits on data bases that are critical to understanding global change. Future initiatives include developing interactive data-analysis systems using a network of computers dispersed throughout the world.

According to Farrell, recent statements by Allan Bromley, President Bush's science advisor, and the establishment of the Interagency Working Group on Data Management for Global Change under the Committee on Earth and Environmental Sciences umbrella suggest that issues in data management are now "recognized as equally important in understanding global change as the research that produces the data."—*Carolyn Krause*

Broadband Absorber Leaves Optical Systems in the Dark

In precision optical systems, such as telescopes, camera lenses, and test equipment, stray reflected light degrades optical performance. Researchers minimize this light by using optically black (nonreflective) surfaces, such as liners, baffles, and beam stops. Unfortunately, the most common methods of creating optically black surfaces—etching, coating, and anodization (an electrochemical process that produces a layer of oxide on metal surfaces)—all have shortcomings that restrict their usefulness.

Etching decreases reflectivity, but only if the wavelength of the light is smaller than the etched surface features. Anodized and coated materials are also effective optical absorbers, but their light-absorbing surfaces are easily damaged. Anodized beryllium, among the most widely used material for optical absorbers, is too reflective to be used at certain wavelengths, and because beryllium can be toxic, precautions increase processing costs.

To get around these shortcomings, Bob Lauf of ORNL's Metals and Ceramics (M&C) Division and Roland Seals of the Oak Ridge Y-12 Plant's Development Division became interested in creating an absorber that would perform over a broad band of wavelengths and be durable enough to withstand normal handling.

They decided to study the feasibility of creating such a broadband absorber using a composite material known as carbon-bonded carbon fiber (CBCF). CBCF, used commercially as a high-temperature furnace insulator, has also been manufactured by other M&C personnel for use as thermal insulation for radioisotope thermoelectric generators aboard the National Aeronautics and Space Administration's space probe, *Ulysses*. The material is made by mixing a water-based slurry of chopped carbon fibers and a resin binder. The slurry is vacuum-molded, dried, and then heated slowly to melt the resin and bind the fibers together. Finally, the resin is converted to carbon at high temperatures, and the component is machined to its final shape.

Lauf and Seals persuaded Clyde Hamby of the M&C Division to formulate several batches of CBFC with less fiber and more binder, hoping to create a material that was more rugged than standard CBFC. After some tinkering with the recipe, Lauf and Seals found what they were looking for.

The resulting material is uniquely well suited for use as an optical absorber for a variety of reasons. First, because CBCF is a bulk material rather than a surface enhancement or coating, it is optically black throughout, making it immune to

surface damage. Another M&C co-worker, Al Akerman, demonstrated that CBFC can be sanded and machined without losing its light-absorbing properties. It is unaffected by small variations in processing, unlike anodized or vapor-deposited coatings, which are highly sensitive to process variables. In addition, it absorbs light over a much wider spectrum than many standard optical absorbers—up to at least 50 microns, compared with 10 microns for etched beryllium. Also, it is lightweight, easily fabricated into almost any shape, and, because of its low atomic weight, it is highly resistant to radiation and thermal damage.

Bob Lauf examines a variety of CBCF components. Because CBCF is optically black throughout, it is immune to surface damage and can be sanded or machined into almost any shape while still retaining its absorbing properties.

"This is an amazing material," says Lauf. "You can make a big billet of CBCF, machine it to any shape you want, and it's automatically optically black. It's much more robust than any of the competing products. You can cut it, file it, or even machine shapes into its surface. Also, because it's carbon, it's not toxic. And it's pretty cheap as high-tech materials go."

CBCF can be used wherever low reflectivity is needed over a wide range of optical wavelengths. Examples include liners and baffles for telescopes and beam stops for laser equipment. In addition, CBCF can be coated with metal and used as a diffuse-reflectivity standard for calibration and testing of optical equipment. The compound is ideally suited for use in standards and other components that must be handled frequently because its optical properties are not affected by surface contact.

For applications in which greater structural strength is needed, CBCF can easily be bonded to a dense graphite backing. Or, if a combination of reflection and absorption is needed, such as in advanced annular baffle systems used to minimize unwanted light in telescopes, it can be attached to sheets of reflective metal.

"We'd like to develop other spin-offs of this technology, " says Lauf. "Using CBCF as an optical absorber is only the first."

—Jim Pearce ornl

Weld Analysis Advance at the HFIR

"The stresses formed in a complex multipass weld as a result of the welding process have been mapped for the first time by a team of scientists using neutron scattering at ORNL."

Steve Spooner (left), Stan David, and Cam Hubbard observe a welded sample whose residual stresses were characterized using neutron beam scattering. The arrows show the direction in which the neutron beam was passed. These ORNL researchers were members of a team that was first to measure residual stresses in a multipass weld, using a neutron beam from ORNL's High Flux Isotope Reactor.

The stresses formed in a complex multipass weld as a result of the welding process have been mapped for the first time by a team of scientists using neutron scattering at ORNL. A multipass weld is a weld formed by passing a welding instrument several times and adding filler metal between two metallic plates to completely join them together.

Residual stresses are stresses remaining in an object when no external force is applied. Knowledge of residual stresses is very important because when the combination of residual stress and applied stress exceeds the yield stress of a material, the object will likely deform or fail.

Members of the research team are Camden Hubbard, Stan David, and Tad Dodson, all of ORNL's Metals and Ceramics Division; Steve Spooner of the Solid State Division; and three researchers from Chalk River Nuclear Laboratories—J. H. Root, J. M. Holdens, and J. Schroder. The team used a specially modified spectrometer system at the High Flux Isotope Reactor (HFIR), built cooperatively by the Solid State and Metals and Ceramics divisions.

"We have shown that the HFIR is a valuable tool for understanding the magnitude and distribution of residual stresses in a weldment," says Hubbard. "This knowledge is important because large tensile residual stresses may lead to catastrophic failure of a weld in service. Because ORNL has a special X-ray facility, the steady-state neutron source offered by the HFIR, and plans for an Advanced Neutron Source, ORNL has the capability of becoming a 'residual stress center' that can nondestructively determine whether various materials have unacceptable levels of residual stress."

The stresses were mapped by studying how the neutrons from the HFIR were scattered from the atoms in a solid weld metal. The mapping was performed on a 30-cm (12-in.) square welded plate of ferritic steel. The sample consisted of two 1.27 cm (1/2-in.)-thick steel plates welded together using a matching ferritic steel wire and gas tungsten arc welding process. This multipass weld required about 12 welding

passes to completely join the two plates of steel together.

Using neutron scattering, the researchers obtained a three-dimensional map of strains in a series of "volume elements" in the weld, the heat-affected zone, and the base metal of the steel plate. Each volume element was several cubic millimeters. From the measurements of the strains (which extend along the length, width, and height of each volume element), the researchers calculated the residual stresses in each of the three principal directions.

Stresses (or forces) on a crystalline material cause lattice strains. The size of a strain can be determined by measuring the distance between the planes of atoms in the material. In a crystalline material containing residual stresses, compressive stresses cause these distances to decrease, and tensile stresses cause them to increase in comparison with lattice spacings in a stress-free material.

The scientists irradiated the welded sample with a neutron beam having a fixed wavelength of 1.65 angstroms, selected to make the scattering angle 90° for a stress-free ferritic steel sample. However, when residual stresses exist, the separation between the atomic planes is smaller or larger than the separation in the stress-free part of the sample, so the neutrons are scattered at slightly different angles. From the observed diffraction angles, the lattice spacings and, therefore, the strains are determined.

By changing the sample position and using a special detector to accurately count the neutrons scattered at various angles, the researchers obtained a detailed map of residual stresses in the weld sample. The key to their success was the computer-controlled sample stage, beam collimators, and detector attachment added to the existing triple-axis neutron spectrometer at the HFIR. These modifications and this study were made possible by support from the ORNL Director's R&D Fund.

In the experiment on the ferritic steel weld sample, the researchers found large tensile stresses parallel to the weld line in the weld metal and out into the steel plate where the stresses eventually became compressive.

"We found that the tensile stresses approach the yield stress of the material and may nearly exceed this stress in the weld zone," Hubbard says. "If these stresses are not minimized, such welds could show signs of cracking after exposure to applied loads. These residual stresses can be reduced in the weld by post-weld, stress-relief heat treatments. Our ability to map residual stresses in welds will allow us to evaluate the effectiveness of such treatments."

Multipass welds are commonly used in many industries. "Our data," says Hubbard, "will be useful in predicting the properties of multipass welds in ferritic plates and will provide a basis for modeling multipass welds." Hubbard adds that the HFIR instrument could also be used to map residual stresses in industrial objects such as ceramic-coated turbine blades or oil well casings.—*Carolyn Krause*

"The HFIR instrument could also be used to map residual stresses in industrial objects such as ceramic-coated turbine blades or oil well casings."

Book Presents Integrated Forest Study Results

A landmark book edited by an ORNL scientist and a former ORNL staff member contains valuable information for researchers and environmental managers. The new book examines the effects of atmospheric pollutants on forests and their implications for forest management and pollution control. One of its surprising findings suggests that some American forests in the Southeast may be more vulnerable than those in the Northeast to acidity from the atmosphere.

The book *Atmospheric Deposition and Nutrient Cycling in Forests* (Springer-Verlag Publishers, New York, 1992) was edited by Dale W. Johnson, a former ORNL soil scientist now with the Desert Research Institute of the University of Nevada, and by Steven E. Lindberg, leader of the Atmospheric and Geochemical Processes Group of ORNL's Environmental Sciences Division (ESD).

A view of the red spruce research site from the 30-m meteorological tower at an elevation of 1740 m in Great Smoky Mountains National Park. The picture was taken following a winter cloud immersion event, which bathed the trees in frozen cloudwater known to contain elevated concentrations of acidity, sulfur, and nitrogen.

Lindberg was recently elected a fellow of the American Association for the Advancement of Science, which cited him "for outstanding research elucidating mechanisms, pathways, and interactions of atmospheric pollutants in forests and for unique creativity in developing techniques to quantify their biogeochemical cycles." He was the first ORNL scientist specializing in atmospheric and hydrospheric sciences to be named an AAAS fellow.

The book is a detailed synthesis of the recently completed Integrated Forest Study (IFS), which was begun in 1985 and was an interdisciplinary project involving experts in the atmospheric, ecological, and soil sciences. IFS studies were carried out at 17 forest research sites in Canada, Norway, and the United States—specifically, in Tennessee, North Carolina, Georgia, Florida, Maine, New York, and Washington. ORNL scientists designed the project, obtained the funding, and managed the work of more than 50 scientists representing 25 institutions and universities in North America and Europe. The data obtained make possible far-reaching conclusions, the editors say, because all sites were monitored over the same period, using comparable instruments and standardized protocols.

For the first time, the IFS accurately measured the total deposition on forests of both wet and dry pollutants from the atmosphere. The IFS measurements were made using a number of remote, automated collectors and sensors, some of which were developed at ORNL, that took samples either during precipitation or after it stopped; in this way, some of the samplers collected rain, snow, and cloudwater and the others collected only dry pollutants. According to Lindberg, "The IFS estimates of the total atmospheric deposition of acidity far exceed those of the National Atmospheric Deposition Program, which used only rain samplers to collect wet deposition for the National Acidic Precipitation Assessment Program."

The primary goal of the IFS was to determine the effects of atmospheric deposition of sulfur and nitrogen oxides, acidity, and ozone on the movements and availability of nutrients that trees take up from forest soils. These nutrients include nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium.

Ions of some of these nutrients can be replaced at their soil sites by ions from deposited atmospheric acids, making these leached nutrients unavailable to trees as they are washed away in soil water. Another element of interest is aluminum, a toxic metal found in the soil. It can be made available for uptake by trees if the soil

becomes acidified by the deposition of sulfate and nitrate.

"The IFS findings," says Johnson, "could improve the accuracy of forecasts of nutrient deficiencies in forests that may result from atmospheric deposition or harvesting."

Among the important findings of the IFS study are these:

- Atmospheric deposition of acidity, sulfate, and nitrate was greatest at the high-elevation sites affected by cloudwater. It was higher in the southeastern United States (e.g., Smoky Mountains) than in the Northeast (e.g., Whiteface Mountain in New Hampshire). This finding is unexpected and could not have been revealed by traditional bulk collector measurements.

- Except perhaps for mountain forests, acidic deposition combined with ozone exposure is unlikely to cause tree leaves to lose significant amounts of their nutrients.

- Deposition of sulfate and nitrate has increased the rate of nutrient leaching from most of the forest soils at IFS sites by 20 to 60%, making these nutrients unavailable for use by trees and forest vegetation. Levels of potentially toxic aluminum rose in the most acidic soils.

- Atmospheric deposition may have contributed to the declining health of some red spruce stands in the Smoky Mountains, particularly Clingmans Dome, by increasing the leaching of both nitrate and aluminum from the soil. As a result, nitrate levels increase in streams and aluminum becomes more available for uptake by trees (in preference to the nutrient calcium) and for transport to streams, where it can harm fish.

According to the IFS, an Oak Ridge loblolly pine site is considered vulnerable to total nutrient leaching by deposited acids because its highly weathered soils are low in minerals that could neutralize these acids. However, because of the high tolerance of loblolly pine to leached aluminum in soil solution, decline of the loblolly pine forest around Oak Ridge is deemed unlikely.

One of the outside reviewers who praised the book said, "This synthesis has provided convincing evidence of many issues in atmospheric deposition, and it will be an important text for years."

Although completed in 1989, the IFS has resulted in spin-off research projects at ORNL and elsewhere. Sandy McLaughlin of ESD built on IFS findings in his proposal of continued studies of the effects of aluminum and calcium on the physiology of spruce trees in the Smoky Mountains. Helga Van Miegroet and Chuck Garten have received ORNL seed money to use nitrogen isotopes to determine the critical sources and sinks for atmospheric and soil nitrogen in Smoky Mountain forests. Supported by the U.S. Forest Service and the National Park Service, Lindberg and Jim Owens have designed and conducted a study of sulfur deposition on forests at different elevations on Clingmans Dome.

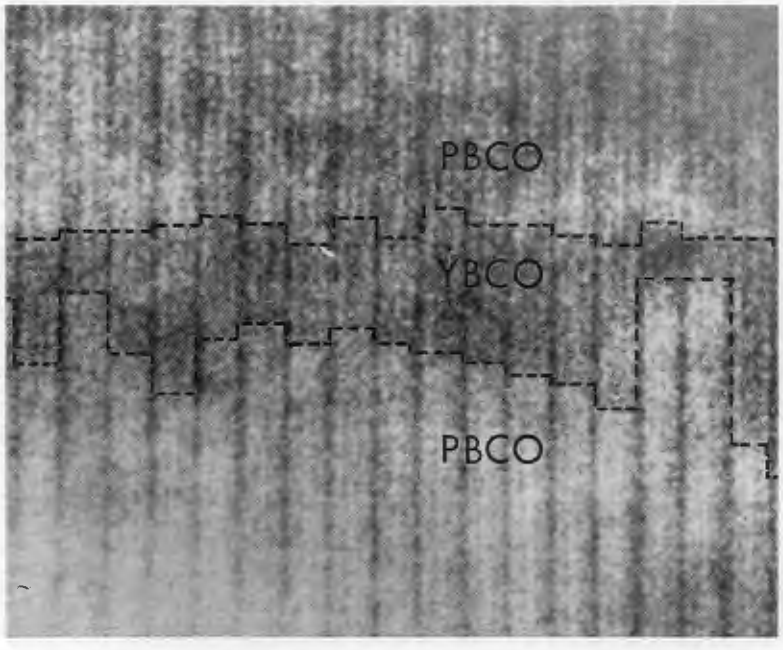
"Because of the IFS findings in the Smokies," says Lindberg, "the National Park Service has committed to establishing a long-term air pollution, water quality, and forest health monitoring study near the IFS site on Clingmans Dome. Clearly, the IFS results continue to influence future research on the effects of air pollution on forests."—*Carolyn Krause*

"Clearly, the IFS results continue to influence future research on the effects of air pollution on forests."

New Electron Microscope Images Show How Superconductors Grow

High-temperature superconductors can be made by using lasers to deposit films on a substrate, one atomic layer at a time. But the ability of the superconductor to carry useful amounts of electrical current depends on its structure, and achieving the best microstructure could require some fine-tuning of the film deposition process.

Steve Pennycook of ORNL's Solid State Division has developed an imaging process using an electron microscope that can reveal in detail how the individual atomic layers of



This micrograph made by Z-contrast electron microscopy provides details on how the individual atomic layers of superconducting and insulating material actually grow. Such information is crucial for researchers trying to make superconducting films that have an improved ability to carry current. Shown here in the outlined darker area is a superconducting layer made of an oxide of yttrium, barium, and copper (YBCO) sandwiched between two insulating layers, composed of an oxide of barium, copper, and the rare earth praseodymium (PBCO). The interface shows the remarkable roughness, on the scale of the individual unit cells (vertical stripes), that developed as a result of rapid deposition.

superconducting and insulating material actually grow. This information is crucial for researchers trying to make superconducting films that have an improved ability to carry current.

Pennycook says his imaging process is the only electron microscopy technique that reveals "the fossil record" of the growth process by which superconducting films are formed. It enabled him to discover that the deposited material forms "islands" that eventually combine into a smooth layer upon which new islands form to make the next layer, and so on. Pennycook reported his findings in an invited talk at the 1992 spring meeting of the Materials Research Society in San Francisco.

"Our technique," he says, "is the only one that shows the size, shape, and rate of growth of the islands. Knowing the details of how these films grow helps us determine and control the microstructure to improve the ability of the film to carry current."

The films are actually "superlattices," alternate layers of superconducting and insulating materials on a magnesium oxide substrate, which serves as a template to properly align the first layer of deposited atoms to obtain the desired microstructure. The superconducting layers are made of an oxide of yttrium, barium, and copper (YBCO). The insulating layer is composed of an oxide of barium, copper, and the rare earth praseodymium.

Pennycook says that an island of YBCO is six atomic layers high, the height of the smallest possible amount of YBCO, known as one unit cell. The typical island is 50 unit cells long. "This material likes to be flat," he says, "and most of its energy is directed toward spreading it out."

Pennycook's special imaging process uses a 100-kilovolt scanning transmission electron microscope (STEM) and a ring-shaped detector to detect electrons scattered at large angles after they penetrate the sample (rather than those passing straight through it). This "Z-contrast" imaging process, which images atoms directly, is so named because atoms having the highest atomic number (number of protons, or Z) scatter more electrons and, therefore, are seen as bright, whereas the lighter atoms are shown as gray or black.

"Z-contrast electron microscopy gives a direct view of materials on an atomic scale," Pennycook says. "It reveals previously unknown atomic arrangements, and the relative brightness of each atomic column indicates composition. It gives us

snapshots of each superconducting layer and can reveal problems in layer structure, such as surface roughness."

Because barium atoms are the heaviest in YBCO, they are bright white in Z-contrast micrographs; however, in images of both the insulating and superconducting layers, praseodymium is the brightest of all imaged atoms because it is the heaviest element present. In some of Pennycook's images, the barium atoms resemble the vertebrae in an X ray of part of a human spinal column. Other images show steps between layers of YBCO unit cells, a record of the presence of islands at that stage of the film's growth.

The details of film growth obtained by Pennycook help Douglas Lowndes and his Solid State Division associates determine how to alter laser ablation to obtain superconducting films that can carry useful amounts of electrical current. Laser ablation is a technique in which bits of superconducting material are evaporated and deposited in a controlled way as a layered film on a substrate.

Pennycook's images indicate whether they should consider changing the oxygen pressure, temperature, and rate of film deposition to improve the film microstructure. "If the material is deposited too fast, there is less time to form islands, and the growth mode changes," Pennycook says. "Increased surface roughness may result, causing short circuits in device structures."

One of the results of the collaboration between Lowndes and Pennycook was the discovery that making a "superlattice" by depositing two layers (instead of one) of a superconducting material between each pair of insulating layers results in a film that is better able to carry electrical current without losing its superconductivity.

Pennycook's imaging capability will improve dramatically later this year with the installation of a newly built 300-kilovolt STEM. This technology will allow him to achieve a resolution of 1.3 angstroms, the highest direct resolution in the world. With his current microscope, he can easily image a YBCO unit cell, which is 12 angstroms high, and a layer of barium atoms, about 2 angstroms high. An angstrom is about one millionth the diameter of a human hair.

With the new capability, Pennycook will obtain sharp images not only of the barium atoms but also of the yttrium and copper atoms in YBCO. He plans also to extend these studies of growth mechanisms to other materials, including semiconductors, metals, and ceramics.—*Carolyn Krause*

ORNL Researchers Cultivate Biomass Energy Program

For thousands of years, trees and grasses have been burned to produce heat. But only recently have scientists recognized that large-scale cultivation of trees and grasses could meet a significant portion of the country's future energy needs.

Growing concern over increased levels of carbon dioxide in the atmosphere, resulting from burning fossil fuels, and their effect on global warming has aroused considerable interest in biomass crops. Janet Cushman, a staff member of ORNL's Environmental Sciences Division and manager of DOE's Biofuels Feedstock Development Program, said when biomass crops are burned for energy, the carbon dioxide produced is merely the recycled carbon dioxide removed from the atmosphere during plant photosynthesis, "a vast improvement over emitting carbon dioxide from fossil stores as you do when coal and oil are burned."

Cushman said biomass is an especially promising option for reducing carbon dioxide emissions from transportation systems because it is the only renewable energy source that can produce liquid fuels, such as methanol and ethanol, for vehicles. "All the others—hydroelectricity, direct solar, geothermal, and wind—produce only electricity or heat," she said. The main obstacle to the widespread use of biomass-derived fuels has been their cost. However, by developing more productive crops and by continuing to decrease production and conversion costs, ORNL researchers believe biomass-derived ethanol costs could be lowered to 60 to 70 cents per gallon within the next 5 to 10 years, a price competitive

"With the new capability, Pennycook will obtain sharp images not only of the barium atoms but also of the yttrium and copper atoms in YBCO."

Helga Van Miegroet, a soil scientist in ORNL's Environmental Sciences Division, samples soil water for nutrients on the Oak Ridge Reservation. She is evaluating four different nitrogen fertilization regimes in a short-rotation sycamore planting to identify the regime that produces the best tree growth.

with $25-per-barrel oil. In this way, biomass fuels could reduce U.S. dependence on unreliable supplies of foreign oil.

Biomass research was first sponsored by DOE after the oil crises of the early 1970s. The original goal of the research was to increase the productivity and lower the cost of growing and harvesting woody plants for energy uses. In 1978, DOE's Biofuels Feedstock Development Program began working with universities and agricultural facilities across the country to identify the tree species most appropriate for biomass fuel crops and to select the types of land most suitable to cultivate those crops. Of 140 tree species screened by 1986, six were targeted as models—poplar, eucalyptus, black locust, sycamore, sweetgum, and silver maple.

Lynn Wright, deputy manager of the Biofuels Feedstock Development Program, said that considerable information about the procedures needed for successful tree farming—site selection and preparation and a variety of weed-control measures—came from this silvicultural research on about 25 species. ORNL has also supported successful research in genetic improvement and tissue culture. "In fact," Cushman said, "essentially all the noncommercial hardwood tissue culture research being done in the United States now is funded through this program."

In 1984 DOE expanded the scope of its energy crop research to include nonwoody, herbaceous plants that could supplement woody crops. Cushman said the original idea was to compare

nonwoody species and to select the best for development. However, the researchers soon realized that different nonwoody species are best for different situations. "A suitable grass crop can be developed for any kind of land that becomes available for energy feedstock production," she said "and grass crops can also be grown and harvested with standard farm equipment, which lowers the cost for interested farmers." Annual crops can be used in rotation with conventional agricultural crops. Perennial crops form dense stands that can protect erosion-prone soils. Legumes can fix nitrogen, reducing fertilizer use. All of these types of crops could have a place in energy production.

After National Energy Strategy activities in 1991, DOE proposed an aggressive biofuels initiative with a goal of having a proven technology for producing ethanol from plants' cellulosic materials—not just the starchy parts of the grain now being used—by the year 2000.

Cushman believes that to arrive at this target, several pilot-scale facilities that process between 40 and 100 tons per day, 300 days per year for 2 years will be needed, so the facilities must be operational no later than 1998. "And if genetically improved trees are to be a part of the project, they must be planted by 1992, since in most parts of the country it takes six years to grow a tree," she said.

"We've received several calls from people interested in biofuels crops. In California there is interest in putting together a consortium of farmers and industries. And in Minnesota, several groups have already been thinking about what it would take to get dedicated energy crop production facilities going," Cushman said. Enthusiasm is clearly building. The next step is to develop the needed support.

Besides the environmental value of carbon dioxide recycling, Wright reported that biomass crops offer other benefits. "A lot of cropland is easily eroded. If we could plant perennial grasses or trees on that land, it would reduce soil loss and at the same time offer an economically viable crop for farmers," Wright said. Biomass crops also offer economic benefits to the United States by reducing dependence on foreign oil and by providing alternative crops that could boost the nation's farm economy.

Wright said it is also important to have a strong scientific understanding of the environmental issues related to biomass crop development. "Of course, environmental issues depend on who you're talking to. If you're from an agricultural background, you want to know that soil productivity can be maintained," she said, noting that some people looking at biomass from an environmental standpoint consider the habitat and biodiversity issues to be most critical. "Some groups are concerned that if new markets are created for agricultural products, additional cropland might be cleared, encroaching into sensitive habitats, like wetlands or stream buffers," she said. To address those issues, such groups as the U.S. Environmental Protection Agency and the Audubon Society are assessing policy options that would encourage environmentally acceptable, large-scale biomass energy systems.

Wright said another environmental concern is the chemicals needed for energy crops, even though they require fewer chemicals than traditional food crops. "The trend is to use fewer chemicals," she said. "We're learning when and how to apply chemicals conservatively—in narrow strips, for example, rather than broadcast over the entire site."

Wright believes the amount of readily available cropland will continue to increase. "Given predictions that in the future more crops will be produced on less land and that export demands will decline, then less land will be needed for food crops," Wright said. "If we can develop fuel crops that produce an average of 10 dry tons per acre, we could ultimately supply half the country's transportation fuel needs on 125 million acres. Although these goals are very optimistic, research could make them achievable within 30 to 40 years."

ORNL researchers make a point of keeping all the groups involved in this research talking to each other. Cushman believes this is one reason the program has been so successful. "Even though most of the crop development research takes place at different universities and agricultural facilities, we feel it's crucial to have a strong central organization that keeps people talking and that

"If we can develop fuel crops that produce an average of 10 dry tons per acre, we could ultimately supply half the country's transportation fuel needs on 125 million acres."

cuts across state, regional, and institutional boundaries," she said. As an example of fruitful interaction, researchers from ORNL and the National Renewable Energy Laboratory of Golden, Colorado, are working together on a project to examine the chemical changes that take place in biomass crops during storage and how these changes might affect the quality of the alcohol produced.

America's farmlands have long been considered the breadbasket of the world. And within the next few years, if ORNL researchers are successful, these farmlands may also become known as an important energy resource for the nation.—*Karen Bowdle*

"The ATF researchers have also made significant contributions to understanding confinement in toroidal plasmas."

ATF Experiment Under Repair

ORNL's Advanced Toroidal Facility (ATF), the world's largest fusion experiment of its type, ceased experiments on November 15, 1991, after nearly four years of operation (and over 20,000 "plasma shots"). The $20-million ATF is a stellarator, which, along with the better-known tokamak, belongs to the family of toroidal (doughnut-shaped) confinement devices that dominate modern controlled fusion research.

Fusion energy is produced by fusing high-energy nuclei of hydrogen isotopes. Magnetic fields can be used to confine these nuclei in a hot ionized gas, or plasma. In this way, loss of plasma energy to the vessel wall is substantially reduced. It is predicted that an improved toroidal device that effectively confines a fusion plasma could lead to a practical source of electricity by the middle of the next century.

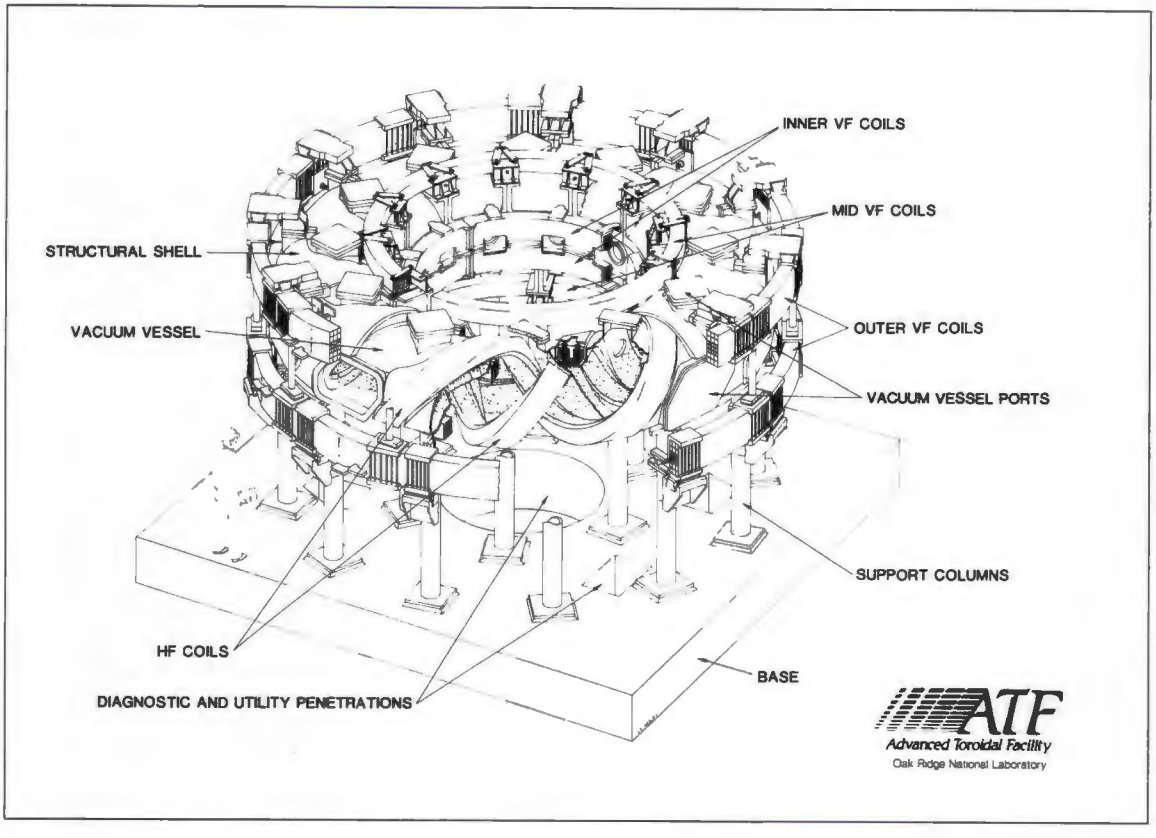
The ATF stellarator (shown in the figure) uses helical windings to create the magnetic field that contains and stabilizes the plasma used in experiments; the circular coils position and shape the plasma. By contrast, for plasma confinement the tokamak requires a plasma current that must be driven for steady-state operation. Other comparably sized stellarators operate in Germany, Japan, and Ukraine. (For background information on the ATF and magnetic fusion research at ORNL, see the Number Four, 1987, issue of the *Review*.)

Since it started operation in January 1988, the ATF has had a distinguished history. The ATF's unique design allowed creation of a wide range of plasma configurations for study of fundamental physics issues relevant to both tokamaks and stellarators.

During the first year, ATF researchers studied a regime of plasma operation that has the potential for confining plasma having more energy content for a longer time at a given magnetic field strength. An unexpected magnetic field perturbation had allowed access to this "second-stability" regime at much lower power than had been otherwise needed.

After compensating for this field perturbation, ATF researchers studied other basic confinement physics issues including the "bootstrap current," an internal self-generated current in toroidal plasmas that must be maximized in tokamaks and minimized in stellarators for optimum performance. The ATF group found that its experimental measurements of this current agreed with theoretically predicted values, giving confidence that the bootstrap current can be used for optimizing future tokamak and stellarator designs.

The ATF researchers have also made significant contributions to understanding confinement in toroidal plasmas. Comparison of measured fluctuations in the edge-plasma parameters in the ATF and in a comparably sized tokamak allowed researchers to gain a better understanding of the role of these fluctuations in causing deterioration in plasma confinement. These studies have been extended to the plasma core in the ATF in a collaborative experiment between ORNL scientists and researchers from the Institute of General Physics in Moscow. Results of preliminary analyses show evidence of a particular plasma instability that was sought in this experiment. Throughout its history, the ATF program has featured collaborations of this type with U.S. universities and fusion laboratories in Japan, Spain, Russia, Ukraine, and Germany.



Schematic of the Advanced Toroidal Facility.

Although the ATF was developed as an experiment to test optimization principles and steady-state operation, budget restrictions have prevented the ORNL stellarator from reaching its full potential. A DOE decision in late 1990 to focus on tokamaks altered the ATF research program and resulted in operation of the ATF at a reduced level in fiscal year 1991 and a plan to mothball it in fiscal year 1992.

At the end of May 1991, an electrical short caused extensive damage to part of one of the large helical windings shown in the schematic above. A limited repair was implemented, and the ATF resumed operation on September 25, making it possible for the ATF group to accomplish most of the goals planned for the summer of 1991.

The ATF is currently being repaired to preserve the option of restarting the ATF program. In addition, the ATF group hopes to double the plasma heating on the ATF and to extend operation to the long-pulse, steady-state regime for which the device was designed. Whether this restart occurs depends on a review of the U.S. fusion program strategy now under way. Encouraging support from the U.S. fusion community and from DOE gives reason for optimism that the ATF program will restart in 1993.—*James F. Lyon, ORNL's Fusion Energy Division*

ORNL Wins Four R&D 100 Awards

In the fall of 1992, four ORNL developments received R&D 100 Awards from *Research & Development* magazine. The magazine's editors selected these developments to be on their list of the top 100 new technology advances in the world.

The winning entries were ion implantation to produce hard-surfaced polymers, a method of accurately blending new compounds with ozone-depleting chlorofluorocarbons (CFCs) in air conditioners and refrigeration units to cut down on the use of CFCs, the surface-enhanced Raman optical data storage system, and a computer technology for identifying the genes in sequences of genetic information.

Since 1967 when the Laboratory first entered the competition, ORNL has received 69 R&D 100 Awards (originally called I•R 100 Awards) and Energy Systems has received 79, placing Oak Ridge first among DOE sites in this competition.

John Henry could have been a polymer-drivin' man. According to song and story, America's hammer-swinging, spike-pounding railroad builder, John Henry, was a "steel-drivin' man." Of course, that's only because he didn't have the benefit of recent developments at ORNL's Triple Ion Irradiation Facility (TIF). If he had, he might have traded in his steel spikes for a set made of ion-implanted Kapton, a light, durable polymer with a surface that is three times as hard as stainless steel.

Created using TIF's three accelerators, this potentially revolutionary material, along with other "hard-surfaced" polymers, is the brainchild of Eal Lee, Monty Lewis, and Lou Mansur, researchers in ORNL's Metals and Ceramics Division. Polymers are chemical "strings," or linear combinations of repeating molecules used in a variety of products, from soft drink bottles to machine gears.

Most ion-beam surface modification research has been aimed at improving the physical characteristics of semiconductors, metals and ceramics to broaden their applications. The use of polymers in severe environments has been limited by their inherent softness and poor resistance to wear, abrasion, and other factors. Researchers hope to overcome these traditional weaknesses by using ion implantation to combine the most useful features of polymers, such as light weight, flexibility, and corrosion resistance, with the hardness of metals and ceramics.

To accomplish this, ORNL researchers are trying to increase the number of bonds between molecules by firing new atoms in the form of positive ions into the polymer's molecular matrix. The new structures created through this process couldn't be achieved using traditional polymer processing techniques because they don't rely on normal chemical reactions; instead, the ions are wedged into the polymers' molecular structure by sheer force. "The ability to create new materials that cannot be synthesized by conventional chemical means," says Mansur, "opens up entirely new areas of materials science and engineering."

This violent union produces new materials, often having physical properties far different from those of the original polymers. "Part of our work is looking at the atomic and molecular basis of the changes in the properties of these materials," says Lee. "Another part is applying what we've learned."

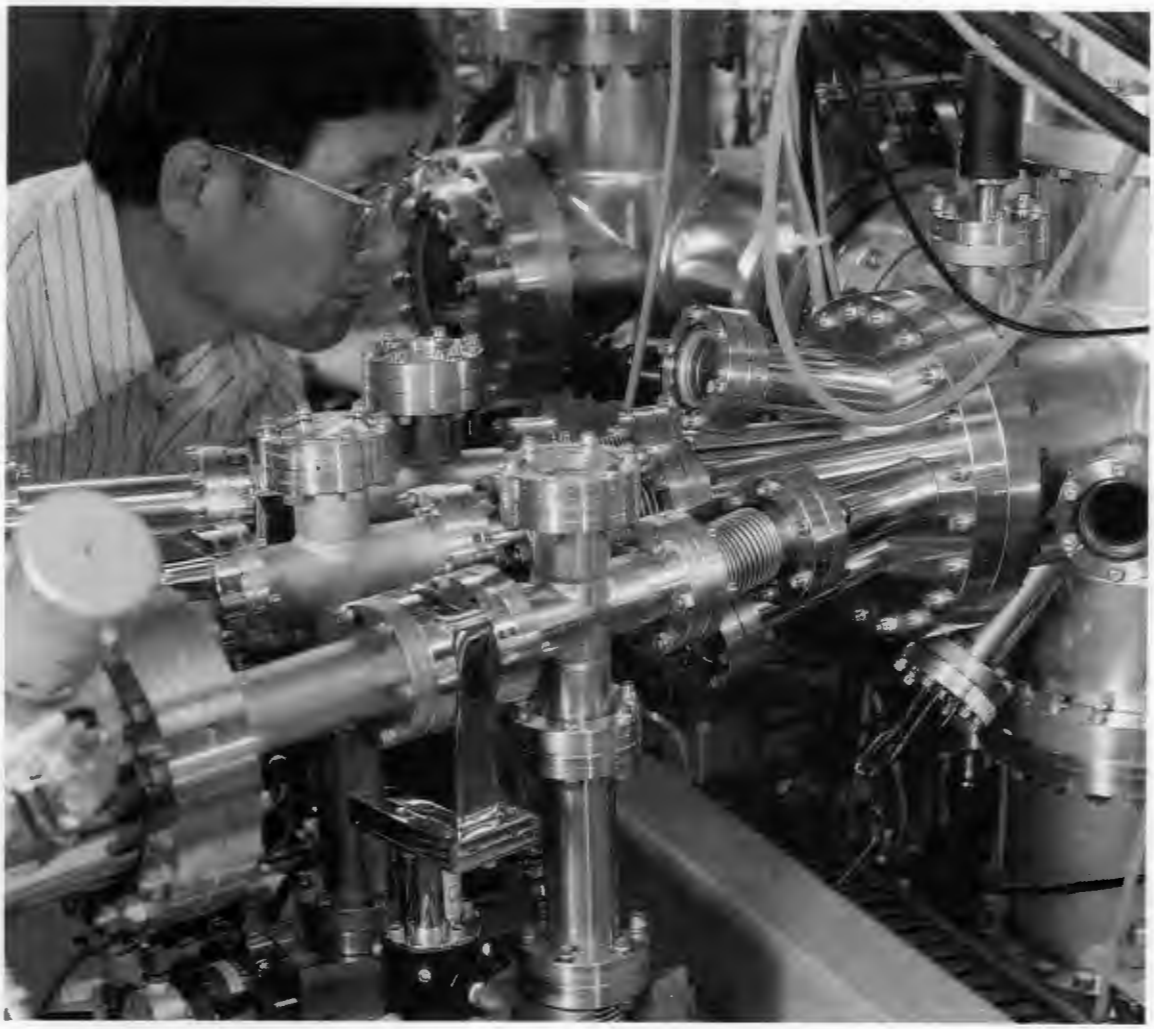
During the studies, polymers are implanted with boron, carbon, silicon, and iron ions by the TIF facility's three accelerators using either single beams or two or three beams simultaneously. The use of multiple beams produces reactions not only between the beams and the target, but also between the ion species of the beams themselves. This approach yields different, and in some cases better, results than using the three beams separately.

To determine the effect of the ion treatments, the implanted materials are analyzed using a number of techniques, including microscopic methods, hardness and wear testing, X-ray analysis, and Raman spectroscopy.

The primary effect of high-energy ion-beam processing on polymers is to produce materials having an increased number of interconnections between molecules in all three dimensions. This increased molecular interaction often results in several enhanced surface features, such as

Hardness. Depending on the type of ion beams used, ion implantation studies at ORNL have produced polymers that are 13 to 41 times as hard as their untreated counterparts.

Wear resistance. Improvement of wear resistance varies with the polymer-ion beam combination used. The most impressive increase in wear



Eal Lee peers into the Triple Ion Irradiation Facility's target chamber where as many as three ion beams are simultaneously focused on a polymer target. This process inserts new atoms into the polymer's molecular matrix, creating materials that cannot be made using conventional chemical means.

resistance resulted when samples of Kapton were treated with single or multiple beams of boron, nitrogen, and carbon ions. These samples showed no signs of wear in abrasion tests with a nylon ball; tests with a chromium-steel ball produced a high degree of wear on the ball and scratches on the polymer surface.

Surface smoothness. Ion-beam treatment generally produced a much smoother surface when compared optically with an untreated surface.

Oxidation resistance. When exposed to an oxygen plasma, untreated Kapton lost six times as much material to oxidation as ion-beam-treated Kapton.

Chemical resistance. Untreated samples of Lexan and polystyrene dissolve in benzene, but treated samples do not.

Conductivity. Implanting certain polymers with metal ions increased their electrical conductivity by a factor of 10^{10}.

Wear-resistant polymers could be used to manufacture high-speed moving parts and lightweight, load-bearing components. Polymer

films can be applied to any surface and ion-beam treated, producing hard, wear-resistant protective coatings. Ion beam processing also improves resistance to oxidation and chemical attack, suggesting that hard-surfaced polymers may be useful in low-earth orbit, where atomic oxygen severely erodes traditional polymers.

An important finding of the project is that the degree of molecular interaction of the treated polymers is closely correlated with their hardness, indicating that ion implantation has increased the carbon content of the backbones of the polymer molecules, producing a more rigid structure. Spectrographic analysis of the samples confirmed that ion-beam treatment increases the number of new bonds between molecules. Because the degree of hardness is dependent upon the type of ions implanted, new types of bonding, not present in the untreated material, are thought to play an important role in increasing hardness.

Currently, ion-implanted polymers are still considered high-tech materials, and their cost of production is too high for the mass market. This will limit initial applications to high-value-added products and critical components; however, costs could come down as demand increases.

Other technologies, such as oxide coating and mineral treatments have been used in the past to improve the surface properties of polymers, and more recently, ultraviolet-cured, scratch-resistant polymers have come onto the market. However, no commercially available product comes close to the hardness achieved by ion-beam processing at ORNL.

Now, just imagine what Paul Bunyan could have done with a hard-surfaced polymer axe....

CFC/HFC ratiometer eases move to ozone-friendly coolants. Chlorofluorocarbons, or CFCs, are gaseous compounds commonly used in automotive, industrial, and residential air conditioning and refrigeration systems. When CFCs are released or leak from these systems, some of them eventually make their way into the upper atmosphere, where they break down the layer of ozone that screens out sunlight's ultraviolet rays. Overexposure to these rays is linked to a variety of ailments, including skin cancer.

To combat the problem of ozone depletion, beginning in 1993, the use and production of CFCs in the U.S. will be drastically curtailed. The good news is that researchers have found ozone-safe substitutes for CFCs. The bad news is that these chlorine-free replacement gases, called hydrofluorocarbons (HFCs), aren't compatible with the existing systems, so they can be used only in new ones.

So, what can be done with existing systems when they need to be recharged with refrigerant? Well, the good news is that several mixtures of HFCs and CFCs have been developed that are both easier on the ozone than CFCs alone and compatible with existing systems. Since CFC/HFC blends are being developed for use in automobile air conditioners over the next few years, it will become increasingly important to identify the kinds of refrigerant used because charging these devices with the wrong kind of refrigerant could cause irreversible damage. Also, the refrigerants must be mixed at specific ratios to function effectively. Unfortunately, some compounds in the mixture are more likely to leak from the system than others. So, the bad news is that, in order to get the correct mixture, either the ratio of gases present in the system must be known *before* it is recharged, or the refrigerant must be replaced entirely.

Traditional methods of determining this ratio include analyzing a sample of the system's contents in a gas chromatograph or an infrared spectrometer. However, the high cost of this equipment and the need for specially trained operators rule these options out for most air conditioning or refrigeration repair contractors. To make this capability more widely accessible, Fang Chen of ORNL's Energy Division and Steve Allman and Winston Chen, both of the Health and Safety Research Division, have developed a CFC/HFC ratiometer, which is capable of identifying the refrigerants present in a given sample and determining the concentration of each component when mixtures are used.

This instrument takes advantage of differences in the electron drift velocities of different gas

mixtures in an electric field. That is, under certain conditions electrons travel much more rapidly through some gases than others—at a characteristic rate for each gas. To determine the drift rate for a particular mixture of gases, a sample is drawn into the ratiometer, where an electric field is applied to the mixture. Then a flash from an ultraviolet light source causes a beryllium plate to produce low-energy electrons to drift a known distance across an electric field.

"Depending on the blend of materials," says Chen, "the speed of the electrons will be retarded by a given amount compared to electrons moving through air." The ratiometer then compares these data to that gathered from analyses of known gas mixtures to determine the composition of the sample.

Fang Chen demonstrates the CFC/HCF ratiometer, a device which may ease the transition from the ozone-depleting chloroflurocarbons used in most air conditioning and refrigeration units to environmentally safer coolant blends.

"We envision that the final product will be a briefcase-sized device that is lightweight, relatively inexpensive—about $1000— and easily used by an auto mechanic or refrigeration technician," says Chen. "And because this instrument is designed specifically for refrigerants, results can be obtained immediately without complex data analysis."

SERODS could hold 18,000 encyclopedias on a CD. The surface-enhanced Raman optical data storage (SERODS) technology, which was developed by Tuan Vo-Dinh of ORNL's Health and Safety Research Division and David L. Stokes, a University of Tennessee graduate student, may have large computer memory applications. It is based on the recently discovered principle that the enhanced light-emitting properties of certain molecules embedded in an optical medium can be altered at the molecular level to store information.

The SERODS system can achieve 1 terabyte (10^{12} bytes) of storage capacity in a 12-in. disk, thus achieving about 100 times greater storage capacity than other conventional optical storage systems. For example, a 12-inch SERODS disk could store 18,000 sets of the *Encyclopedia Britannica*, or 450 million pages of text.

Several organizations in both government and private industry have expressed interest and are pursuing licensing agreements for using SERODS technology for supercomputer memories, health care (e.g., medical data banks for hospitals and medical imaging), space satellite data storage for global environmental studies, integrated data

The surface-enhanced Raman optical data storage (SERODS) system, developed by Tuan Vo-Dinh (left) and David L. Stokes, achieves about 100 times the storage capacity of conventional optical storage systems. A 12-inch SERODS disk can store 450 million pages of text.

storage systems for "paperless" navy ships, and entertainment (optical disks for movie rental companies).

"The ORNL system could be used for virtually any activity requiring large-memory data storage," Vo-Dinh said. "Examples are archive storage for the insurance industry, data banks for financial firms and banks, global data storage for the proposed U.S. orbiting space laboratory of the National Aeronautics and Space Administration, optical archives for the Library of Congress, and DNA information storage for the Human Genome Project."

SERODS is the only system available that offers three-dimensional data storage for replacing conventional two-dimensional disk surfaces, thus greatly increasing data storage capacity. It also provides protection for sensitive and proprietary information because such data can be accessed only if the frequency of the vibrating molecules used for the optical layer is known.

The SERODS system uses a writing laser, a reading laser, a photometric detector, and an optical disk or a three-dimensional multilayer optical storage medium. A sample SERODS optical disk contains a plastic or glass substrate covered with silver-coated polystyrene microspheres and an optical layer containing light-emitting molecules. When they are close to such a surface, molecules in the optical layer interact with its microstructures, causing the molecules to scatter more and emit what is known as surface-enhanced Raman light.

A writing laser is used to encode bit information by altering the light-emitting properties of specific clusters of molecules on the disk while leaving other molecules intact. A reading laser excites all the molecules in the optical layer, inducing specific microregions of the disk to produce altered light signals and unaltered signals that correspond with "one" bits and "zero" bits, respectively. A photometric detector tuned to the frequency of the Raman emissions is used to retrieve the stored information (for details, see "Technical Highlights," *ORNL Review*, Vol. 23, No. 1, 1990, p. 85).

GRAIL separates genetic wheat from chaff. In ancient times, kernels of wheat for making flour were gathered by hand—a slow and inefficient process. Then, an innovative approach was developed. First, the grain was crushed to loosen the kernels of wheat from their husks, or chaff. Then this mixture of wheat and chaff was thrown into the air. The slightest breeze would blow the light chaff to the side, and the heavier wheat would fall down in a pile.

Genetic researchers face a similar dilemma as they try to separate areas of biologically relevant information from the rest of the sequence of DNA bases that makes up the human genome. What makes their job even more difficult is that about 95% of the genetic information they look at is chaff. Only 3–5% of the DNA bases contain instructions for manufacturing proteins, the molecules that govern the chemical processes necessary for life.

Not surprisingly, developing the technology to locate genes in DNA sequences is a primary goal of DOE's Human Genome Project. This challenge

has been largely met by ORNL researchers through the construction of the Gene Recognition and Analysis Internet Link (GRAIL) system. Ed Uberbacher, Reinhold Mann, and Ralph Einstein of the Engineering Physics and Mathematics Division and Richard Mural and Xiaojun Guan of the Biology Division have integrated biological insight about genes and the proteins they code for into this state-of-the-art, computer-based artificial intelligence system.

Richard Mural and Ed Uberbacher work at a GRAIL terminal. The system employs neural networks to simulate the function of neurons in the brain as it "learns" to recognize the characteristics of genes in a DNA sequence.

Using neural networks, which simulate the function of neurons in the brain, and other intelligent machine principles being developed at ORNL's Center for Engineering Systems Advanced Research, GRAIL "learns" to recognize the characteristics of genes in a DNA sequence. Combining the information it gathers from examining known genes with biological knowledge provided to it, GRAIL develops principles that it uses to locate new genes. Each party contributes expertise in this partnership between human and machine, resulting in new insights into the problem of gene recognition.

The system is already being used to analyze the DNA sequence for the genes responsible for Huntington's chorea, various muscular dystrophies, and a number of other genetic diseases. Once the gene or genes responsible for a particular disease have been located and analyzed, the potential exists for the development of genetic screening tests for prospective parents and prenatal diagnosis of the disease. The degree to which these relevant portions of the genome can be identified and understood will largely determine whether knowledge of the human genome can be applied to problems in biotechnology, gene therapy, and the development of pharmaceuticals—technologies which are based on the manipulation of genes and their protein products.

About 400 biotechnology companies and research laboratories currently use GRAIL to analyze DNA sequences, primarily to locate genes that may play a role in human disease or have applications in medicine, biotechnology, or pharmaceuticals. In the long term, it is likely that gene therapies or cures for some of the thousands of genetic diseases that affect humans will be developed from genetic insights provided by GRAIL. ornl

ORNL Expertise Used in 30 CRADAs

Maureen Baker counts the number of Chinese hamster ovary cells that survived exposure to sparked sulfur hexafluoride (SF_6), a commonly used insulating gas. By combining biological testing with chemical analysis, ORNL researchers determined that disulfur decafluoride, which is formed in sparked SF_6, is responsible for the toxicity of the sparked gas.

In the two years since August 1990, Energy Systems has entered into 37 cooperative research and development agreements (CRADAs). Of these, 30 take advantage of ORNL expertise.

CRADAs are designed to foster cooperative research between industry and government laboratories by offering private firms advantageous rights to patents and other intellectual property from the joint research, trade-secret-like protection of joint data, and streamlined government approval of the agreement.

Several of the CRADAs not previously highlighted in the *Review* are described on the following pages.

Study of toxic by-product in insulating gas. The significance of the presence of an extremely toxic by-product in an electrical insulating gas, which was first revealed by ORNL studies, is the subject of a CRADA signed by Energy Systems in October 1991. The toxic compound formed by electrical decomposition in sulfur hexafluoride (SF_6)—an insulating gas used in circuit breakers, transformers, switchgear, and underground electrical transmission lines—is being studied under a CRADA involving ORNL, the National Institute of Standards and Technology (NIST), and Ontario Hydro (a Canadian electric power utility).

The compound, disulfur decafluoride (S_2F_{10}), was found to be toxic in cell cultures grown at ORNL, was shown to cause lung damage in animals, and is believed to cause lung damage in humans. Exposure to decomposed SF_6 can be hazardous to human health, as indicated in the September-October 1991 issue of *Electrical Review*. In an article entitled "JET Workers Lucky To Be Alive," it was reported that two men who had been exposed to decomposed SF_6 at the Joint European Torus, a fusion research facility in England, developed pulmonary edema. The compound or compounds responsible for this effect were not unequivocally identified.

ORNL research participants in the CRADA are Isidor Sauers and Guy Griffin, both of the Health and Safety Research Division, and Randy James, who is providing technical program management through the Power Systems Technology Program in the Energy Division. Sauers, who was the first to measure the amount of S_2F_{10} produced in a given volume of SF_6, will develop a sensitive method employing cryogenic enrichment–gas chromatography techniques for detecting low levels of the toxic compound in SF_6. (Sauers has also collaborated with NIST in developing another sensitive technique, using gas chromatography–mass spectrometry, that measures constituents of gases at parts-per-billion levels.) Griffin, the first to show that the toxicity of sparked SF_6 was chiefly a result of the presence of S_2F_{10}, will further study the gaseous by-product's toxicity.

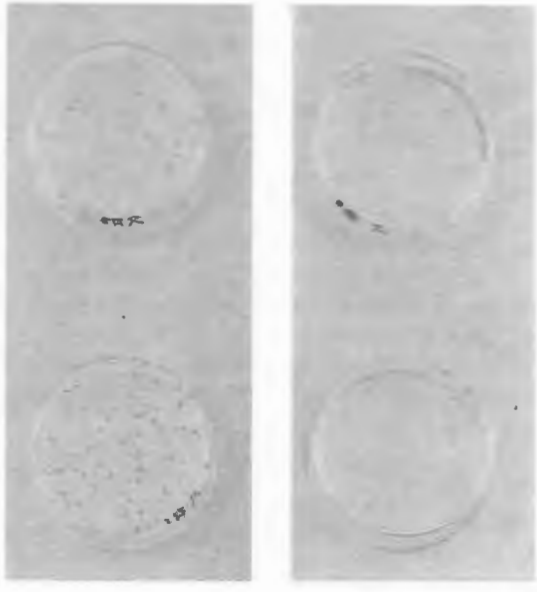
"Although S_2F_{10} has been found in the laboratory, we do not know if it exists in actual power equipment," James says. "Utilities, government agencies, and manufacturers are interested in the results of this CRADA because the safe operation and maintenance of circuit breakers and other electrical equipment using SF_6 are important to them."

In a recent talk, Griffin said, "Our biological testing led us to discover the presence of S_2F_{10} in SF_6. In 1980 I exposed Chinese hamster lung cells and Chinese hamster ovary cells to sparked SF_6 and found that 86% of them died. Then I exposed them to SF_6 alone and known by-products of electrical discharges in SF_6, such as SOF_2, SOF_4, SO_2F_2, and SO_2, and discovered that none of these products singly or in combination with the others was as toxic as sparked SF_6.

"This finding suggested that an unknown by-product was responsible for the toxicity. So in 1985–86 Isidor Sauers worked on identifying the toxic product. When we found that heating a sample of sparked SF_6 eliminated its toxicity, we had indirect evidence of the presence of S_2F_{10} because S_2F_{10} decomposes upon heating, whereas most of the other breakdown products of SF_6 are stable at temperatures below about 300°C.

"Using the techniques of gas chromatography," Griffin added, "Sauers detected a significant amount of S_2F_{10}—about 260 parts per million—in a sample of sparked SF_6. Our later biological studies showed that S_2F_{10} is orders of magnitude more toxic than the other by-products in sparked SF_6."

The goals of the CRADA are to (1) study the formation and destruction mechanisms of S_2F_{10}, its stability, thermal and chemical properties, and its toxicity under a variety of conditions; (2) develop sensitive techniques to detect the toxic compound in amounts as small as 10 parts per billion, the maximum permitted by the Occupational Safety and Health Administration (OSHA), in a large amount of SF_6; (3) review gas-handling techniques and perform field sampling; (4) if necessary, develop an absorbent or some other way to remove S_2F_{10} from SF_6 when the insulating gas is withdrawn from electrical equipment during repairs; and (5) disseminate information and transfer relevant technology. OSHA has delayed enforcement of the 10-parts-per-billion S_2F_{10} ceiling limit until a suitable detection method is developed, tested, and approved.



In the control experiment (left), most Chinese hamster ovary cells survived exposure to sulfur hexafluoride, but virtually none survived exposure to disulfur decafluoride, a decomposition product of sparked sulfur hexafluoride.

"Although S_2F_{10} has been found in the laboratory, we do not know if it exists in actual power equipment."

The CRADA project will receive $1.8 million over three years from the DOE Office of Energy Management, the Electric Power Research Institute, Ontario Hydro, Empire State Electric Energy Research Corporation, and the Canadian Electrical Association. The Bonneville Power Administration and the Tennessee Valley Authority will also contribute funds, although they were not signatories to the CRADA.

Packaging for thin-film batteries. Under a CRADA, ORNL and the Eveready Battery Company of Westlake, Ohio, are developing a method for packaging rechargeable thin-film lithium batteries. These batteries, which are as

"Eventually, thin-film technology will make possible the development of batteries as small as the period at the end of this sentence."

small as shirt buttons and thinner than plastic wrap, must be sealed to protect them from air.

Eveready has been developing a 2.5-V solid-state, thin-film rechargeable lithium battery, and recently ORNL developed its own rechargeable 3.7-V thin-film lithium battery. The ORNL and Eveready batteries have several potential applications as miniature power supplies for microelectronics, including miniature sensors and micromotors. (For details on the ORNL development, see the article "Thin Films for Advanced Batteries" on p. 46 in this issue.)

"Our goal is to develop a microbattery that could be fabricated directly onto a computer memory chip to preserve information in the event of a power failure," says John Bates, principal investigator for the CRADA and leader of the Ceramic Thin Films Group of ORNL's Solid State Division. "But before the thin-film battery is ready for commercialization, we must develop a protective thin-film coating."

Under a CRADA signed in March 1992 by Eveready and Martin Marietta Energy Systems, Inc., the two organizations will develop a thin-film technique to seal the batteries and protect them from exposure to air. Currently, the batteries must be stored in a protective argon atmosphere to prevent corrosion of the lithium film. A successful packaging technology will make possible the rapid commercialization of the ORNL and Eveready thin-film batteries.

Bates and his colleagues—Nancy Dudney, Greg Gruzalski, and Chris Luck, researchers in the Solid State Division—have been developing a rechargeable thin-film battery that could be fabricated directly onto a chip or its package. Currently, nonrechargeable batteries much larger than the chips are used to prevent loss of data during power failures and must be added to circuits as separate components. A thin-film battery could be incorporated directly into the integrated circuit of a computer memory chip during its manufacture.

To make its thin-film batteries, the ORNL group uses special equipment to deposit one layer of material at a time on a ceramic or glass surface, called a substrate. The first layer, made of noncrystalline vanadium oxide, forms the positively charged electrode, or cathode. The second layer is the electrolyte, a new material discovered by the group in 1991 and called lithium phosphorous oxynitride. The electrolyte conducts lithium ions and separates the electrodes between which electrons flow in an external circuit, providing needed electrical energy. The third and top layer deposited is lithium, which forms the negatively charged electrode, or anode.

The ORNL group will work with the Eveready Battery Company, which uses lithium for the anode but different materials for the cathode and electrolyte. The researchers will deposit protective layers on test cells supplied by Eveready. The procedure will allow the battery to be sealed in place on, for example, a carrier for a computer memory chip.

"We will work with Eveready on determining which thin-film material or combination of materials could best seal up the battery without altering the properties of the films," Bates says. He predicts the group will develop a self-contained thin-film battery of more than 3.5 volts during 1992. "Eventually," he says, "thin-film technology will make possible the development of batteries as small as the period at the end of this sentence."

Computer images and geographic data for characterizing environmental conditions. ORNL researchers are working under a CRADA with staff from the Vitro Corporation of Silver Spring, Maryland, on the application of ORNL-developed computer software to the remediation of environmental problems. The CRADA partners will use commercial systems and Geographic Information Systems (GIS) software developed at ORNL to aid in site characterization and remediation studies. The long-term goal is to design, construct, and apply advanced GIS technology to support environmental assessment and restoration.

GIS software is a computer tool to aid in the management, analysis, and display of geographic and environmental data. Environmental measurement data (e.g., concentrations of groundwater contaminants) are combined with spatial information provided by maps of land

surface and subsurface features, aerial photography, and remotely sensed imagery to help assess the geographic extent, characteristics, and distribution of waste material.

For example, a study of groundwater contaminant plumes, surface hydrology and drainage, and thermal imagery for seeps and springs may reveal potential pathways by which pollutants might migrate into nearby streams and rivers.

Results can be presented as two- or three-dimensional displays to help develop insights and remedy environmental problems and to provide managers with decision support tools to help justify and plan remediation actions. The principal investigators for the CRADA at ORNL are Richard Durfee and Jerry Dobson, both of the Computing and Telecommunications Division, in cooperation with the Environmental Sciences Division. DOE funds in the partnership are being provided by the Environmental Restoration and Waste Management Program.

Richard Durfee uses Geographic Information Systems software developed at ORNL to examine data on groundwater contamination and movement to characterize subsurface conditions within hazardous waste areas.

"The long-term goal is to design, construct, and apply advanced GIS technology to support environmental assessment and restoration."

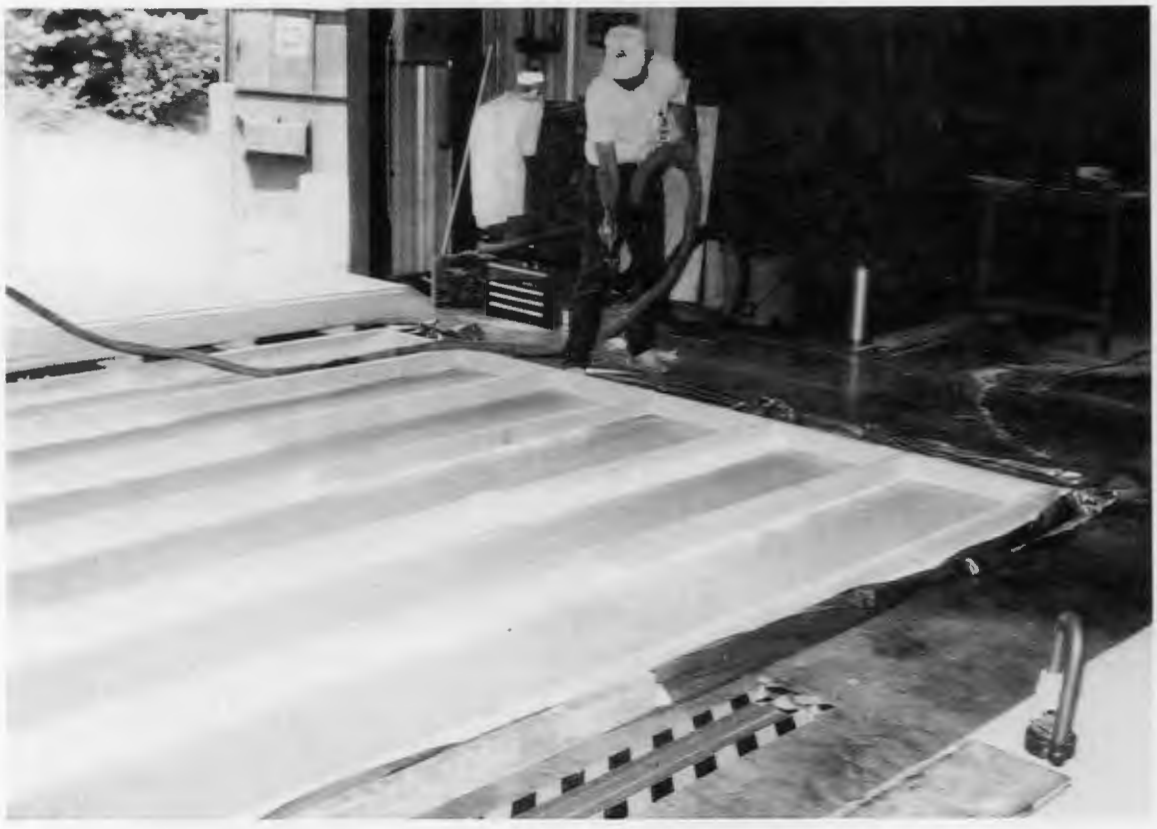
Vitro Corporation, which is owned by Penn Central Corporation, provides software engineering and systems integration support at various military installations. The first phase of the GIS effort will focus on site characterization for a Navy facility in Washington state. Later phases will develop and test advanced GIS concepts in a network-based architecture. Such GIS technologies will be important in guiding the cleanup of hundreds of military sites, at a cost as high as $200 billion, by early in the next century.

Microwave sintering of capacitors. ORNL and AVX Tantalum Corporation of Biddeford, Maine, are collaborating under a CRADA in developing a method for manufacturing tantalum capacitors—electrical components used in cardiac pacemakers, electronic devices for the U.S. armed forces, and other applications requiring very high reliability. Microwave furnaces at ORNL and the Oak Ridge Y-12 Plant will be used for sintering the capacitors' tantalum anodes under various conditions. The goal is to heat powdered tantalum to a rigid yet porous state.

The expected results of the CRADA partnership are improvements in the quality and reliability of tantalum capacitors, which are desired by the AVX Tantalum Corporation, and a demonstration that microwave sintering can have industrial applications, which is important for the technology transfer efforts of ORNL and the Y-12 Plant.

AVX Tantalum Corporation manufactures tantalum capacitors by conventional vacuum sintering. Microwave sintering is being tested to determine if it can surpass the conventional technique by removing surface impurities from the tantalum particles, thereby improving the quality of the dielectric film, reducing cycle time, tightening process control, and increasing total capacitance.

Research is under way at ORNL to identify and explain the physical changes in materials as they are heated by microwaves. Observations of the



A Foamseal technician constructs a polyurethane-adhered roof assembly for thermal testing in ORNL's Large-Scale Climate Simulator.

surface chemistry and morphology of processed tantalum capacitors may give ORNL researchers fundamental insights into the actual mechanisms by which microwave sintering alters a material's properties. The principal investigator of the CRADA at ORNL is Robert Lauf of the Metals and Ceramics Division.

Thermal performance of ceiling panels. ORNL's Energy Division and the Urethane Technology Division of Foamseal, Inc., are working together under a CRADA to measure the thermal performance of ceiling panels used in the construction of manufactured housing. The panels, which use a polyurethane adhesive manufactured by Foamseal, were tested in the Large-Scale Climate Simulator of the Roof Research Center, a DOE user facility at ORNL.

The goal of the CRADA is to help Foamseal improve its ceiling panels so that they more effectively prevent heat from escaping houses in winter and from entering them in summer. The CRADA will help DOE's Building Thermal Envelope Systems and Materials Program meet its goals and increase industrial use of the Roof Research Center.

Two test ceiling panels were constructed by attaching dry wall to ceiling joists. One panel used mechanical fasteners, and the other used Foamseal's polyurethane adhesive for the attachment. These two panels were tested at three different temperature conditions in the Large-Scale Climate Simulator.

The heat flow measured on the panel using urethane foam was about 10.5% lower than that measured on the panel using conventional mechanical fasteners. The measured thermal resistance of the panel using urethane foam was 13.3± 0.4% higher than that measured on the panel using mechanical fasteners.

"The foam adhesive offers an insulating benefit," says Jeff Christian of the Energy Division, one of the principal investigators for the CRADA. The other ORNL investigators are Ken Wilkes and Phil Childs, both of the Energy Division.

Thermal performance of roof insulation. ORNL's Energy Division, the Society of the Plastics Industry, and the Polyisocyanurate Insulation Manufacturers Association are collaborating under a CRADA. Their goal is to determine the thermal performance of experimental foam insulation boardstock produced by U.S. insulation manufacturers.

ORNL's Roof Research Center is being used to conduct thermal testing and determine the relative aging characteristics of ozone-safe roof insulation. The foam contains hydrochlorofluorocarbons (HCFCs), which do not persist nearly as long in the stratosphere as chlorofluorocarbons (CFCs).

One outcome of this work may be an improved HCFC-blown roofing insulation that is nearly as efficient in its thermal performance as CFC insulation. As a result, it may be possible to accelerate the elimination of CFC insulation for roofs and help preserve the stratospheric ozone layer that protects humans from hazardous solar radiation.

A second major outcome is the development of a procedure to accelerate the thermal aging process of these foams so that the long-term resistance to heat flow (R value) of these HFC-blown closed-cell foam insulations can be predicted. These foams lose some of their thermal resistance as a result of the diffusion of air into the foam and the diffusion of the blowing agent out of the foam. An accurate estimation of the lifetime R-value of these foam insulations will provide a benchmark for developing even better insulations.

The principal investigators from ORNL for this CRADA are Ron Graves of the Metals and Ceramics Division and Jeff Christian, George Courville, and Randy Linkous, all of the Energy Division.

Heat transfer studies of Kalina power cycle systems. ORNL and Exergy, Inc., of Hayward, California, are working together under a CRADA to improve the design of condenser-absorbers for generating electricity using a Kalina power cycle. Kalina power cycles, which use working fluid mixtures such as ammonia and water, will be more efficient than conventional steam power systems and can be used with a variety of energy sources, such as fossil, nuclear, solar, and geothermal energy.

"The Kalina power cycle system is like a refrigerator working in reverse," says Fang Chen, ORNL's principal investigator for the CRADA and a member of the Energy Division. "Instead of using electricity to make it work as a refrigerator, the device uses a refrigerant for converting heat into electricity in the same way as water is used to make steam to drive a turbine. The Kalina power cycle is more efficient than the steam power cycle because the working fluid boils and condenses at a variable temperature whereas water in a steam cycle boils and condenses at a constant temperature."

ORNL researchers from the Energy and Engineering Technology divisions are conducting heat transfer tests of ammonia-water mixtures under various conditions of a Kalina power cycle. They use condenser-absorber tubes supplied by Exergy for the condensing heat transfer tests.

The researchers will determine the effects of ammonia-water film condensation at various thicknesses on the heat transfer of tube surfaces under various conditions of the Kalina power cycle. The results of the tests will be used to develop an engineering design data base to improve the design and development of cost-effective condenser-absorbers for Kalina power cycle systems. This project is a part of the Thermal Sciences Program of DOE's Office of Industrial Technologies.

Development of radiation detector. ORNL and Pellissippi International, Inc. (PI), of Knoxville have signed a CRADA to develop a new type of radiation detector.

ORNL scientists will conduct research and design studies for a dosimeter that, for the first time, could detect neutrons through optical imaging of charged-particle tracks in a gas. As

"ORNL scientists will conduct research and design studies for a dosimeter that, for the first time, could detect neutrons through optical imaging of charged-particle tracks in a gas."

part of an anticipated two-year joint effort, PI will develop a prototype optical detector chamber to which ORNL will have access for research.

Neutron measurements are required for personnel protection at facilities where this radiation occurs. An improved radiation detector employing this latest technique could monitor neutron radiation levels more accurately and provide additional information beyond existing capabilities. If successful, the new cooperative research also could open new avenues of research in radiation physics.

James E. Turner and Robert N. Hamm, both of ORNL's Health and Safety Research Division, developed the optical detector in collaboration with former staff members Scott R. Hunter, G. Samuel Hurst, and Harvel A.Wright. For the idea, the group was awarded a patent, which has been assigned to PI. The work there is being coordinated by Hunter and PI's president, William A. Gibson.

The research is being sponsored by DOE's Office of Health and Environmental Research and the National Cancer Institute.

CRADA with Detroit Diesel on Ceramic Engine Parts

Energy Systems and Detroit Diesel Corporation have signed a CRADA for developing advanced technology and manufacturing practices to machine and inspect ceramic components used in heavy-duty diesel engines. Detroit Diesel has become a leading manufacturer of such engines and has been responsible for such innovations as the electronically-timed unit fuel injector.

The CRADA was signed in Detroit Diesel Corporation's headquarters by Roger Penske, chairman and chief executive officer of Detroit Diesel, and William W. Carpenter, Energy Systems vice president for Technology Transfer. The signing was witnessed by Richard A. Claytor, Assistant Secretary for Defense Programs, U.S. Department of Energy.

The research effort will rely on the expertise of DOE's Oak Ridge Y-12 Plant in precision machining, developed from manufacturing components for nuclear weapons, and ORNL's expertise in advanced materials. These capabilities are being combined in the recently established Ceramic Manufacturability Center jointly funded by DOE's Conservation and Renewable Energy and Defense Programs offices.

"This collaboration in the field of precision machining of ceramics parts is in the middle of one of our fields of expertise," Carpenter said. "That a large manufacturer of diesel engines is willing to collaborate with us in this field is a testament of great value to us. We intend to use our expertise to assist Detroit Diesel in its commercial quests. We both can benefit greatly."

Objectives of the project include improving the accuracy and consistency of critical dimensions on ceramic components such as diesel engine fire decks, cam roller followers, engine valves, injector components, and other similar parts. Manufacturability issues will be addressed using techniques such as component thermal analysis, finite element modeling, and fluid flow analysis.

The project will support DOE's Defense Programs and Conservation and Renewable Energy technical needs in manufacturing hard materials and will enable U.S. industry to maintain a position of leadership in the structural ceramics field.

Under this three-year agreement, costs of the cooperative research effort will be equally shared by Detroit Diesel Corporation and DOE (through Martin Marietta Energy Systems) at a total cost of $2.4 million.

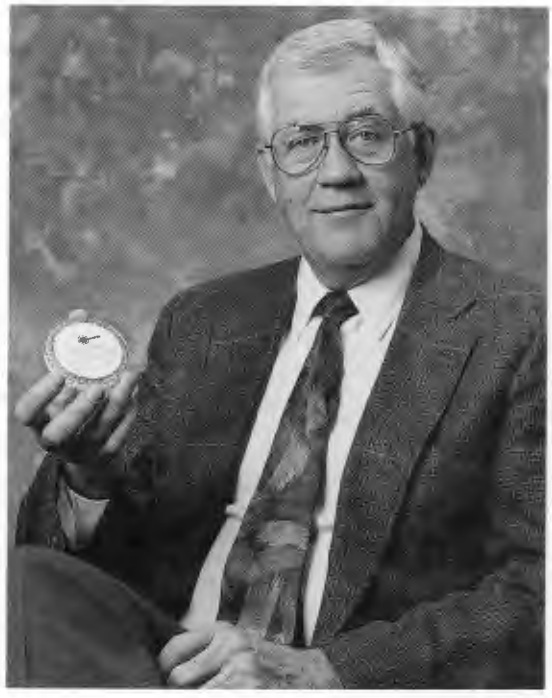
Operations will be conducted in a Ceramic Manufacturability Center now being established at ORNL's High Temperature Materials Laboratory (HTML) under a cooperative program for Precision Machining of Cost-Effective Ceramics Components. Location of the center in the HTML enables Detroit Diesel Corporation and other industrial participants in the program to take advantage of the world-class materials capabilities available at the HTML.

Ceramics are an attractive material for use in engines. They are stronger and lighter than steel

and can tolerate much higher temperatures. Because engines are more efficient when operated at higher temperatures, ceramics have long been envisioned for use in advanced engines.

Materials research funded by DOE has led to the development of several promising ceramics compounds for industrial applications, but the development of machining and quality inspection techniques necessary to mass produce cost-effective ceramics has not kept pace with the development of the materials.

The lack of precision machining is considered to be a principal barrier to the use of ceramics in engines. Precision machining technologies for ceramics and other hard materials have been developed at the Y-12 Plant as part of manufacturing nuclear weapons components.



Carl Burtis shows the Abaxis disposable rotor that will be used to monitor patient health.

ORNL's Blood Rotor Licensed to Abaxis

A new medical device, about the size of a small toaster, that can analyze a single drop of blood will be available next year to help physicians assess the health of their patients. This is the hope of Abaxis Corporation of Mount View, California, which is completing the development of this product based on an ORNL technology. Abaxis will be marketing the medical analyzer throughout the world in 1993 under a recent licensing agreement with Energy Systems.

The Abaxis device is a miniaturized and computerized version of a centrifugal analyzer, an instrument invented in 1967 at ORNL by Norman Anderson and his associates. The unique feature of the Abaxis analyzer is a sophisticated disposable rotor, a clear plastic disk that fits in the palm of your hand. It is based on a rotor developed by Carl Burtis of ORNL's Chemical Technology Division and two retired employees—Wayne Johnson, formerly of the Instrumentation and Controls Division, and Bill Walker, formerly of the Plant and Equipment Division.

Each rotor in the analyzer contains the chemical agents and processing chambers needed to automatically process and analyze a single drop of whole blood for substances of medical interest.

Abaxis plans initially to produce different types of rotors, each of which will be designed to monitor a specific health function. For example, some of the first rotors available will be used for general health monitoring, and others will be used to assess the health status of specific organs such as the liver or heart.

The new device will analyze blood for cholesterol, glucose, total protein, and other chemicals that indicate whether a patient's heart, liver, kidneys, and metabolism are functioning properly. For example, elevated levels of certain proteins called enzymes can indicate organ malfunction.

To begin an analysis, a technician first removes a rotor from its foil package and introduces a drop of a patient's blood onto the rotor's loading port. Capillary tubes in the rotor draw the blood into a central mixing chamber where it is diluted. The rotor is then placed into the analyzer and alternately spun and stopped to remove blood cells from the plasma in the sample. The plasma, which contains the chemicals of interest, is radially moved from the

"The unique feature of the Abaxis analyzer is a sophisticated disposable rotor, a clear plastic disk that fits in the palm of your hand."

central chamber to the rotor periphery, where portions of it are mixed with reagents present in the individual reaction chambers.

The reagents react with specific components of the blood to form chemical compounds. The rates of individual chemical reactions and the concentrations of the newly formed light-absorbing compounds can be determined by passing light into the chambers and measuring the emerging light signals. Light signals are transmitted and measured by a stationary optical system within the analyzer.

The amount of light transmitted through a chamber indicates the level of a particular body chemical in the blood. Variation in light intensity over time indicates reaction rate and, thus, the levels of other chemicals.

The system's software converts the measured light-transmission signals into units of concentration or activity (reaction rates) and prints or stores this information, which is later uploaded to a larger computer. From this information, physicians can diagnose disease and organ malfunction or pronounce the patient to be in good health.

DOE Labs and Utilities Interact

ORNL is one of several DOE laboratories involved in the Optical Sensing Manufacturers/ Utilities Group (OPSM/UG), an organization formed in 1991 to match the needs of electric utilities with technology for new optical sensing applications. The group also encourages its members to jointly develop, test, and demonstrate new technologies.

For the utilities, sensors using advanced optical detection technologies will play a key role in addressing increasingly complex issues in environmental monitoring, power generation, power distribution, and load control.

Eric Wachter, a research staff member in ORNL's Health and Safety Research Division, said DOE will benefit from its involvement. "Much of the technology that DOE is committed to develop, such as that needed for environmental monitoring, can be used by private industry," Wachter said. "By working with utilities and optical sensing manufacturers, we will be able to develop joint approaches to sensing applications."

OPSM/UG's first meeting, held April 15, 1992, was hosted by Southern California Edison at its research center in Irwindale, California, and was timed to coincide with the Expo Sensors West exposition in nearby Anaheim. ornl

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Next Issue

Oak Ridge National Laboratory is celebrating its 50th anniversary. As part of this observance, a history of ORNL will be presented in a forthcoming double issue of the *Review*.