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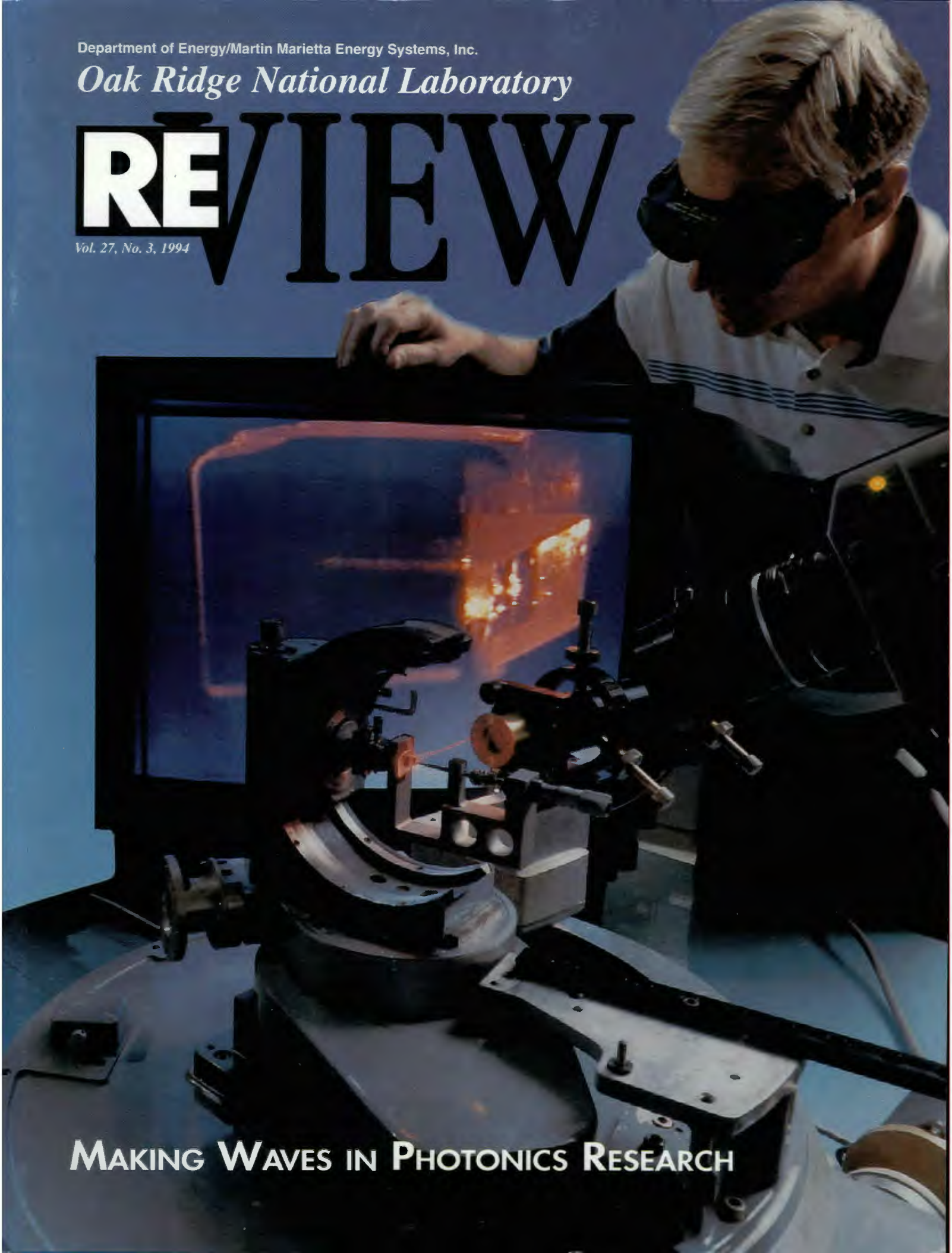

MAKING WAVES IN PHOTONICS RESEARCH

COVER CAPTION

Rodney McKee of ORNL's Metals and Ceramics Division views a video camera image of a laser beam passing through a waveguide material he and Fred Walker developed. In front of the monitor screen are a laser, laser beam, waveguide sample, and camera. ORNL's development of a thin-film waveguide for possible use in telecommunications and computers is described in the article beginning on p. 34. *Photograph by Bill Norris.*

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REVIEW

Volume 27
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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.

That Nobel Feeling

Clifford Shull (right), who with Ernest Wollan (left) pioneered reactor-based neutron scattering at ORNL's Graphite Reactor, won the 1994 Nobel Prize for physics. He shared it with Bertram Brockhouse of McMaster University in Canada. Shull, recently retired from the Massachusetts Institute of Technology, conducted much of his pioneering work in neutron scattering from 1946 to 1955 at ORNL. His ORNL collaborators included Mike Wilkinson and his students included ORNL's Herb Mook, Ralph Moon, and Steve Spooner.

I have always found it gratifying to observe the reaction of the scientific community when Nobel Prizes are awarded. A grand feeling of warmth, sharing, and gratitude permeates the entire scientific community much like most people's reactions to acts of extraordinary kindness or festive holidays. It is both humbling and stimulating to see work by your peers that uplifts the condition of mankind and adds dignity to your own endeavors. Such is the feeling I experienced at ORNL on the awarding of the 1994 Nobel Prize for physics to Clifford Shull and Bertram Brockhouse for their seminal contributions to neutron scattering.

Cliff Shull conducted his pioneering work in elastic neutron scattering at ORNL from 1946 to 1955 using neutrons from the Graphite Reactor. He came to ORNL to join Ernie Wollan, who had already constructed a diffractometer and started investigations to understand neutron diffraction as a probe of the atomic structure of solids. If Wollan were still alive, he would almost certainly have shared in the prize.

Wollan and Shull developed a method for using patterns of scattered neutrons to determine the arrangement of ordinary and magnetic atoms in solid samples. This research opened the door to understanding magnets at the atomic level, leading to such developments as efficient magnets for motors and magnetic storage of information.

Brockhouse also did his work at a national laboratory, the Chalk River Nuclear Laboratories in Ontario, Canada. These pioneering accomplishments, like those in high-energy physics recognized by many previous Nobel Prizes, would not have been possible without national laboratories. The reason: these labs play an almost unique role in designing, constructing, and operating major facilities for science.

The Shull-Brockhouse research is noteworthy for two reasons: it spawned neutron science, and the results of neutron science have had broad impact on other fields of science as well as practical implications for mankind. By my count, no fewer than eight Nobel prizes have been awarded for work in physics, chemistry, biology, and materials science that benefited directly from neutron science since Shull did his research. These winners are Glenn Seaborg (1951); Louis Neel (1970); Paul Flory (1974); Philip Anderson, Nevill Mott, and John Van Vleck (1977); Jerome Karle (1985); Johannes Bednorz and Alex Muller (1987); Norman Ramsey (1989); and Pierre-Gilles de Gennes (1991).

The contributions of neutron science to society range from medical isotopes for diagnosis and treatment, to electronic chips and magnetic recording media, to high-tech polymers and plastics. I am convinced that we scientists get a warm feeling of pride over Nobel Prizes for justifiable reasons.—*Bill Appleton, ORNL Associate Director for the Advanced Neutron Source.*

Nobel Laureate Dies

Eugene Paul Wigner, Nobel laureate who strongly influenced nuclear reactor development died at the age of 92 on January 1, 1995, at Princeton, New Jersey. Except for stints at the universities of Chicago and Wisconsin and in Oak Ridge, he worked as a theoretical physicist and active faculty member at Princeton University from 1930 to 1971.

In 1946–1947, Wigner was director of research and development at Clinton Laboratories, predecessor of ORNL. He returned to ORNL for a year in 1964 to organize a civil defense research project, which became an early model of collaboration among social scientists and engineers in attacking complex issues.

Wigner, who was present at Stagg Field in Chicago in December 1942 when the first self-sustaining nuclear chain reaction was observed, became concerned in 1939 that Nazi Germany would develop the atomic bomb before the United States. He and Leo Szilard expressed this concern to German physicist Albert Einstein, who dictated a letter in German to President Roosevelt about the need for an American crash project to develop the bomb before Germany did; Wigner translated it into English. To develop an American bomb as fast as possible, he persuaded the Metallurgical Laboratory in Chicago to replace the proposed high-temperature, helium-cooled reactor with his water-cooled reactor concept. Wigner's reactor was built by the DuPont company in Hanford, Washington.

Wigner also influenced development of reactors at ORNL, including the Graphite Reactor. He proposed the design of the Materials Testing Reactor (MTR), developed at ORNL and built in Idaho. This reactor design was the basis for the designs of ORNL's Oak Ridge Research Reactor, High Flux Isotope Reactor, and proposed Advanced Neutron Source.

Eugene Wigner (1902-1995)

Pressurized versions of the MTR became the predominant reactor type for submarine propulsion and commercial nuclear power. In addition, he proposed the aqueous homogeneous breeder in which the fuel, moderator, and coolant are combined as a fluid. This concept, embraced by former ORNL Director Alvin Weinberg, led to ORNL's development of an aqueous homogeneous reactor and molten-salt reactor for breeding fissionable uranium-233 from thorium. Wigner and Weinberg coauthored the 1958 classic *The Physical Theory of Nuclear Chain Reactors.*

In his 1994 book *The First Nuclear Era: The Life and Times of a Technological Fixer*, Weinberg wrote of Wigner: "While in his twenties he introduced the ideas of symmetry and group theory into quantum mechanics, an achievement for which he received the Nobel Prize in 1963. Later he was one of the founders of theoretical nuclear physics. His most notable contribution to nuclear physics was his visualization of the compound nucleus (entirely independently of Niels Bohr to whom the idea is usually attributed)."

Oddly enough, according to Weinberg, Wigner never had a course in physics. Born in 1902 in Budapest, Hungary, he received his doctoral degree in chemical engineering in 1925 from the Technische Hochschule in Berlin. His best friend was John von Neumann, father of the modern computer who introduced him to mathematical group theory. When he came to Princeton, Wigner had an international reputation as a theoretical physicist. His first student was Frederick Seitz, who worked at ORNL and later became president of the National Academy of Sciences and of Rockefeller University. His second student was John Bardeen, who helped develop the transistor and won two Nobel Prizes in physics.

During his directorship in Oak Ridge, Wigner founded the Clinton Training School, which became the Oak Ridge School of Reactor Technology. Also, during his time at ORNL, the first reactor-produced radioisotopes were provided to a cancer research hospital. His recruitment of Alexander Hollaender led to the formation of ORNL's Biology Division, one of the world's strongest centers of basic biology. Despite his successes, Wigner thought he had no aptitude for administration and became increasingly frustrated with bureaucracy in Oak Ridge.

In a tribute to Wigner at ORNL on January 9, 1995, Weinberg called him "my scientific mentor," "a person who cared," and the "patron saint of Oak Ridge National Laboratory." Joanne S. Gailar, who worked with Wigner on civil defense in 1964, remembered him as "courteous, thoughtful, unpretentious, and lovable."

Advanced Photonics at ORNL: Shedding Light on a New Initiative

By William S. Key and John C. Miller

Light—or photons—is the key to many recent developments at ORNL. Consider these examples:

A new laser technique for nonsurgically diagnosing certain cancers.

A much less expensive test for detecting polychlorinated biphenyls (PCBs) in environmental samples using strips of chemically treated paper that glow if they are exposed to PCBs and then excited by ultraviolet light.

A thin-film light-wave guide that could be used to make an optical switch to increase the amount of "data traffic" on the information superhighway.

A phosphate glass originally developed to isolate radioactive waste that shows promise for lenses and optical fibers for such uses as laser surgery.

Use of diamond turning, a precision-machining technique well-honed at the Oak Ridge Y-12 Plant, to make better mirrors and lenses.

A spectroelectrochemical sensor that uses light to detect groundwater pollutants.

Use of a photon emission measurement technique to determine composition of materials as they are being produced for application in production process control in the metal plating, aluminum, and organic polymer industries.

These developments and other research performed at Oak Ridge National Laboratory related to lasers, lenses, optical fibers, fluorescent materials, and special manufacturing techniques can be collectively referred to as photonics technology. Scattered ORNL research related to light has been brought under the umbrella of the Laboratory's new Advanced Photonics Initiative. In this way, we hope to highlight our capabilities in a growing field deemed essential to development of new materials, energy and environmental technologies, information technologies, and manufacturing technologies to improve the nation's economic competitiveness. In this issue of the *Review*, we present the breadth of work being performed in photonics, its relevance and importance to other research activities, and the significance of ORNL's accomplishments in the field.

What is photonics? According to the magazine *Photonics Spectra*, photonics is "the technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. The range of applications of photonics extends from energy generation to detection to communications and information processing." Those of us working in this field believe it is one of the most important fields of science at the Laboratory. This belief is supported by indicators such as the amount of photonics-related research being performed at ORNL ($25 million annually), the number of Laboratory divisions involved (most technical divisions), the number of researchers involved (more than 140), and the importance of the accomplishments (a large percentage of ORNL's 82 R&D 100 awards have had significant photonics contributions).

Those of us working in photonics believe it is one of the most important fields of science at the Laboratory.

To provide a flavor of the breadth of local photonics work, brief descriptions of current research written by Carolyn Krause are presented following this article. Two other articles published in this issue on photonics-related research are Brigham Thomas's article on the Ultraprecision Manufacturing Technology Center (see p. 24) and an article on ORNL's development of thin-film waveguides (see p. 34). Previous issues of the *Review* have covered photonics research. A partial listing of *Review* articles on photonics research over the past four years appears on p. 21.

Most of the photonics-related research at the Laboratory falls into three broad technical categories: materials and materials processing, process diagnostics, and environmental sensing. More specifically, ORNL work is focused on optical materials, laser materials processing, optical manufacturing, spectroscopy, advanced infrared and far infrared laser diagnostics, hybrid optical processing, image processing, environmental and physical sensors, and fiber-optic sensors.

Display of optical parts fabricated by the former Optics MODIL, now the Ultraprecision Manufacturing Technology Center at the Oak Ridge Y-12 Plant. The metal mirrors remain shiny after many years because they resist the formation of thick oxide layers that cloud surfaces.

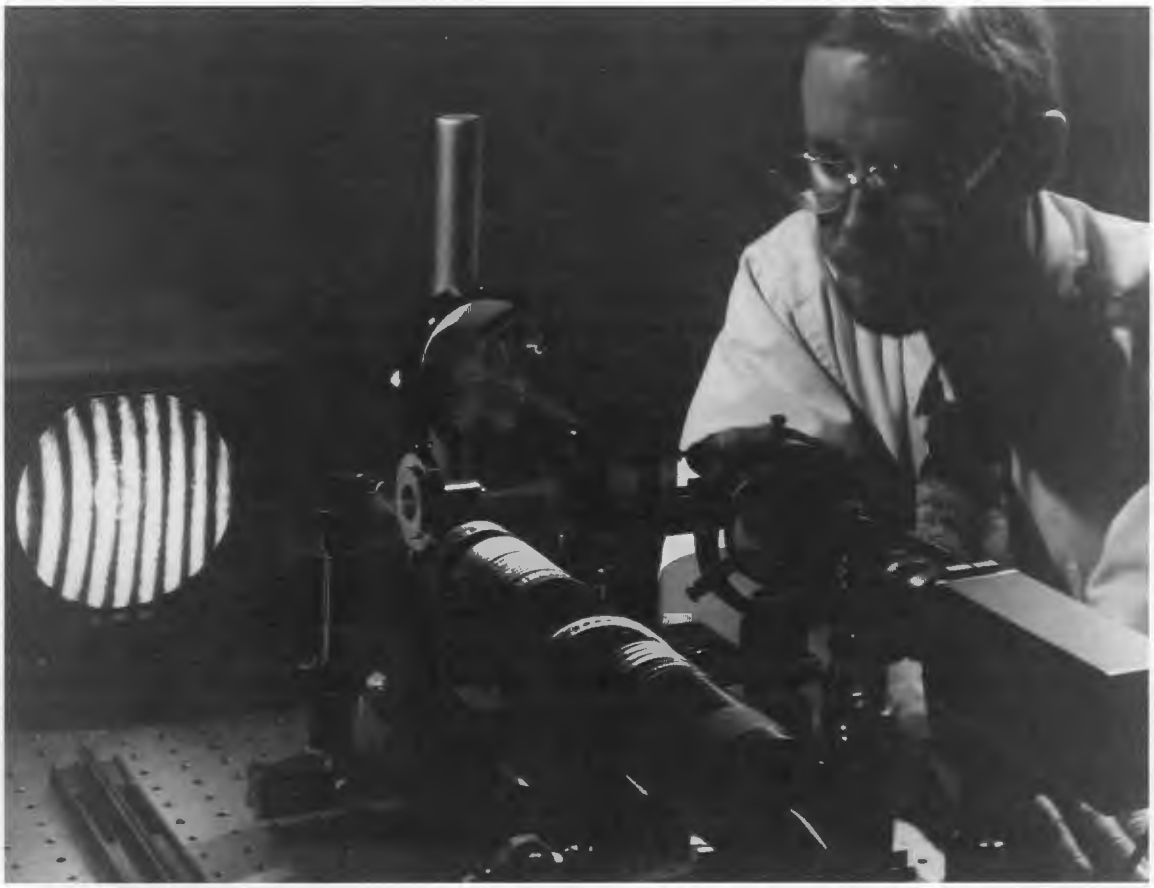
Tuan Vo-Dinh, a corporate fellow of Martin Marietta Energy Systems, Inc., demonstrates the use of his new method for on-site testing for polychlorinated biphenyls (PCBs).

Out of the Darkness

Until three years ago, few people at ORNL were aware that so much photonics-related research was being conducted at the Laboratory. The reason: the dispersion of these activities throughout many groups and divisions. In 1991, a grass-roots effort was made to unify the researchers working in the field through a voluntary organization called the Advanced Photonics Initiative. The purpose of this initiative was to increase the Laboratory's visibility in the photonics field by (1) improving communications among individual researchers and research groups doing photonics research, (2) encouraging the formation of multidivisional project teams, (3) raising the awareness of our colleagues within DOE and industry concerning ORNL's rich capabilities in photonics research, and (4) helping to identify and secure new research programs in photonics. Although the initiative started with collaborations among the Health Sciences Research Division, the Engineering Technology Division, and the Instrumentation and Controls Division, it soon grew to encompass 10 divisions at ORNL, the Development Division at the Oak Ridge Y-12 Plant, and the Technical Division at the Oak Ridge K-25 Site. Thus, the Advanced Photonics Initiative has become an initiative of Martin Marietta Energy Systems, Inc., which manages the three Oak Ridge facilities for the Department of Energy.

Recent actions have helped ORNL strengthen research programs in photonics and gain national recognition as a center of photonics research. For example, in December 1993, under the sponsorship of DOE, an industry-laboratory workshop was held at ORNL on "Optical Diagnostics in Manufacturing and Process Control." In January 1994 the Advanced Photonics Initiative received financial support from both the ORNL Executive Committee and the Oak Ridge Centers for Manufacturing Technology. Although not yet singled out as a core competency, photonics is being recognized throughout Energy Systems as a key technical area. Likewise, efforts to educate individuals and organizations within Oak Ridge about our significant photonics capabilities and to inform others through increased publications in trade magazines and newspapers are being carried out successfully.

An additional objective of our efforts is to strengthen the infrastructure supporting photonics



Curt Maxey evaluates the patterns generated by interfering light beams from a point reference polarization interferometer to measure the curvature of mirrors and other optical parts during manufacture.

Photonics is being recognized throughout Energy Systems as a key technical area.

research, an important consideration in these days of scarce resources. Some benefits of improved communications and networking stimulated by the initiative have been identification of resources (such as lasers), resource sharing, and determination of future needs for photonics-related research.

Future Bright for Studies of Light

The future for photonics at ORNL appears promising, particularly when viewed in terms of many new research and development (R&D) opportunities. Photonics is becoming an increasingly important technology in all aspects of our society. Examples of new applications and continuing areas of R&D are flat panel displays, high-definition television, optical information storage, and optical computing. The economic impact of the technologies can be tremendous. For example, the opto-electronics industry has estimated that flat panel displays are the key technology for products having an estimated market of $200 billion by 2000.

The importance of photonics has been recognized by the Clinton administration and Congress for its positive impact on the U.S. economy, job creation, defense, and the environment. For example, one congressional committee recently noted that "optics is a rapidly growing, highly diversified [field that is supporting the] international economy" and that "the United States is in the midst of an optics revolution."

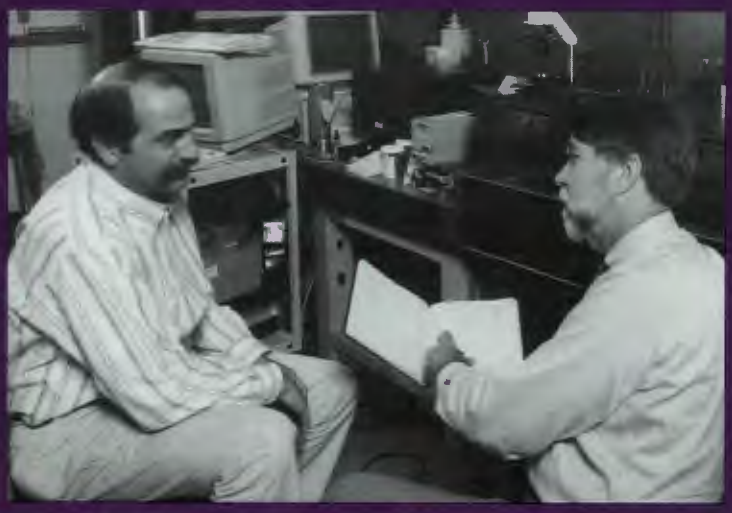
Photonics has been recognized by the Clinton administration and Congress for its positive impact on the U.S. economy, job creation, defense, and environment.

Within ORNL, photonics is closely aligned with three other significant Laboratory and Energy Systems initiatives: the Intelligent Measurement Systems Laboratory, a new instrumentation user center modeled after the High Temperature Materials Center; the Oak Ridge Centers for Manufacturing Technology, which draws upon the manufacturing capabilities of the Y-12 Plant and the R&D capabilities of ORNL and the K-25 Site; and the proposed Environmental, Life, and Social Sciences Complex. Plans for this complex include building not only the Center for Biological Sciences but also the Biological Imaging and Advanced Photonics Laboratory. The newly formed Biotechnology Center also will explore photonics technologies such as biosensors.

ORNL is also building external relationships to provide for its future in photonics. The Laboratory, which is a member of the Alliance for Optical Technology of Huntsville, Alabama, is a participant in the alliance's residence training program in optics established through a U.S. Advanced Research Projects Agency award. ORNL is working with other photonics centers in the Southeast, such as the Fiber and Electro-optics Research Center at Virginia Polytechnic Institute and State University, the Center for Luminescent Materials at the Georgia Institute of Technology, and the Center for Research in Electro-Optics and Lasers at the University of South Florida. ORNL's network of photonics-related partnerships is expected to expand. In the future, the Laboratory plans to form ties with sister DOE laboratories, such as Sandia National Laboratories, where photonics research complementary to that at ORNL is under way. Beneficial partnerships with industry may also be forged through cooperative research and development agreements in areas such as phosphor coatings for flat panel displays.

The Laboratory shows strengths in three areas of photonics R&D—process diagnostics, environmental sensing, and materials processing. It has been forming ties with other institutions involved in photonics research. Opportunities in photonics are growing in ORNL mission areas such as energy and the environment. It is no wonder that as we look toward the future through the photonics tunnel, the light we see at the other end is very bright indeed.

Biographical Sketches



John Miller (left) and Bill Key discuss photonics research next to ORNL's new femtosecond laser.

William S. Key is project leader for the Advanced Photonics Program Development Project for Martin Marietta Energy Systems, Inc., and head of the Engineering Physics Section of ORNL's Engineering Technology Division (the section is located at the Oak Ridge K-25 Site). He came to Oak Ridge in 1976 when he joined the Centrifuge Division as a staff scientist with the Centrifuge Physics Department. He served as manager of this department from 1981 to 1985. Before coming to Oak Ridge, he worked for nine years as a principal technologist for Teledyne Brown Engineering Company. There he worked on the National Aeronautics and Space Administration's Skylab Apollo Telescope Mount, Apollo-Soyuz Mission experiments, and early stages of the Hubble Space Telescope now in orbit. He has an M.S. degree in physics from the University of Alabama at Huntsville.

John C. Miller is leader of the Advanced Photonics Initiative, which embraces photonics-related research throughout Energy Systems. He is head of the Chemical Physics Section in ORNL's Health Sciences Research Division. He has a Ph. D. degree in physical chemistry from the University of Colorado in Boulder. Miller came to ORNL in 1979, and four years later received an IR•100 Award from *Industrial Research* magazine for his development of a vacuum ultraviolet spectrometer. He has been an adjunct professor of chemistry at the University of Tennessee in Knoxville. He has been a NATO International Collaboration Fellow and a visiting scientist in France in 1982 and 1992. He is a fellow of both the American Physical Society and the Optical Society of America.

Hybrid Optics: Two Complementary Lenses for the Price of One?

Michelle Destefano peers at a hybrid-optic lens developed by ORNL's David Sitter for use in a miniature camera

"The idea is to take a light-refracting lens and etch a pattern on it that diffracts light."

Such high-performance hybrid optics are expected to find uses in high-radiation or hazardous chemical environments.

Refraction and diffraction may rhyme, but ORNL researchers are more interested in making them work together in a lens than in a poem.

The lenses in eyeglasses refract light. Light rays are bent as they pass into and out of the lens. The focusing effect of the lens is used to improve vision.

The glistening three-dimensional image that shows up on many credit cards when turned toward the light is a hologram, an example of diffraction. It is made possible by a specially etched pattern of fine lines that diffracts light as bands of color.

Some photonics researchers at ORNL and elsewhere are seeking novel applications for and economical ways of making a lens that both refracts and diffracts light. Such lenses, which are now being made using an expensive process called microlithography, are called hybrid optics.

"The idea is to take a light-refracting lens and etch a pattern on it that diffracts light," says David Sitter of ORNL's Instrumentation and Controls Division. "In this way, one lens can do the work of two, reducing the size, weight, and cost of a lens system and eliminating problems of aligning two lenses."

One use for a single-element "hybrid optics" lens might be to replace and improve the quality of lenses used to focus laser light in compact-disc read-only memory (CD-ROM) drives for personal computers. Such lenses could make future CD-ROM drives smaller, lighter, simpler, and less costly.

Sitter has designed, built, and tested a miniature camera that uses a hybrid-optics lens for use as a sensor. This two-lens camera, he says, performed as well as a commercial camera with three refractive lenses.

"The advantage of the hybrid approach," Sitter says, "is that the diffractive effects can compensate for the undesirable effects of refraction. Each optic balances the other because they have opposite dispersive behavior. For example, in refraction, blue light is bent more than red light, but in diffraction, red light is bent more than blue light. In addition, the diffractive element may be designed to compensate for imaging aberrations, leading to sharper images."

Hybrid-optic lenses are expensive to make because of the high cost of microlithography. In this slow tedious process, chemicals or reactive ions are used to etch miniature patterns in a glass lens to make it diffractive as well as refractive.

ORNL researchers are seeking to develop a less costly process of manufacturing hybrid optics. Bruce Bernacki and Curt Maxey, both of the I&C Division, and Art Miller of the Oak Ridge Y-12 Plant Development Division are studying the possible use of single-point diamond turning for fabrication of hybrid-optic lenses. Modern diamond turning is a computer-controlled machining process that stems from work in the late 1960s at DOE laboratories. It was first used to make sophisticated mirrors for high-energy laser systems. It uses a precisely contoured and polished single-crystal diamond cutting edge that is driven by an ultrahigh-resolution machine to cut precisely curved surfaces. The applications of diamond turning to manufacturing optics are being studied at the Ultraprecision Manufacturing Technology Center at the Y-12 Plant (see article on p. 24).

"Our plan is to use diamond turning to make metal molds for lenses with the diffractive pattern precisely cut into each mold," Miller says. "The plastic placed in the mold will then pick up the diffractive pattern, forming a hybrid optic having an arbitrary shape such as a sphere."

The group is also working with an industrial partner, Geltech, Inc., of Alachua, Florida, to develop hybrid-optic lenses made from silica glass instead of plastic. To mass produce glass lenses, liquid glass will be cast in molds made by diamond turning. Fused silica offers several advantages over plastic for hybrid optics: it is more resistant to corrosive chemicals, does not release gas molecules under vacuum, undergoes fewer undesirable changes in dimensions and optical performance resulting from temperature changes, and is insensitive to ionizing radiation. As a result, such high-performance hybrid optics are expected to find uses in high-radiation or hazardous chemical environments on earth and in space.

The lens of the future will likely be a "lens on a lens," with one being diffractive and the other refractive. Once the cost of making hybrid optics is lowered to a reasonable level, thanks to photonics research, two lenses may be available for the price of one.

PHOSPHATE GLASS FOR PHOTONICS

"One possible use for phosphate glass may be in improved optical fibers for laser surgery."

Lenses made from a lead indium phosphate composition developed at ORNL.

The phosphate glass is also a promising material for lenses.

A phosphate glass originally developed at ORNL to isolate radioactive waste shows promise as a novel optical material for collecting, delivering, focusing, or amplifying light. One possible use for phosphate glass may be in improved optical fibers for laser surgery.

A phosphate glass containing lead and indium, whose composition is based on that of a high-durability glass, was developed and patented in the late 1980s by Lynn Boatner and Brian Sales in ORNL's Solid State Division. More recently, Boatner and Sales in collaboration with Steve Allison of ORNL's Engineering Technology Division have fabricated optical fibers and lenses from this phosphate glass—a good example of how interdivisional cooperation can advance research and development opportunities in photonics.

"Our phosphate glass exhibits a unique combination of properties," Boatner says. "It has a high index of refraction and the ability to bend light at high angles. It is also chemically stable and durable. In addition, it has a low melting point and is transparent over a wide range of wavelengths. Perhaps most important, it readily dissolves rare-earth elements, so it can be used in developing new optically active devices such as fiber-optic amplifiers and new lasers."

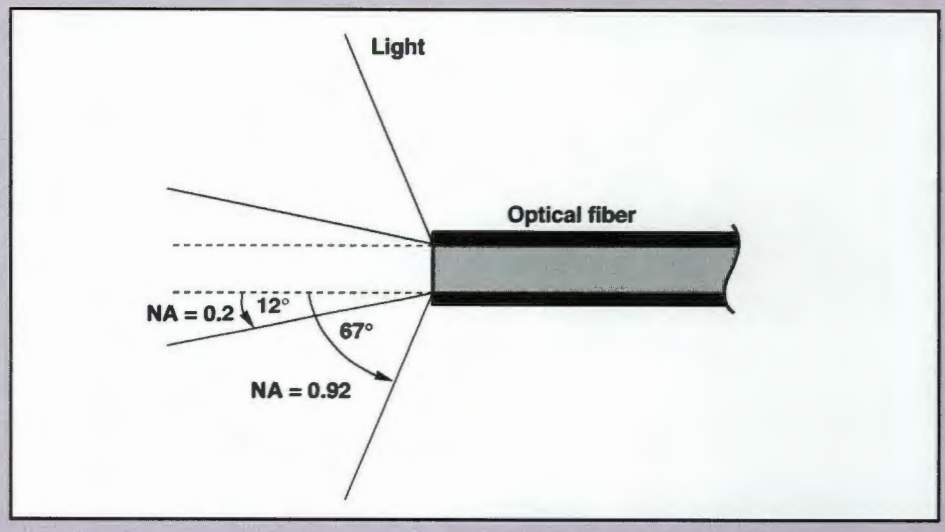
The ORNL researchers recently tested optical fibers made at Virginia Polytechnic Institute and State University from the phosphate glass covered with a conventional silicone-polymer cladding. They found that the fibers exhibited a very high numerical aperture—a measure of the largest angle at which incoming light can enter a fiber and pass through it efficiently.

"For normal communication-grade fiber, this input angle may be only 12° from the normal of the surface," Allison says. "High-numerical-aperture fiber made from our phosphate glass can transmit light at incident angles of almost 70°. Thus, this fiber should be much better at collecting light from diffuse sources."

The ORNL researchers say the phosphate glass has great potential for use in specialized fiber sensors for strain, temperature, and electric-field measurements and in light-delivery systems, including optical displays and laser surgery. "Fluoride fibers used to carry infrared laser light to patients tend to be easily damaged by water vapor," Allison says. "We think the ORNL glass fiber may be better suited for this type of laser surgery, whose advantages over conventional surgery include reduced pain and faster healing."

The phosphate glass is also a promising material for lenses. "Because of the material's high index of refraction, less curvature is required for a lens of a given power," Allison says. "The lower the curvature, the smaller the lens aberrations that can distort and limit a lens' usefulness."

Thanks to its unique set of characteristics, ORNL's new material may have a wide variety of applications, making it one of the most interesting new optical glasses.



This drawing of an optical fiber and incoming light compares the angles at which incoming light can enter a fiber and pass through it efficiently. Light can enter the ORNL-developed fiber from an angle of 67° compared with only 12° for normal communication-grade fiber. Thus, ORNL's high-numerical-aperture (NA) fiber can accept light from more diffuse sources.

Single Dye Molecule Detected in Droplet

"Our technique . . . could revolutionize ultrasensitive chemical measurement."

Mike Barnes adjusts the droplet generator that produces a microdroplet of liquid in which a dissolved single molecule of dye is illuminated by laser light. Fluorescence from the laser-excited dye molecule can be distinguished from light emitted by about a trillion molecules of solution.

"With this technique, we could have the world's smallest chemical test tube."

Single molecules of a fluorescent dye in microscopic droplets of solution have been detected by ORNL researchers. The laser-based technique enables target molecules to be counted in very small volumes of liquid, providing far greater sensitivity than bulk analysis schemes. The technique could be used to characterize gene-containing material that may be responsible for inherited diseases or to track flow of pollutants in rivers.

The group at ORNL has conducted a "needle-in-the-haystack" detection experiment in which the fluorescence signal from a single dye molecule is distinguished from light emitted by about one trillion solvent molecules. In the experiment, a "microdroplet" produced by a device similar to an ink-jet printer head is suspended in the center of the analysis chamber. The droplet is then illuminated by the green light of a continuous-wave argon-ion laser.

The dye molecule repeatedly absorbs the green laser light and then relaxes by emitting red light in individual packets called photons. The photons emitted from the dye molecules are then counted using a sensitive light detector, and the number of molecules in the drop is determined roughly by the number of photons detected.

The technique was developed by Mike Barnes, Bill Whitten, and Mike Ramsey, all of the Analytical Spectroscopy Section of ORNL's Chemical and Analytical Sciences Division. Other collaborators in the project have been Steve Arnold of Polytechnic University of New York (who developed the droplet generator), Burt Bronk of the U.S. Army's Edgewood Research and Development Engineering Center, and Kin Ng of California State University at Fresno.

"Our technique for detecting the presence or absence of a single fluorescent molecule (or two or three such molecules) could revolutionize ultrasensitive chemical measurement," Ramsey says. "The ultimate goal of liquid chemical analysis is to measure trace chemical concentrations by counting molecules in a very small sample of solution. We have shown that one, two, or three—or no—molecules can be detected in a tiny drop of solution."

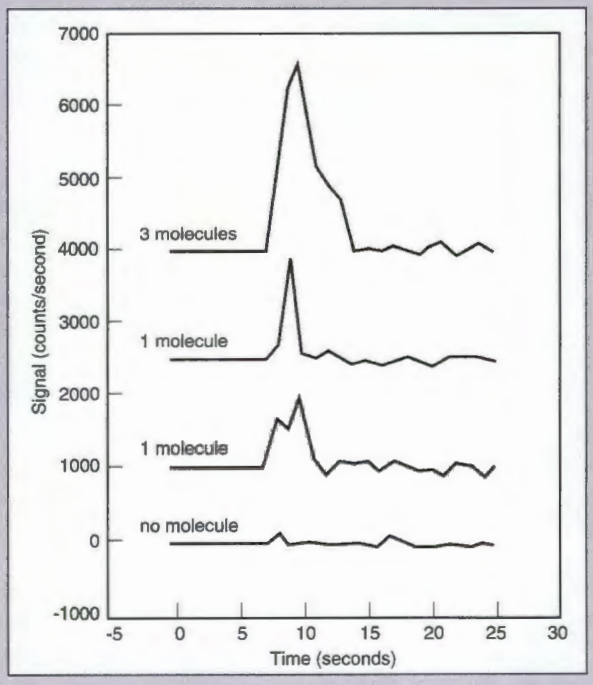
The ORNL scientists say that ultrasensitive analysis can also be performed on materials that are not normally fluorescent by attaching dye molecules as fluorescent tags. For example, detection of dye molecules attached to DNA molecules could provide information on the sizes of DNA fragments. If the dye molecules are attached at intervals along the DNA strand, then the total fluorescence signal can be related to strand size. Such information could be useful for the national Human Genome Project for understanding the genetic makeup of humans and the origins of genetic disorders.

Another important use of this technique is tracking pollutant flow in rivers and locating sources. "As the pollutant spreads out from the source, the number of molecules concentrated in one place becomes smaller and smaller," says Ramsey. "With our technique, we could detect a few molecules in a tiny drop of river water and work upstream to determine the origin of the contamination."

Ramsey says the technique shows promise for carrying out fundamental chemical experiments. "We may be able to study chemical reactions between single molecules in a microdroplet," he notes. "Chemistry in a drop has the advantage of fewer impurities, no container, and a very small sample. With this technique, we could have the world's smallest chemical test tube."

The key to the technique's success is the extremely small size of the liquid drop. "It is important to reduce the number of solvent molecules as much as possible to decrease background emission from the solvent molecules," Whitten says. Filters, he explained, separate light emission of one color (fluorescence from the molecule of interest) from that emitted by the drop's solvent molecules (Raman scattering). As a result, the signal from the target molecules is easily detected over the noise of the solvent molecules, just as the solo of a trumpet player standing at a microphone is heard over the background of numerous accompanying stringed instruments.

The persistence of the droplet is also important. Whitten says that glycerin was selected as a droplet solvent because its low evaporation rate causes it to exist a long time in the measurement apparatus. As a result, the target molecules remain in the laser light long enough for the maximum number of signal photons to be extracted.



Fluorescence signals from 3 rhodamine molecules, 1 molecule, and no molecules were detected in suspended microdroplets by a technique pioneered by three ORNL scientists and collaborators.

The fundamental aspects of this work were supported by DOE's Office of Basic Energy Sciences. The U.S. Army supported a project at ORNL to determine whether single-molecule detection can be used to detect minute traces of chemical or biological warfare agents. Practical applications of single-molecule detection for assisting in detection of nuclear weapons proliferation are now being supported by DOE's Office of Nonproliferation and National Security.

Molecular Clusters, Laser Snow, and the Ozone Layer

Researchers report the detection of a new form of laser snow.

Howard Carman (center), Bob Compton (right), and visiting professor Bruce Thomas (left) combine several laser beams into a molecular beam machine to probe the reactions of excited atoms with molecules and clusters.

Cluster chemistry—the study of interactions among closely packed atoms or molecules ranging from 2 to 1000 in number—is gathering public as well as scientific interest. One of the most exciting objects of study is the cluster of carbon atoms known as buckyball. Also intriguing to scientists are chemical reactions in a cluster because they may imitate the processes of catalysis, materials synthesis, and atmospheric chemistry.

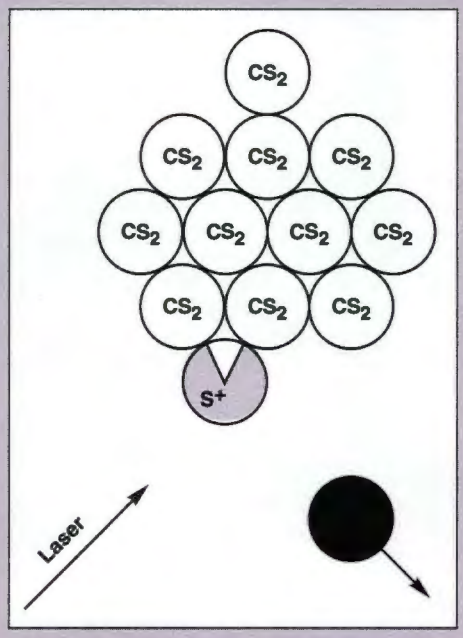
Clusters have been called the fifth state of matter, after solids, liquids, gases, and plasmas. The unique properties of clusters fall between those of single atoms and molecules and those of bulk solids. John Miller and Howard Carman, both of ORNL's Health Sciences Research Division, have applied novel laser-based techniques to the study of molecular clusters.

One property of clusters has made it possible for Miller to identify a new form of "laser snow." Laser snow was first observed and named in 1975 by William Happer of Columbia University in New York City. He witnessed the precipitation of white particles after exciting a gaseous mixture of cesium and hydrogen with a laser beam. The excited cesium atoms collided and reacted with hydrogen molecules, producing a cesium hydride precipitate. Laser snow was also detected in experiments with sulfur hexafluoride, thiophenol, and carbon disulfide.

At an April 1994 meeting of the American Physical Society, Miller reported the detection of a different form of laser snow by using a laser beam to ionize one molecule in a cluster of carbon disulfide molecules. This time, the proximity of the molecules to each other in the cluster, rather than collisions between them, was responsible for the new form of laser snow. Another difference between this experiment and the earlier laser snow studies is that the products of the chemical reaction are ions that can be easily detected by mass spectrometry.

Miller, who collaborated with University of Tennessee (UT) professor Charles Feigerle and graduate student Sunil Desai on this work, says, "Although visible particles were not observed in our low-pressure experiment, the mass spectrum revealed the presence of sulfur and carbon sulfide polymers. These are the same species observed in earlier laser snow experiments with high-pressure gases."

In the ORNL-UT experiment, the laser beam ionized a carbon disulfide (CS_2) molecule, breaking it into an S^+ ion and a CS molecule and freeing an electron. The S^+ ion reacted with a nearby CS_2 molecule, forming an S_2^+ ion. This ion then grabs a sulfur atom from another neighboring carbon disulfide molecule, and so on. In this snowball effect, a sulfur polymer as large as S_{12}^+ can be formed. Some carbon sulfide ions also latched onto neighboring carbon disulfide molecules, forming polymers as large as $(CS)_4^+$. A mass spectrometer detected the presence and masses of the sulfur and carbon sulfide ions. It also detected intermediate species that provide clues to how these polymers are formed.



A laser beam ionizes a carbon disulfide (CS_2) molecule, breaking it into an S^+ ion and a CS molecule and freeing an electron. The S^+ ion reacts with a nearby CS_2 molecule, forming an S_2^+ ion, which grabs a sulfur atom from another neighboring carbon disulfide molecule, and so on. Thus, the initially ionized molecule "eats" its way through the cluster like a molecular "Pac Man," creating bigger and bigger polymers with each bite.

Miller says that the cluster mechanism eliminates the need for collisions to induce chemical reactions. "When one member of a cluster of CS_2 molecules is excited, it finds its next-door neighbor to be a suitable reaction partner and no collision is needed. Any extra energy from the reaction can be used to eject weakly bound molecules from the cluster. The initially ionized molecule 'eats' its way through the cluster like a molecular 'Pac Man,' creating bigger and bigger polymers with each bite."

Miller and Desai use a high-power picosecond laser to generate positive ions of molecular clusters. They have also studied nitric oxide clusters mixed with other important species found in the atmosphere.

Carman's research focuses on producing negative ions of clusters that are then detected in a mass spectrometer. In his technique, developed with C. E. Klots and Robert Compton of the same division, several tunable lasers are used to excite the outer electrons of alkali atoms (e.g., cesium). Each excited electron is very far from the atomic nucleus and thus looks like a "free electron" to any nearby particle. If the cluster under study encounters such an electron, it may grab it to form a negatively charged cluster ion, which is then detected. In this way, Carman has produced negative cluster ions of carbon $(C)_n^-$, cousins of the famous fullerenes that include buckyballs. He has also produced negative cluster ions of nitric oxide, a species in polluted atmospheres.

It is now possible to generate in a molecular beam apparatus microscopic clusters containing nitric oxides, sulfur oxides, and chlorine-containing molecules attached to a small number of water molecules. The concentrations, sizes, and temperatures of these clusters can be experimentally varied. These "binary" clusters can serve as models for the study of atmospheric processes in water droplets or ice crystals.

Recently, it has been observed that chlorine-nitrate reactions on ice crystals in polar stratospheric clouds convert inert chlorine into photochemically active chlorine (Cl_2). Active chlorine is thought to be primarily responsible for destruction of the earth's protective ozone layer. The energy of sunlight converts the active chlorine to products that stimulate ozone-destroying chain reactions.

Miller and Carman propose to perfect the generation in the laboratory of these binary clusters. They hope to study the photochemistry of clusters of chlorine-containing compounds on ice crystals to identify the products that lead to ozone losses. They also wish to explore binary clusters to gain knowledge about stratospheric sulfate and nitrate aerosols. The payoff could be better understanding of the atmosphere through cluster chemistry.

PHOTONICS ON THE PRODUCTION LINE

New photonic methods are improving manufacturing efficiency.

A fiber-optic Raman probe is used to analyze the composition of molten polyethylene. Such a tool is useful in industrial environments for characterizing products as they are being produced.

Real-time Raman analysis allows polymer composition to be adjusted during production.

When sheets of metal are plated or plastic fibers are formed in large quantities on the production line, the actual composition of these materials is not known until after a batch has been produced and analyzed. If part of the batch has the incorrect composition, it is discarded. Then the production process is altered to correct the composition for the next run.

Production could be made more efficient by determining the composition of industrial materials during manufacture, detecting compositional variations, making midproduction corrections, and otherwise controlling the process to achieve the desired composition. In this way, a larger percentage of the products would meet customer requirements, reducing waste, saving money and energy, and increasing the competitiveness of American industry.

New photonic methods for improving manufacturing efficiency are being developed through a collaborative effort among ORNL, the Y-12 Plant, and the University of Tennessee at Knoxville (UTK). Principal investigators are Eric Wachter, a physical-analytical chemist in ORNL's Health Sciences Research Division; Jennings Cline, a physical-analytical chemist in the Development Division of the Y-12 Plant; and Marion Hansen, a professor of chemical engineering at UTK.

This research team is adapting Raman spectroscopy, normally a complex laboratory technique, to the industrial environment. Through use of this technique, the composition of many industrial materials can be monitored in real time on the production line. In addition, the production process can be controlled while materials are being produced rather than after a batch is completed.

"Timely control of production offers several advantages," Wachter says. "They include improved product consistency, reduced waste generation, and increased energy efficiency. These improvements will help maintain industrial profitability in a competitive global marketplace."

Raman spectroscopy is based on the Raman effect, discovered by the Indian physicist C. V. Raman in 1928. In this phenomenon, light of a single frequency (color) is scattered by each target molecule in a transparent medium. The scattered light undergoes a change in frequency based on the characteristic energies of rotation and vibration of each target molecule. In Raman spectroscopy, the measured intensities and frequencies of scattered light are used to identify and quantify different molecules in the medium.

The ORNL, Y-12 Plant, and UTK team are hoping to find applications for Raman analysis in the metal plating, aluminum, and organic polymer industries. These areas were selected as a result of discussions with industrial representatives. Such industries could benefit from improved control of composition during production. Such control could be achieved by relaying the real-time results of Raman analysis to a computer programmed to adjust the production process in response to messages about compositional variations.

How would this technique be useful in the polymer business? According to Wachter, "Physical properties of organic polymers, such as flexibility or hardness, are often determined by varying the proportion of constituents incorporated during fabrication. Traditionally, components have been added at roughly the desired levels, and then the batch is analyzed after production. If the composition is not correct, the batch often must be scrapped. Real-time Raman analysis allows polymer composition to be monitored and adjusted during production to avoid errors in formulation of the final product."

Although current local efforts are focused on these applications, the lessons learned can be applied to numerous other industrial needs for measurement. "Raman analysis is an extremely flexible method that can solve complex characterization problems in a timely and cost-effective manner," Wachter says. "The different backgrounds and capabilities of the ORNL–Y-12–UTK team have proven critical for effectively and rapidly applying Raman spectroscopy to industrial problems. We expect further successes."

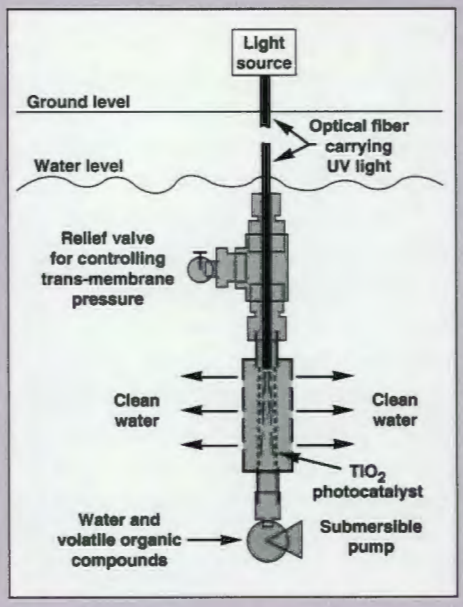
Illuminated Membranes Cleanse Groundwater

Because of its ability to remove grease and dirt, trichloroethylene (TCE) was once used by nearly every metal machining shop, automotive repair shop, and dry cleaner in the United States. Since 1976 environmental regulations have greatly raised the costs of TCE disposal, so its use has been discontinued. However, because some of the TCE used widely in the past was released to the environment, it is now one of the most commonly found contaminants in groundwater. Among its resting places are most Department of Energy sites.

In hopes of cleaning up groundwater and process streams contaminated with TCE and other volatile organic compounds, Oak Ridge K-25 Site scientists are testing the use of special inorganic membranes illuminated by near-ultraviolet (near-uv) light. In this scheme, the contaminated water is circulated through membranes in a cleanup module. The membranes both filter the water and destroy TCE molecules through a photocatalytic interaction on the surface. Specifically, when photons of near-uv light interact with a titanium oxide (TiO_2) photocatalyst on the wet membrane surface, active sites are created that break down TCE into benign molecules.

The membranes were based on technology developed for separating uranium isotopes. The K-25 Site has been a center of inorganic membrane research for many years. The technology can be adapted to fabricate new classes of membranes that are of no value for uranium enrichment but have enormous commercial value for a variety of uses.

"A key advantage of the photocatalytic membrane," says John Stockdale, a developer, "is that the contaminant molecules are brought into close contact with the active surface as the stream flows through the membrane. Other photocatalytic remediation schemes have attempted to overcome this 'contact' problem but are less successful. One method disperses the photocatalyst into the process stream, but the photocatalyst must be added and then filtered out. Another method coats the photocatalyst onto surfaces surrounding the process stream, but ensuring good contact between contaminants and the active surface is difficult."



Schematic of a cleanup module.

The researchers have proposed building a cleanup module and lowering it into a contaminated underground aquifer through a vertical borehole at a DOE site. A mercury arc lamp at the surface will supply near-uv light to an optical fiber. The fiber will carry the light down to the cylindrical membrane where it would emit a cone of near-uv light into the interior of the membrane, illuminating it fairly evenly along a 25-centimeter (10-inch) length.

"A practical groundwater remediation system will contain a bundle of membrane tubes," Stockdale says. "Each tube will be illuminated by a fiber split out from a fiber bundle coming down from the surface. Contaminated water will be pumped into the membrane by a small submersible pump, and clean water will be returned to the aquifer." (See drawing.)

Such an in situ remediation system will be designed for long-term unattended operation. It could be used to purify industrial process and waste streams to protect the environment.

The K-25 Site researchers have been testing membranes under various flow and illumination conditions. Their goal is to improve the photocatalytic process so that visible light will be effective.

"If visible light could be used," Stockdale says, "it might be possible to develop a solar-powered device. Sunlight would be used by solar cells to power the water pump and by the membranes to break apart pollutants. Currently, only 1% of sunlight falls within a wavelength band suitable for photocatalysis. However, a field of implanted solar-powered devices might enable the use of natural sunlight to decontaminate groundwater."

This work is partly supported by DOE's Environmental Restoration and Waste Management Program. Developers of the system are Stockdale, Douglas Fain, and Brian Bischoff, all of the Membrane Technology Department of the Technical Division, K-25 Site, which is managed by Martin Marietta Energy Systems.

Other Photonics Highlights at ORNL

ORNL researchers have helped develop a new laser technique for nonsurgically diagnosing certain cancers.

Tuan Vo-Dinh has developed surface-enhanced Raman optical data storage (SERODS), which may enable industry to create compact discs capable of storing more than a million 300-page books. The technology was recently licensed to SEROTECH, a sister company to World Library Inc., in California.

In the past four years, ORNL researchers have worked on many projects that are now categorized as photonics-related research. Achievements in photonics previously covered in the *ORNL Review* are described here.

ORNL researchers led by Tuan Vo-Dinh of the Health Sciences Research Division and researchers at the Thompson Cancer Survival Center in Knoxville, Tennessee, have developed a new laser technique for nonsurgically diagnosing certain cancers. Using ORNL's special data analysis method and laser light for "optical biopsy" diagnosis, physicians at the center can determine whether a tumor in the esophagus is malignant or noncancerous (see "Nonsurgical Laser Technique Detects Cancerous Tumors," Vol. 26, Nos. 3 and 4, 1993, p. 46).

Vo-Dinh and his ORNL colleagues also have developed a much less expensive test for detecting polychlorinated biphenyls (PCBs) in environmental samples (see "On-Site Test for PCB Contamination," Nos. 3 and 4, 1993, p. 46). The test uses strips of chemically treated paper that glow if exposed to PCBs and then excited by ultraviolet light. In 1994 this development received an R&D 100 Award from *R&D* magazine.

"Using lasers and mass spectrometers, ORNL scientists are detecting structural and chemical changes in small fragments of DNA."

Another development by Vo-Dinh's group is surface-enhanced Raman optical data storage (SERODS). This laser-based technology, which has been licensed to a local company, uses the light-emitting properties of molecules to pack considerably more information onto compact discs. When fully developed, a 12-inch SERODS disc should be able to store information from 18,000 sets of the *Encyclopedia Brittanica* (see "ORNL Concept Would Greatly Increase Optical Data Storage, Vol. 23, No. 1, 1990, p. 85).

Vo-Dinh also developed a surface-enhanced Raman scattering (SERS) technique for measuring concentrations of chemical contaminants in water, soil, and wastes. This technology was licensed to a California company (see "SERS Technology Licensed to GAMMA-METRICS," Vol. 24, No. 1, 1991, p. 62).

A sensitive high-tech SERS probe combining a computer, laser, optical fibers, and a power supply has been developed at ORNL to detect trace pollutants in groundwater. In field tests, the probe detected the groundwater contaminant trichloroethylene at levels as low as 150 parts per million (see "New Probe Detects Trace Pollutants in Groundwater," Vol. 26, No. 2, 1993, p. 65).

Another ORNL invention has been a solar-powered "tracking" microchip smaller than a penny that emits an infrared signal. In addition, a receiver for detecting the microchip's signal from a distance at least twice as far as can be sent by other transmitters of comparable size has been devised and tested. The transmitter and receiver have agricultural and military applications (see "Infrared Microchip and Signal Receiver Being Developed," Vol. 23, No. 2, 1990, p. 56).

Dosimeter badges now in use at Martin Marietta Energy Systems, Inc., are the products of a thermoluminescent dosimetry (TLD) system developed jointly by ORNL and Y-12 Plant researchers. The TLD system automatically measures the amount and type of ionizing radiation to which personnel and the environment are exposed. It also analyzes, stores, and reports this information (see "Radiation Dosimetry System," Vol. 23, No. 3, 1990, p. 74).

Brian Sales and Lynn Boatner in the Solid State Division have found that a higher degree of disorder is present in a crystal surface bombarded with ions than in a glass sample of the same composition. The work helps scientists better understand disordered solids and their effects on light transmission (see "Differing Structures of Amorphous Solids," Vol. 23, No. 4, 1990, p. 19).

Using lasers and mass spectrometers, ORNL scientists Bob Hettich and Michelle Buchanan in the Chemical and Analytical Sciences Division are detecting structural and chemical changes in small fragments of DNA (see "New Way To Detect Changes in DNA," Vol. 23, No. 4, 1990, p. 56). In the Health Sciences Research Division, C. H. Chen and his colleagues have used laser mass spectrometry to measure the masses of DNA molecules and their ions up to 130 chemical bases in length. This system offers the potential for rapid sequencing of DNA bases to determine the composition of human genes (see "Lasers Accelerate DNA Sequencing," Vol. 26, No. 2, 1993, p. 58).

ORNL researchers led by Loucas Christophorou in the Health Sciences Research Division have studied the behavior of electrons in matter. Applications of such knowledge include pulsed power switches, particle detectors, and insulating gases for underground transmission of electricity (see "Chasing Electrons in Gases and Liquids," Vol. 24, Nos. 3 and 4, 1991, p. 9).

An optical sensor using two beams of laser light that can help monitor reactor performance has been developed by Marc Simpson of the Instrumentation and Controls Division (see "Sensors for Health and Safety," Vol. 24, Nos. 3 and 4, 1991, p. 39).

ORNL researchers led by Mike Cates in the Engineering Technology Division have found that fluorescence from phosphorus on hot surfaces in operating centrifuges and engines can reveal surface temperatures (see "New Light on Measuring Temperature," Vol. 24, Nos. 3 and 4, 1991, p. 46).

ORNL's Doug Mashburn has worked with Neocera, Inc., to develop a software-driven, pulsed-laser system for depositing high-temperature superconducting films of a desired composition and thickness. Mashburn's own elaborate laser ablation device shows promise for making thick superconducting films for use in wires and for synthesizing new materials and better phosphor coatings for flat display panels (see "Cooperative Agreement for Automated Film Deposition by Laser," Vol. 26, No. 2, 1993, p. 68, and "Laser Ablation: Opening Doors to New Materials for Industry" Vol. 27, Nos. 1 and 2, 1994, p. 40).

ORNL has evaluated technologies for making optical mirrors originally needed by U.S. defense programs to direct beams of light and particles toward military targets in space. These technologies, which are of interest to the optics industry, include single-point diamond machining that cuts metal at precise angles to get the correct mirror

Doug Mashburn's elaborate laser ablation device shows promise for making thick superconducting films for use in wires and for synthesizing better phosphor coatings for flat-panel displays.

curvature. Such technologies, which were developed at the Y-12 Plant for making weapons components, are now being shared with industrial partners through cooperative research and development agreements (see "ORNL Evaluates Technology for Optical Mirrors," Vol. 23, No. 4, 1990, p. 59; "CRADA on Precision Optics," Vol. 25, No. 1, 1992, p. 91; "New Oak Ridge CRADAs for SDI Optical Systems," Vol. 26, No. 1, 1993, p. 73; "Second Optics MODIL CRADA with UTOS," Vol. 26, No. 1, 1993, p. 73; and "Diamond Tools Evaluated for SDIO Mirrors," Vol. 26, No. 1, 1993, p. 76).

In short, ORNL researchers have been working on a variety of photonics-related projects. Clearly, ORNL has been gaining expertise in this new area of science and technology while using its resources to solve problems in the information, energy, and environmental fields.

Ultraprecision Manufacturing Technologies for Optics

By Brigham Thomas

To help make the United States more competitive in world markets, the U.S. optics industry needs new technologies for flexible production of optical components ranging from contact lenses to giant mirrors. America's smaller companies, in particular, find it risky to develop new manufacturing techniques and expensive to implement them. Government-industry-university collaborations in manufacturing technology are needed now, just as they were back in the mid-1980s when the Ballistic Missile Defense Organization of the Department of Defense (DOD) established a new type of manufacturing research center at federally funded facilities. These Manufacturing Operations Development and Integration Laboratories (MODILs) allowed industrial firms with limited resources to perform research and development for new products while providing DOD with affordable, high-tech weaponry components. The MODIL in Oak Ridge (now called the Ultraprecision Manufacturing Technology Center) has become a model for a new Department of Energy (DOE) effort to improve the competitiveness of the U.S. precision machining industry.

system integrators, and product users talk to each other early in the product cycle. The SDI goal was to identify potential bottlenecks to introducing a new product into the marketplace and to expedite solutions to these problems.

In 1988 the Optics MODIL was located at the Oak Ridge Y-12 Plant (in an ORNL division) to develop and "prove" the effectiveness of new manufacturing processes for making optical parts.

The Optics MODIL was located at Oak Ridge to "prove" the effectiveness of new manufacturing processes for making optical parts.

Brigham Thomas shows then Senator Gore optical components manufactured using precision machining at the Optics MODIL in Oak Ridge. Following congressional hearings on the Hubble Space Telescope problem, Gore was especially interested in Oak Ridge's efforts to certify optics before they left the fabricating machines.

Looking Back

The MODIL concept centered around the "concurrent engineering" approach to manufacturing defense systems, specifically for DOD's Strategic Defense Initiative (SDI) Organization. In this approach, raw material suppliers, designers, manufacturing engineers,

The Y-12 Plant had already used such processes to fabricate mirrors that sent beams of light from the earth to mirrors on satellites to communicate messages and pictures around the world.

The mission of the Optics MODIL was to develop and validate the manufacture of high-

Then Senator Albert Gore, now Vice President of the United States, inspects an Optics MODIL mirror while Gordon Fee, now president of Martin Marietta Energy Systems, looks on.

A lightweight structure and a precision-machined surface are typical features of mirrors used in military systems.

Joe Cunningham adjusts a diamond turning machine used to cut aluminum and other metals to make precisely curved optical components.

precision telescope components, such as mirrors, windows, lenses, and baffles (optical parts having porous surface textures that keep unwanted light from bouncing, or scattering, onto mirrors) for DOD's SDI ("Star Wars") program. These components were considered fundamental to the Star Wars defense concept because of their ability to assist in the early detection of and defense against missiles launched toward the United States. For example, the Optics MODIL worked on developing better optical mirrors for directing beams of light and particles toward military targets in space. Some mirrors were to be used to guide light from enemy launch sites and missiles in flight to detectors that signal interceptor systems to destroy enemy targets.

As these high risk–high benefit technologies became available, the precision optics community incorporated them into their manufacturing processes. The U.S. military benefited from the increased capabilities established at their suppliers' facilities. The result was a "win-win" situation for both industry and government.

Oak Ridge was a logical site for the Optics MODIL; the extensive experience with precision machining at the Y-12 Plant and the collegial atmosphere of ORNL combined to provide a neutral site where firms could develop technologies while protecting proprietary information. This new government-industry relationship did not come easily, though. When the MODIL concept was introduced, many companies looked at Oak Ridge as competition. Some companies had heard the phrase "we are the government, and we are here to help" too many times! But when the program ended five years later, our industry partners made comments such as ". . . (the Optics MODIL) brought together some of the leading optics engineers in the country and fostered real, rather than guarded, dialogue toward solving some of our mutual production problems" and "(we) found the Optics MODIL to be an important forum for technology transfer, industry capability, and government program directions."

Passing the Torch of Technology

The Optics MODIL management believed that technology transfer could best be achieved as a "contact sport" in which industrial researchers visit the site of the government researchers for hands-on activities. Thus, the Optics MODIL entered into seven cooperative research and development agreements (CRADAs) with industrial firms. In fact, the Optics MODIL had the highest per capita number of CRADAs in Oak Ridge for a short time.

Troy Marlar observes a ductile grinding machine as it shapes a spherical section of a silicon carbide mirror substrate.

"The Optics MODIL fostered real dialogue toward solving some of our mutual production problems."

The MODIL also provided sponsorship for university professors interested in performing engineering research at industrial locations. This on-site activity helped mesh representatives of the industrial and academic communities.

The MODIL sponsored numerous industrial briefings and workshops to bring together various companies and organizations in the optics community. Industrial briefings were held twice a year at various locations around the nation to provide small businesses on limited budgets an opportunity to attend. Between 100 and 150 persons attended—a sizable representation of the precision optics industry. One day of the briefing was devoted to an overview and tour of the host facility, providing an opportunity for members of the optics community to gain insights into the operations of other companies, including their competitors.

Workshops were held as needed to help focus MODIL efforts on "burning issues." By limiting attendance to key decision makers, tangible solutions to industry-defined problems resulted. Problems were solved in such areas as environmental controls, diamond tools, "snap-together" design, and optical scatter measurements.

The workshop on environmental controls was especially helpful to our industrial partners. Precise control of a diamond turning machine's thermal environment is one of the most important factors in fabricating high-accuracy components such as precisely curved mirrors. Temperature variations are detrimental to the final product being machined, just as temperature variations and thermal mismatches make it difficult to unscrew a mayonnaise jar lid after it's been in the refrigerator.

It came to our attention that many of our industry partners did not recognize the importance of temperature control. This problem hit home when investigations into a poorly machined part revealed that a manufacturer's diamond turning machine was located directly under an air conditioning vent.

The Optics MODIL had a workshop to showcase our maunfacturing cells built using off-the-shelf equipment at a materials cost affordable to small business. The cells are designed to

Kathy Hylton mounts an optical component in preparation for ion beam milling to shape precisely curved surfaces.

The workshop on environmental controls was especially helpful to our industrial partners.

Joe Cunningham (left) and Art Miller check a device used to measure the shape and curvature of a mirror produced by diamond turning at the Optics MODIL.

control the temperature to within a tenth of a degree, enabling the manufacture of ultraprecise components. The workshop participants took back to their companies information on building manufacturing cells to suit their needs.

One unprecedented workshop on lessons learned was held early in the program. The Optics MODIL wanted to determine the optics industry's capabilities for manufacturing precisely curved, lightweight mirrors. Industry's response ran along the lines of "send us the money and we can make it." Because precision optics were typically made under cost-plus contracts on a best-effort basis, that response was the norm. So the Optics MODIL put industry to the test by requesting mirrors with a defined specification, at a fixed price, with a defined delivery date. The two companies that were awarded the contract worked diligently to produce the ordered pieces. However, both companies delivered mirrors that failed to meet our specification. They had to absorb most of the cost as a result of unexpected overruns, and they were late in delivering the mirrors.

To determine the problems these companies had encountered in making the product, the Optics MODIL sponsored a Lessons Learned Workshop. Incredibly, representatives of the two companies told their competitors what they did wrong (hindsight is 20/20) and what they would do differently the next time. By the beginning of the second day of the workshop, the interactions among attendees were astounding; it was almost like being at a revival. Confessions were made such as "we should not have tried to polish the mirror so early." And support was offered. "Yes, we've made that mistake before," said one attendee, "and this is how we corrected it." This workshop proved that competing firms can work together toward the common goal of improving their collective position against foreign competition.

Because technology transfer was one of the major thrusts, we were innovative and proactive in pursuing effective means of transferring information that would be most beneficial to our industrial and academic partners. Our approach was sometimes to "do first and ask later!"

For example, we did not ask permission from our sponsor or DOE for a third party to host a briefing on issues of interest to the optics industry. Instead, we approached companies, universities, and other government laboratories and asked if they were interested. They were more than willing to host an industrial briefing and showcase their facilities. These hosts included, among many others, the universities of Alabama and Arizona, North Carolina State University, the National Institute of Standards and Technology, Hughes, Martin Marietta, and Lockheed.

The Oak Ridge facility is unique because it demonstrates integration of these manufacturing technologies to produce parts right the first time.

Curt Maxey aligns a paraboloidal segment of a beryllium mirror in laser light to measure the quality of its shape. The interfering light beams from the laser interferometer are used to map imperfections in the mirror surface.

The Technology

Some technologies employed at the Y-12 Plant for making precisely curved mirrors for lasers have been used for manufacturing optics by the Optics MODIL and its successor, the Ultraprecision Manufacturing Technology Center. These technologies are described here.

Single-point diamond turning is a computer-controlled machining process developed in the late 1960s at DOE laboratories and first used to make sophisticated mirrors for high-energy laser systems. It uses a gem-quality diamond in a lathe-type action to create a precisely shaped, smooth surface on a part, eliminating the time-consuming, unreliable step of polishing. Thanks to the Rank Pneumo Nanoform 600 machine in Oak Ridge, complex-shaped surfaces can routinely be generated to an accuracy of 1/4 wave (wavelength = 0.633 micrometers) in aluminum, copper, nickel plating, and numerous other materials. To illustrate this machine's precision, consider a typical mirror that is 12.7 centimeters (5 inches) in diameter and has a surface accuracy of 1/4 wave; this accuracy is comparable to limiting the elevation of the highest mountain peaks in the state of Arizona to 0.6 meter (2 feet). Accuracies like that are needed in military satellites deployed in space to detect missiles launched from the earth's surface.

Ductile grinding is a precision method for machining brittle ceramics by shearing material off the surface. Materials such as silicon carbide and sapphire can be machined with minimal subsurface damage. The Optics MODIL worked cooperatively with university and industrial partners to develop an acoustic emission technique to "listen" to the process. When machining parameters are not ideal, cracks and chips form in the surface of the material. The sound of a propagating crack can be detected, just as the cracking of a fine china plate can be heard. The potential benefit to industry of this manufacturing technology is the ability to use acoustic feedback along with machine controls to automatically maintain a more favorable ductile-shearing mode of operation.

Ion beam milling uses ions in gas to shape surfaces. The ions, acting like billiard balls, knock atoms off the surface of a material. Users of this technique can improve a surface to an accuracy of 1/20 wave. This level of precision is equivalent to creating a state of Arizona that has no point higher than 12.7 centimeters (5 inches) above the ground surface!

All three of these manufacturing techniques are available in industry in one form or another. However, the Ultraprecision Manufacturing Technology Center in Oak Ridge is the only facility in the United States that has all three capabilities under one roof. The Oak Ridge facility is unique because it can demonstrate the integration of these manufacturing technologies to produce parts right the first time, eliminating the need for rework or for scrapping a defective part.

A key to integrating these manufacturing techniques is on-process characterization. In industry, an optical component is typically generated on the machine, removed, and then taken to another facility for inspection. If the part does not meet specification (e.g., the shape is not right), it must be remounted on the machine and reworked. This approach is time-consuming, expensive, and not always successful. The Oak Ridge center promotes on-process inspection to verify the accuracy of the part while it is still on the machine, thus improving the manufacturing efficiency and reducing the cost of optics manufacturing.

Maxey demonstrates the stability of a vibration-free polarization shearing interferometer. This robust machine helps solve a variety of high-resolution measurement problems in manufacturing environments.

An example of our support of on-process inspection is the development by one industry partner of a revolutionary tabletop scatterometer that can determine light-scattering properties over wide angles in real time. Applications for this instrument include rapid nondestructive testing of magnetic and optical disks, machined parts, and laser printer drums. The Optics MODIL commonly awarded subcontracts (as in this example) to small and large companies on challenging activities to help industries help themselves by developing new products and processes.

The Personnel

More than 50 people, including a core staff of 18, contributed to the Optics MODIL program over the past five years. The program's well-rounded staff of designers, engineers, scientists, physicists, technicians, and administrative support represented all three sites in Oak Ridge. People often ask the staff, "How did you pull it off?" There is no one-word answer to this question. Effective leadership, a proactive sponsor, a highly motivated staff that was willing to go the extra mile to get things done, and an atmosphere of having fun on the job have been among the top contributing factors to this successful program.

A New Mission

DOE recognizes that the research talent, manufacturing expertise, and fully equipped facility developed by DOD's Optics MODIL program is a national resource that can contribute to the global competitiveness of the precision manufacturing industry. Thus, DOE is funding this activity under a new name. Called the Ultraprecision Manufacturing Technology Center, it is one of the Centers for Manufacturing Technology at the Y-12 Plant. The center has a new and expanded mission. It no longer focuses only on manufacturing processes for optical systems. Instead, its resources are being applied to the many industries that need ultraprecision components, such as the medical, environmental, and electronics enterprises.

The Ultraprecision Manufacturing Technology Center is now a designated DOE user facility; it provides a convenient mechanism for visiting researchers to use our state-of-the-art equipment. The transition from one agency sponsor to another

The center's resources are being applied to medical, environmental, and electronics enterprises.

A CRADA was recently negotiated to help this small business beat out foreign competition!

illustrates the government's goal of using resources most effectively to benefit taxpayers.

The center staff is excited about new opportunities as its horizons move beyond optics for defense applications. The center has been working with an environmental firm in Knoxville, Tennessee, that manufactures air quality monitors. This small business is losing market share to a German competitor. Discussions between technical staffs revealed areas for improvement in the design and manufacture of their product. By making a contact through the National Machine Tool Partnership, a multiagency-sponsored assistance program, this firm got an introductory feel for our capabilities. Next, the company came to the center as a "user" to conduct hands-on research. Finally, a CRADA was recently negotiated to bring this effort to closure and help this small business beat out foreign competition!

Another demonstration of our commitment to supporting domestic industry involves an effort with a contact lens manufacturer. The characterization of contact lenses presents many challenges, not only because the product is flimsy and slippery but also because its demand is high. Each lens must be measured for performance (will it correct a wearer's vision as intended?) and appearance (does the lens have scratches?). A cooperative effort investigated methods of automating the contact lens inspection process.

The Ultraprecision Manufacturing Technology Center staff has also worked closely with U.S. suppliers of single-point diamond tools. Many of these U.S. firms are small businesses that are competing with large, well-established foreign companies that have large resources. Because the shape of the tool is instrumental in forming extremely accurate contoured parts, the tool companies needed a method of measuring the tool's roundness within a few millionths of an inch. They also needed a map showing the size and location of roundness errors.

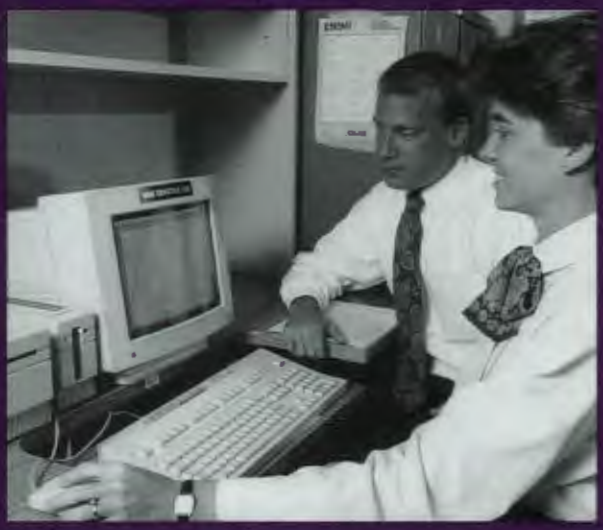
The problem was that users of the tool had to do in-house inspections to determine if the tool met their needs. The users had to machine and inspect a part; if it failed to measure up, it would eventually be scrapped. Unless this situation changed, the U.S. tool suppliers were at risk of losing customers.

We developed a user-friendly technique with an easy-to-read output that verifies the accuracy of the diamond tool edge for the tool industry. Now, the diamond tool supplier can provide data to the tool user that verify the tool's accuracy. Our technique saves the user time and money because in-house acceptance testing is no longer needed.

By working with a number of private companies, we have been able to pinpoint areas for improvement in the design and manufacture of their product. This capability, combined with providing companies access to the center's research facilities, helps to create partnerships that benefit business, the center, and the nation.

Biographical Sketch

Brigham Thomas, a ceramic engineer at ORNL, was manager of the Optics MODIL Program in 1992–93 and of the Ultraprecision Manufacturing Technology Center in 1993–94. Recently, she served as liaison between the Department of Energy and the National Institute of Standards and Technology (NIST); in this capacity, she facilitated relationships and collaborations between NIST and DOE staff and laboratory researchers. She is now participating in program development within ORNL's Engineering Technology Division.



Involving university students in the Optics MODIL program was one of its many successful outreach activities. Here, Brigham Thomas works with Bill Cole, then a graduate student at the University of Tennessee.

A native of High Point, North Carolina, she earned a B.S. degree in ceramic engineering from Clemson University in 1984. She then went to Texas to develop materials with special electromagnetic properties for the Materials and Processes Group of the General Dynamics–Fort Worth Division. She also participated in a joint program between General Dynamics and McDonnell Douglas for developing the next-generation Navy attack plane. She then joined the Advanced Composites Group at Pratt & Whitney in West Palm Beach, Florida. Working in an Air Force–sponsored R&D program there, she helped develop fiber-reinforced ceramic composites for engines.

In 1990 she joined ORNL's Engineering Technology Division as Optics MODIL project manager. She managed subcontracts to evaluate industry's ability to cost-effectively manufacture precision optics. In 1991–1992 she served as technical assistant to the ORNL associate director for Engineering and Manufacturing Technologies, which included robotics, instrumentation and controls, engineering technology, and guest and user interaction.

In 1985 she was a charter member of the Fort Worth section of the Society of Women Engineers. She is currently serving on the Executive Committee of the American Society of Mechanical Engineers–Management Division.

We have helped private companies improve their design and manufacture of products.

ORNL's Thin-Film Waveguide and the Information Highway

By Carolyn Krause

More and more Americans are cruising the information highway. They are accessing the Internet and sending electronic mail throughout the world. They are looking forward to the day when they can tune in to hundreds of cable television channels. Eventually, they will use their telephones and television sets to call up their favorite movies to watch immediately or store for later viewing. They will be able to receive airline schedules, news, and catalog shopping information when they want them.

To speed communication and retrieval of information as the number of users increases, the evolving information highway must be constructed to expand its high-speed data traffic. A possible solution to this capacity problem is a promising new material developed by researchers at Oak Ridge National Laboratory. The material is being studied for possible use in optical switches for networks of glass, or optical, fibers that are as fine as human hair. Preliminary results indicate that the ORNL material could pave the way for much greater use of the emerging information highway.

Using a technique called molecular beam epitaxy (MBE), Rodney McKee and Fred Walker, scientists in ORNL's Metals and Ceramics (M&C) Division, have developed an optically clear ceramic film for transmitting waves of light. This "waveguide" material consists of barium titanate, deposited one atom-layer at a time on a crystal of magnesium oxide. They have also shown that the waveguide material can be deposited on silicon. Their goal is to develop an optical switch consisting of silicon on which is deposited magnesium oxide, the barium titanate waveguide, and appropriately configured electrodes.

The light-transmitting ability of the barium titanate films has been verified in tests at ORNL, Wright-Patterson Research and Development Center in Ohio, Hughes Aircraft Corporation in California, and AT&T in New Jersey. In these tests a laser is used to transmit a 1-millimeter-wide beam of light through the waveguide medium, but ultimately a 1-micrometer-wide channel, or optical path, will be used.

Even with today's technology, an optical fiber uses less than 1% of its theoretical capacity, or bandwidth, for carrying information. In other words, the information highway has room for considerably more high-speed data traffic if the appropriate technology is developed.

"Switches using this type of waveguide could increase the amount of information carried by fiber-optic cables by 100 times," McKee says.

ORNL researchers have developed a new class of thin-film waveguides.

A light beam from a laser at left (shown on front cover) is bent by a prism (darkened triangular solid in foreground) before entering and passing through a thin-film waveguide, whose borders are also illuminated by laser light. The light-conducting material, made of barium titanate deposited on magnesium oxide, is of interest to industry and the government because of its potential for improving optical switches and other devices.

Rodney McKee (standing) and Fred Walker view a video camera image of a laser beam passing through a waveguide material they developed. In front of the monitor screen are a laser, laser beam, waveguide sample, and camera.

Since the advent of lasers in the early sixties, scientists have dreamed of replacing electrical circuits with all-optical circuitry.

"Since the advent of lasers in the early sixties, scientists have dreamed of replacing electrical circuits with all-optical circuitry or integrated electro-optical devices in silicon-based technology. With these materials, our dreams may soon become reality."

Over the next few decades, copper wire for telecommunications will be replaced with optical fibers made of glass. Glass is much cheaper and more common than copper. Even more important, glass fiber can carry 250,000 times as much information in the form of light from lasers as does a standard copper telephone wire conducting electrical signals. The reason: glass conducts light signals of much higher frequency—number of waves per second—than copper can for electrical signals. The higher the frequency, the more information can be packed into light signals.

The ORNL achievement will contribute to recent developments that have enabled the transmission of increased amounts of information by light. They include miniature lasers on silicon chips (laser diodes), improved optical fibers that carry light longer distances, and optical switches, which convert electrical signals to light signals.

Such technology must economically produce key components of the information highway. It should use a single fabrication process to incorporate laser diodes, microcircuits, electrodes, and optical switches on a silicon chip, or substrate (the physical structure that provides electrical and mechanical support for microelectronic components). Silicon is the choice support structure for these components because of its purity, crystal perfection, and associated electronic and physical properties.

Optical Switches

Although a number of material systems are being studied, the waveguide material chiefly in commercial use today for optical switches is lithium niobate. However, this material is damaged after repeated passage of laser light, making the laser signal too weak for the switch to work. Another drawback is that no way has been found to integrate this material with other components on silicon. Currently, lithium niobate cannot be deposited as a thin film on silicon as can barium titanate. ORNL's ability to grow barium titanate as a single-crystal thin film one layer of atoms at a time can produce a well-ordered and nearly defect-free material with electro-optical properties potentially 35 times better than those of lithium niobate. In other words, a barium titanate switch could be 35 times smaller or use 35 times less electricity than a lithium niobate switch.

Each piece of digital information traveling on the information highway is called a binary digit, or bit. A bit is either a 1 or 0; a combination of 8 bits, which can define a letter or number, is called a byte. Bits can be transmitted into a glass or copper-wire cable by a switch. If a switch is on, it lets through a high-intensity light or electrical signal that represents a 1; if the switch is off, it passes a low-intensity signal that represents a 0. Each combination of high-intensity and low-intensity signals represents a word, number, or other data.

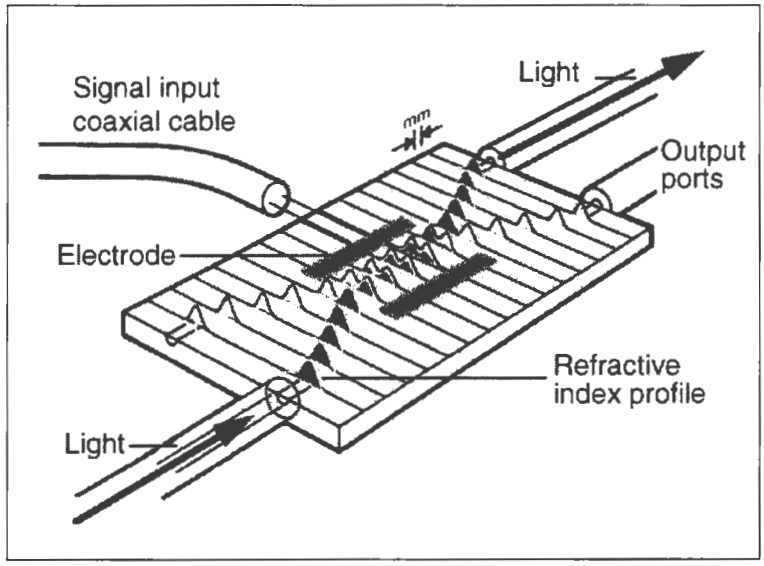
Today digital pulses, or bits, of information are sent down optical fiber by gating—turning on and off—laser diodes, tiny sources of light of different frequencies (representing different telephone conversations, for example). More advanced technology uses lithium niobate to gate light from a continuous laser source. Although lithium niobate switches are faster than switched lasers, the data transmission rate is still limited to a frequency level of 1 to 10 gigahertz. With barium titanate (which has a larger "bandwidth"), the data transmission rate can reach 1000 gigahertz, permitting about 100 times more information to be transmitted.

In optical guided wave devices such as optical switches, electric fields are pulsed to switch the light signals on and off in the waveguides, which have a much faster response than the laser diodes. The reverse is also true: Light signals to waveguides on silicon chips are rapidly converted to electrical signals.

In an optical switch using barium titanate, light is split into two paths. An alternating electric field is applied to the electrodes of one of the beam paths. When the field is on, it changes the phase of the light signal in one path relative to the other path; in other words, the field causes the waveguide material to shift the positions of

the crests and troughs of the light waves passing through. When the two beams of light recombine, they mutually interfere, reducing the intensity as the light exits. When the field is off, the split light beams recombine as a signal with the same intensity they had entering the switch. The resulting combinations of increases and decreases in light intensity serve as rapid "on-off" switches, greatly increasing the amount of information transmitted.

McKee and Walker are developing a prototype optical switch using barium titanate as a planar waveguide with aluminum electrodes attached to do the on-and-off switching. They are also working with AT&T on an optical switch in which narrow channels for light about the size of the wavelength of visible light are etched into the ORNL waveguide material. It is these channel waveguides that allow practical optical circuits to be integrated into the material. This new class of waveguide structures and their potential for integration into silicon-based technology, if exploited in a timely manner, could advance communications technologies, benefiting consumers, industry, and the federal government.



Drawing of an optical switch for use in fiber-optic telecommunications.

The light was efficiently conducted through the waveguide with practically no loss of intensity.

Formation of Thin Films

Since 1989 McKee and Walker have been using the demanding technology of MBE to form these light-transmitting ceramic thin films on an optical isolation layer of magnesium oxide on silicon. Although their research and approaches to this materials development problem have been at a very fundamental level, they have developed practical technology while making scientific advances. As a result of their work, they have received one patent, applied for three more, and published a series of journal articles in *Applied Physics Letters* and *Physical Review Letters.*

The ORNL researchers were the first to grow high-performance thin-film ferroelectric oxides with low losses of light. They use MBE to build each film layer by layer, creating a desired ordered structure to enable the transmission of light. To produce the optical waveguide on silicon, the researchers first grow a transition oxide a few atom layers thick on a single-crystal silicon substrate. This transition oxide is a critical component that provides a structural match to magnesium oxide (MgO). Magnesium oxide was chosen because of its optical properties, crystal structure, and stability. As an isolation layer, it separates the waveguide from the substrate, preventing the silicon from absorbing and dissipating light passing through. Also, its atoms can be lined up with those of silicon, the unique transition oxide, and barium titanate, permitting properly oriented growth of these materials.

MgO is an alkaline earth oxide like barium oxide, calcium oxide, and strontium oxide. The ORNL researchers thought that atoms of any of these materials could be lined up with those of silicon and barium titanate, the waveguide material. The researchers used barium oxide (BaO) first as an isolation layer, but they found that it reacted with water vapor during the deposition process, forming barium hydroxide. In

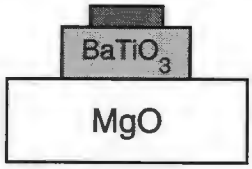
McKee (foreground) and Fred Walker optimize the process whereby molecular-beam epitaxy techniques are used to deposit a light-conducting barium titanate film on a layer of magnesium oxide. The result of this process is a thin-film waveguide.

their experiments they found that MgO worked much better as an isolation layer.

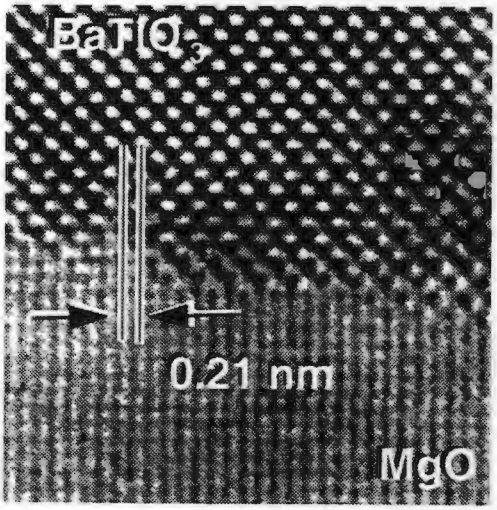
Barium titanate is both a perovskite (a mineral with a roughly cubic crystal structure like that of silicon and MgO) and a ferroelectric (a material in which the positive and negative ions move apart, setting up electric fields within the crystal). The interaction between the internal electric field and the applied external field controls the material's ability to influence the information content in a guided light wave.

The ORNL group formed a transparent film of alternate one-atom-layer-thick deposits of titanium oxide (TiO_2) and BaO. The researchers aligned the atoms of TiO_2 with respect to the atoms in the MgO layer. Next they added a BaO layer in proper alignment with the TiO_2. They repeated the process many times, fabricating a barium titanate film thick enough to transmit a thin laser light beam. The light was efficiently conducted through the waveguide with practically no loss of intensity. In addition, the researchers showed that the waveguide film and isolation layer could be deposited on a silicon substrate. They are now working on growing these films on larger-diameter silicon to reduce the cost of each optical switch and make the manufacturing process more economical.

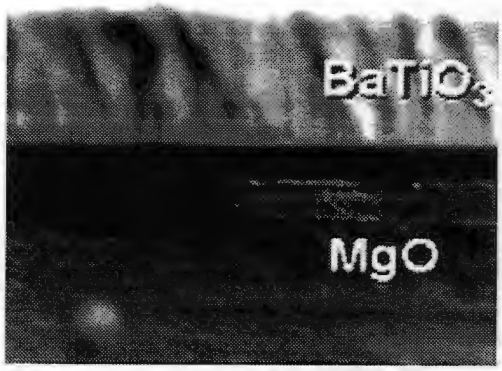
In making a $BaTiO_3$ film, why is a TiO_2 layer rather than a BaO layer deposited first on the MgO layer? The reason, McKee says, is that the arrangement of the atoms makes for a good electrostatic fit, or proper "ionic coordination," between the layers. The positively charged titanium ions in the waveguide layer interfacing with the isolation layer are attracted electrostatically to the negatively charged oxygen ions in the MgO layer, and the positively charged magnesium ions are attracted electrostatically to the negative oxygen ions in the TiO_2 layer. Depositing a BaO layer on the MgO layer first does not work; when placed near each other, the atoms in both layers (barium atoms on magnesium atoms, and oxygen atoms on oxygen atoms) will repel each other because of like charges. Deposition of the TiO_2 layer, which is formed by vaporizing a titanium sample in low-pressure oxygen, is followed by deposition of a BaO layer,



A thin film of barium titanate has been deposited on magnesium oxide to make a waveguide material that can be integrated with silicon.

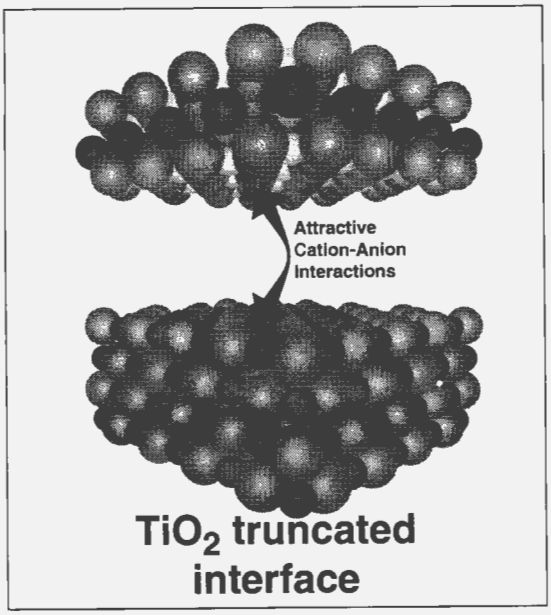


This transmission electron micrograph shows that the interface between the waveguide's barium titanate and magnesium oxide lattices is chemically and structurally sharp.



This scanning electron micrograph clearly shows the interface between barium titanate and magnesium oxide in a fracture cross section. The barium titanate film is 0.6 micrometers thick.

Our tests show that magnesium oxide is an effective isolation layer.



This drawing shows the attractive electrostatic interaction between positively charged titanium ions in the waveguide's titanium oxide layer and the negatively charged oxygen ions in the magnesium oxide layer below and between the positively charged magnesium ions and the negative oxygen ions in the titanium oxide layer. Deposition of a barium oxide layer on the magnesium oxide layer first (instead of the titanium oxide layer) does not work. When placed near each other, the atoms in both layers (barium atoms on magnesium atoms, and oxygen atoms on oxygen atoms), will repel each other because of like charges.

then a TiO_2 layer, then a BaO layer, and so on to form $BaTiO_3$.

"This technique is called planar stacking," McKee says, "because layers are stacked to form a compound of both a desired composition and structure. We hope to improve the properties of existing compounds and synthesize new materials this way."

Layered Structure

An obvious example of a waveguide is a mirror placed upon a mirror so that only the silver backing is visible. If light is passed between the two mirrors, it will be reflected between them as it moves from one end to the other. The most familiar waveguide is the optical fiber. Light is guided along an optical fiber by undergoing total internal reflection at the interface between the air and the glass fiber.

Glass fibers and other transparent materials can form waveguides if their index of refraction is significantly higher than that of the surrounding medium. In such a case, light trying to escape the waveguide into the medium will be bent back, or internally reflected, into the waveguide. The best waveguides minimize optical losses.

Because of the importance of the refractive index in keeping the light inside the waveguide, the ORNL researchers in collaboration with David Zelmon of Wright-Patterson Research and Development Center in Ohio developed a four-layer waveguide structure. The first three layers are silicon, MgO, and $BaTiO_3$. The fourth layer, air, acts as an isolation layer like MgO.

"To make a ferroelectric waveguide," says McKee, "we could not simply deposit barium titanate on silicon to make a three-layer waveguide (with air as the top layer) because silicon's index of refraction is higher than that of barium titanate. Because silicon will absorb and dissipate light, we had to put down an optical isolation layer between the substrate and guiding layer. We chose magnesium oxide because its index of refraction is lower than that of barium titanate and because its atoms can be lined up with those of silicon and barium titanate, making a good epitaxial film. Our tests show that magnesium oxide is an effective isolation layer."

The index of refraction for $BaTiO_3$ is 2.4, significantly higher than the refractive indices for the two isolation layers. For MgO it is 1.8, and for air it is 1. The differences keep the light traveling in the $BaTiO_3$ layer.

Molecular Beam Epitaxy

Using MBE techniques to make the thin films, the researchers heat a magnesium oxide crystal grown by Lynn Boatner of ORNL's Solid State Division. The crystal's MgO molecules vaporize in a chamber containing a silicon substrate in ultrahigh vacuum. Because the chamber is kept at extremely low air pressure, the vaporized MgO

molecules reach the silicon without encountering many air molecules. Titanium and barium are vaporized and reacted with oxygen to make alternating layers of titanium oxide and barium oxide, which are aligned to form a barium titanate waveguide film.

"To produce a thin film with good optical quality," McKee explains, "we maintain stringent synthesis and processing requirements at the near-interface regions. We have to regulate the arrival rate of the oxygen, the temperature of the metal being vaporized, and the temperature of the substrate. Source-shuttering MBE techniques give us control at the atomistic level of materials development."

To make defect-free, crystalline films in which all the atoms are epitaxially aligned, the ORNL researchers monitor film formation using reflection high-energy electron diffraction (RHEED). RHEED directs a high-energy electron beam at the sample at a very low angle (1 to 2°) to obtain detailed surface information. If the monitoring technique indicates poor atomic alignment and crystalline imperfections, then the researchers change temperatures, pressures, and other parameters to improve film quality.

"When RHEED electrons strike the atoms of the film," says McKee, "they are deflected to a phosphor screen, and the points of light there show the arrangement of the atoms in a crystalline pattern and indicate whether the film is growing across the substrate surface in an orderly way. Distortions in the electron pattern can indicate defects in the crystalline structure, telling us that we must fine-tune the film-forming process."

"Our group at ORNL has achieved the first demonstration of optical clarity in thin-film barium titanate."

Thin-Film Waveguides and Optical Computers

Improved waveguides are needed in the world of data processing, where faster is better. To speed up calculations, silicon-based optical computers are envisioned in which optical waveguides and optical interconnects are incorporated to reliably transmit light signals.

Currently, there is a significant technological barrier to efficent transmission and attempts at manipulation of large data arrays. Today's electronic switching technology, which converts light to electrons and back to light again, cannot convey all the information crammed into the initial light signal at the highest possible speed.

Viewers of teleconferences are aware of this problem. Today, a person in a tele-conferencing image appears in black and white and makes jerky hand motions. This is a bandwidth problem; even a slow optical switch can switch a very wide bandwidth optical signal more effectively. Integrated optical guided wave devices and optical interconnects of the future will render teleconference images that are in color and show continuous movements.

Besides its wider bandwidth, light offers two other advantages over electrons for data processing. The way an optical signal can be processed using optical waveguides and interconnects could greatly increase the speed of future computers. For both serial processing and parallel processing of data, light pulses—or bits of information—in an optical signal can be generated at rates that are at least 1000 times faster than electronic pulse rates. This advantage should make possible ultrafast serial data processing that cannot be achieved electronically. Moreover, a digitized image that might contain 10^8 bits/cm^2 can be transmitted as a multiple-wavelength optical signal in an optical computer, and parallel processing can be used to speed up the image manipulation for display.

In a world where faster is better, thin-film waveguides like those being developed at ORNL may be the key to tomorrow's computers and data-handling devices.

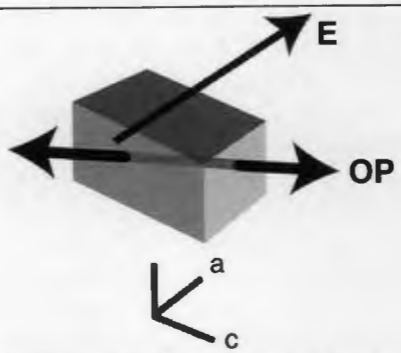
Evaluating the Waveguide

A variety of ORNL resources have been called upon to analyze the material and optical properties of the thin-film waveguide. Kathi Alexander, a materials researcher in the M&C Division, has been studying the waveguide's crystalline lattice structure using the Hitachi field-emission gun transmission electron microscope at ORNL's High Temperature Materials Laboratory. She hopes to determine the structure of the magnesium oxide–barium titanate interface that provides optical clarity. Scanning electron microscope images produced in the M&C, Solid State, and Health Sciences Research divisions have shown that the thin-film waveguide's optical properties are superior to the bulk materials now used.

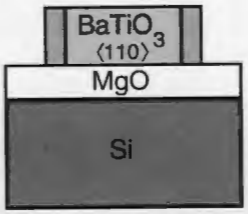
In the fall of 1994, McKee and Walker demonstrated that this new class of waveguides could be integrated with silicon.

"Our group at ORNL," says McKee, "has achieved the first demonstration of optical clarity in thin-film barium titanate. Characterization of our waveguides produced by growing nearly perfect thin films of barium titanate on magnesium oxide has shown that their ability to channel light with little loss in intensity is as good or better than that of bulk titanium-drifted lithium niobate waveguides. This materials synthesis achievement points the way towards development of a whole new class of waveguides—thin-film perovskites on alkaline earth oxides.

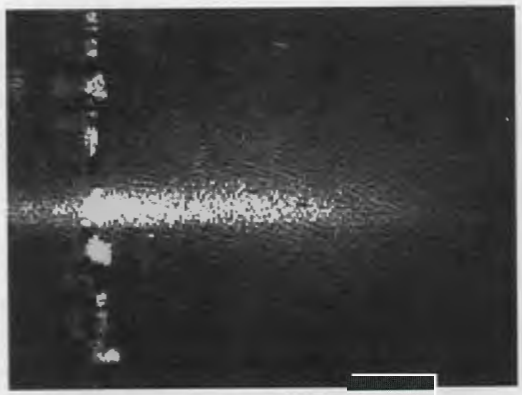
"This ORNL development is important for several reasons. First, the bandwidth achievable for these thin-film waveguides is about 100 times that of a bulk ferroelectric like lithium niobate. Second, the electro-optic coefficient is 35 times larger than that of lithium niobate and 300 times larger than that of gallium arsenide. Such a high-performance characteristic would enable fabrication of smaller, faster, and more efficient devices. Third, we have shown that, unlike lithium niobate, our barium titanate—magnesium oxide composite waveguide can be deposited on silicon and that, fortunately, the problems we anticipated in integrating our waveguide material with silicon to make practical devices can be avoided."



In the ferroelectric state represented by c/a, the internal electric field polarization is parallel to the c direction. The optical polarization (OP) is at 45° to both the internal and applied electric (E) fields.



The barium titanate and magnesium oxide composite thin films are deposited on silicon. The MgO provides optical isolation, confining the light to the $BaTiO_3$ layer. Electrodes at the side apply an electric field at 90° to the internal electric field, and the best possible electro-optic properties are obtained in the $BaTiO_3$ waveguide from its deposition on silicon.



ORNL researchers recently demonstrated that light can be channeled through barium titanate and magnesium oxide composite thin films that have been deposited on silicon, as shown in this video image.

The Silicon Solution

When efforts were initiated to try integrating these waveguide structures with silicon, McKee, Walker, and others were concerned about the structural change that occurs when the $BaTiO_3$-MgO films cool after being deposited on silicon. The question was this: although the waveguide material is chemically compatible with silicon, is it structurally compatible after deposition as a film?

In the fall of 1994, McKee and Walker demonstrated that this new class of waveguides could be integrated with silicon. McKee reported this success at the Materials Research Society annual meeting in November 1994. He also reported their finding that the structural change that caused concern actually favors the fabrication of a silicon-based waveguide!

When deposited on silicon, the $BaTiO_3$ film is in its cubic phase. As the $BaTiO_3$ film and silicon substrate cool, the film tries to shrink but stays in place on the substrate. As a result, the microstructure of $BaTiO_3$ is stretched—from a cubic to a tetragonal configuration. In other words, if the structural change could be greatly magnified, you would see stacks and rows of cubic boxes turned into stacks and rows of upright milk cartons.

To relieve this tension, the molecules shift 90°C or "lie down," thereby aligning their long axis with the surface of the plane. Viewed another way, the "milk cartons" are laid down on their sides.

"This transformation is critical to waveguide development," McKee says. "The new alignment makes it possible to obtain barium titanate's optimum electro-optic coefficient. It allows us to easily orient the applied electric field with the crystal's internal ferroelectric field and optical polarization of the traveling light wave signal—that is, the orientation of the light wave vibrations. Thus, this favorable structural change will enable us to integrate our waveguide material with silicon and to control the waveguide structure so that practical silicon-based optical guided wave devices can be built."

McKee explains the technical basis for his concern about integrating the waveguide material with silicon. "The electro-optic properties of barium titanate are directionally dependent," he says. "So we were concerned about the spontaneous polarization—the collective displacement of charged ions—and the domain structure—regions in which positive and negative ions separate, setting up electric fields—in the crystalline film of barium titanate.

"We knew that barium titanate's spontaneous polarization and domain structure could couple to thermal strain in the silicon substrate, making it difficult to achieve the best possible electro-optic response. But Nature has been kind to us. We found that a unique and potentially advantageous domain structure can be obtained for our barium titanate–magnesium oxide waveguides if we grow them on silicon."

For their silicon demonstration, McKee and Walker received support from ORNL's Laboratory Director's R&D Fund. They are using this funding to develop methods of depositing waveguide material on silicon at a lower temperature—a range of 300 to 500°C instead of 500 to 800°C. A lower temperature is required to make silicon chips that integrate microcircuits, laser diodes, and optical switches using a single economical fabrication process. To accomplish this goal, McKee says, adjustments must be made in the oxygen pressure of the film-growth chamber and the arrival rate and time for oxygen in contact with the vaporized metals of magnesium, barium, and titanium.

McKee and Walker will continue work with collaborators to achieve the correct thicknesses of the light-guiding and isolation layers for the four-layered waveguide structure, to develop better optical switches, and to make possible the economical manufacture of silicon chips that integrate optical switches with laser diodes and microcircuits. These developments could help the United States win the global race to find ways to significantly speed up communications and computations (see sidebar on p. 41), greatly improving the information superhighway.

"Nature has been kind to us. We found that a potentially advantageous domain structure can be obtained for our waveguides if we grow them on silicon."

Early Signs of Environmental Damage and Recovery

By S. Marshall Adams

The American public is becoming increasingly aware that the natural environment is fragile. The news media have reported on many instances of environmental changes affecting animal life, often as a result of pollutants from human activities. Recent reports have focused on

- Deaths and population declines of birds and fish because of the large oil spill in Prince William Sound in Alaska;
- Deaths of porpoises and whales along the east coast of the United States, possibly as a result of pollutants and disease;
- Fish contaminated with polychlorinated biphenyls (PCBs) in Fort Loudoun, Tellico, Watts Bar, and other East Tennessee reservoirs;
- Contamination of the Pigeon River in Tennessee and North Carolina by dioxin and other pollutants that may cause cancer and reproductive disorders.

These events may be omens that other forms of life, including people, could become threatened if environmental conditions continue to worsen. But how much worse must conditions be before wildlife and human life are in danger? Or are they in danger already? Clearly, better methods are needed to predict the probability of future environmental and health problems based on present evidence. Such information could guide environmental regulators and decision makers in taking actions in time to minimize damage to the environment and human health.

Biological events, such as increases in the populations of pollution-sensitive species in a river or the return of a fish species to a once-polluted stream, can also indicate recovery of an ecosystem. Such information helps scientists determine the extent to which remediation of a contaminated waterway has been successful.

Biological events that provide information about the environment include more, however, than increases and decreases in animal and plant species. A variety of pollutants resulting from human activities can interfere with the normal functioning of an organism, making it less able to grow normally or reproduce successfully in its environment. Short of death, some of the more common but serious effects of environmental

Marshall Adams takes a blood sample from a fish collected from Watts Bar Reservoir for bioindicator studies.

stressors on aquatic organisms are changes in behavior, growth, and reproduction. These changes in individual organisms, known as biological indicators (or bioindicators, for short), can eventually result in large-scale changes in biological communities and even ecological systems.

A variety of pollutants resulting from human activities can interfere with the normal functioning of an organism.

Analysis of fish blood could indicate the presence of environmental threats to wildlife and people.

Bioindicators are useful because they are telltale signs of impending environmental problems.

ORNL researchers collect fish samples from East Fork Poplar Creek in Oak Ridge.

Researchers in the Environmental Sciences Division (ESD) at Oak Ridge National Laboratory are using wildlife species, such as fish and waterfowl, as bioindicators of ecosystem health. Our goal is to develop and improve our capabilities for detecting and predicting the effects of environmental stress on key, or "sentinel," ecological species. This information could lead to appropriate actions that prevent undesirable and irreversible effects in ecological systems such as streams, rivers, and lakes.

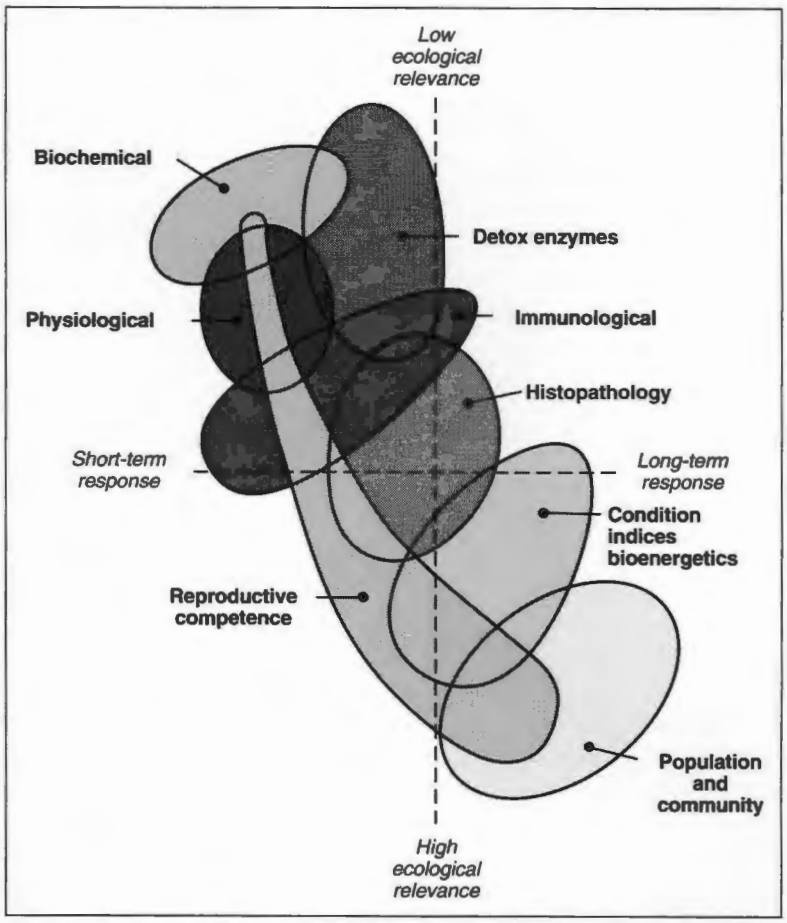
At ORNL Mark Greeley, Rhonda Epler, Kai-Lin Lee, Lee Shugart, and I are involved in research to identify biomolecular, biochemical, physiological, and other organism-level responses of aquatic organisms to environmental stressors such as contaminants. ORNL researchers have developed bioindicators of pollutant stress and used these indicators to assess ecological health in creeks, reservoirs, rivers, and marine systems. We have applied this approach to determining biological effects of contaminants in various waterways on or near the Oak Ridge Reservation: East Fork Poplar Creek, White Oak Creek, Mitchell Branch, the Clinch River, and Watts Bar Reservoir. We have studied bioindicators in the Pigeon River and in estuaries in South Carolina, all of which are polluted by pulp and paper mill effluents. We have looked at ecological effects in reservoirs in South Carolina and Georgia, which are contaminated by high levels of PCBs, and in natural lakes at Cape Cod, Massachusetts, which receive underground plumes of contaminants from a nearby military facility.

Early Warnings of Environmental Damage

Bioindicators are useful because they are telltale signs of impending environmental problems. Early effects of pollution initially occur at the lower levels of biological organization. Changes in genes, cells, tissues, body chemical processes, and basic body functions appear before more severe disturbances occur in populations and ecosystems. These biochemical and molecular effects can be detected as changes in enzyme levels, in structure of cell membranes, and in genetic material, or DNA. Changes at these subcellular levels induce a series of structural and functional responses at the next level of biological organization. For example, complex processes such as hormonal regulation, metabolism, and immune system responses can be impaired. These effects may eventually alter the organism's ability to grow, reproduce, or even survive. All these measurable changes serve as bioindicators of pollutant stress. They provide early warnings of environmental damage.

Ultimately, irreversible and detrimental effects may be observed at the population and community level, adversely affecting the health

of the entire ecosystem. Dramatic examples of these effects are mass deaths of whales and porpoises along the eastern U.S. and Gulf of Mexico coasts, wholesale shifts in aquatic species and community structure in the Great Lakes of the United States, and biologically dead rivers and reservoirs in Russia. These examples attest to the highly destructive effects of pollutants on the environment.



Detectible changes in genes, cells, and tissues of an organism may later be the first signal of more severe disturbances in its population and community.

Bioindicators of pollutant stress range from organ damage responses to increased mortality rates of organisms.

Examples of Bioindicators

One way a physician can determine the cause of a patient's health problems is to analyze a blood sample. The health of a fish can be determined in a similar way. Analysis of blood from a fish can indicate problems in organ function—a bioindicator. For example, the presence of specific types of enzymes (tranaminases) in fish blood can indicate liver impairment. Just as alcohol can cause liver damage, or cirrhosis, in humans, PCBs and polycyclic aromatic hydrocarbons in the aquatic environment can inflict liver damage in fish, leading to more serious problems.

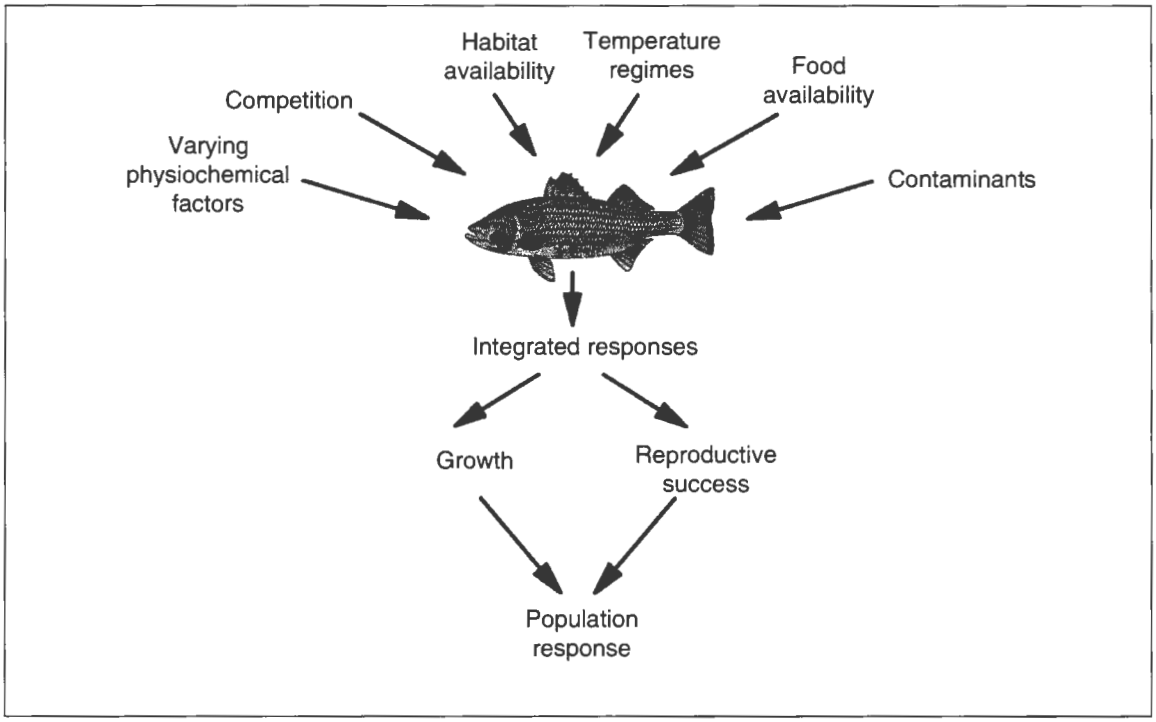
Elevated levels of another bioindicator, urea nitrogen, in fish blood reflect abnormalities in gill function, or respiratory problems. When functioning normally, fish gills as well as kidneys excrete nitrogen-bearing waste products from the body. Fish gills can be damaged by heavy metals—mercury and aluminum—and acidified water. We have found evidence of such effects in fish from the Great South Fork Recreational Area in Tennessee and Kentucky. In this area, drainage from abandoned coal mines contributes both to high levels of heavy metals and to highly acidified surface waters. In the Great Smoky Mountains acid rain can drastically raise the acidity level of mountain streams, periodically killing trout in hatcheries.

As these examples show, bioindicators of pollutant stress range from organ damage responses to increased mortality rates of organisms.

Uses for Bioindicators

The bioindicator approach is not the only method for monitoring possible ecological effects of pollutants. One traditional method is direct

Bioindicators can provide early warning signals of potential human health effects.



The health of an animal reflects the combined effects of environmental stresses acting on it. Studying an animals' reproductive success and other factors enables researchers to predict the population response and assess the nature and extent of environmental degradation.

measurement of chemical pollutants in streams or in the organisms themselves. Another is the laboratory toxicity test in which the toxicity of a pollutant is determined by the death rate of exposed organisms. Compared to the bioindicator approach, these methods often provide only limited information.

Bioindicators offer several types of rather unique information not available from other methods: (1) early warning of environmental damage; (2) the integrated effect of a variety of environmental stresses on the health of an organism and the population, community, and ecosystem; (3) relationships between the individual responses of exposed organisms to pollution and the effects at the population level; (4) early warning of potential harm to human health based on the responses of wildlife to pollution; and (5) the effectiveness of remediation efforts in decontaminating waterways.

The physiological condition of an animal reflects the combined effects of all its environmental stresses, such as contaminants, unfavorable temperature, suspended sediments, insufficient oxygen, and food shortages. Largemouth bass and striped bass—important sport fish commonly found in reservoirs in East Tennessee reservoirs—are particularly good integrators of environmental stress because they are at the top of the aquatic food chain. Signs of impaired health in fish enable scientists to assess the nature and extent of environmental degradation.

Bioindicators can be used to establish cause-and-effect relationships between different levels of response to pollutants in individual organisms and for the entire population. For example, if a diseased fish is found in a stream, it should be possible to determine not only the cause of the disease but also the potential consequences of that disease for the individual fish and for the population. If the disease kills young fish and impairs reproduction in older fish, then the population may decline or even disappear over time.

The Champion Plant in Canton, North Carolina, is a paper and pulp mill that has discharged dioxins and other pollutants to the Pigeon River for many years.

Bioindicators and Human Health

For many years, coal miners would place a canary into a newly opened part of the mine to test the toxicity level of gases. If the canary died, the miners knew it was too dangerous to work; if the canary survived, they continued their work. The fate of the canary served as a bioindicator of pollutant toxicity that could threaten human health and possibly cause death.

We have found that bioindicators in the environment can also provide early warning signals of potential human health effects. Several years ago, we were asked by the Environmental Protection Agency to study the health of fish in the Pigeon River. This river was contaminated with chlorine-containing compounds called dioxins and other pollutants, primarily from a nearby paper and pulp mill—the Champion Plant in Canton, North Carolina. Dioxins are produced when elemental chlorine is used to bleach paper. People downstream of the mill expressed concerns about its health effects, such as increased cancer rates, and even filed a lawsuit, which was eventually settled out of court.

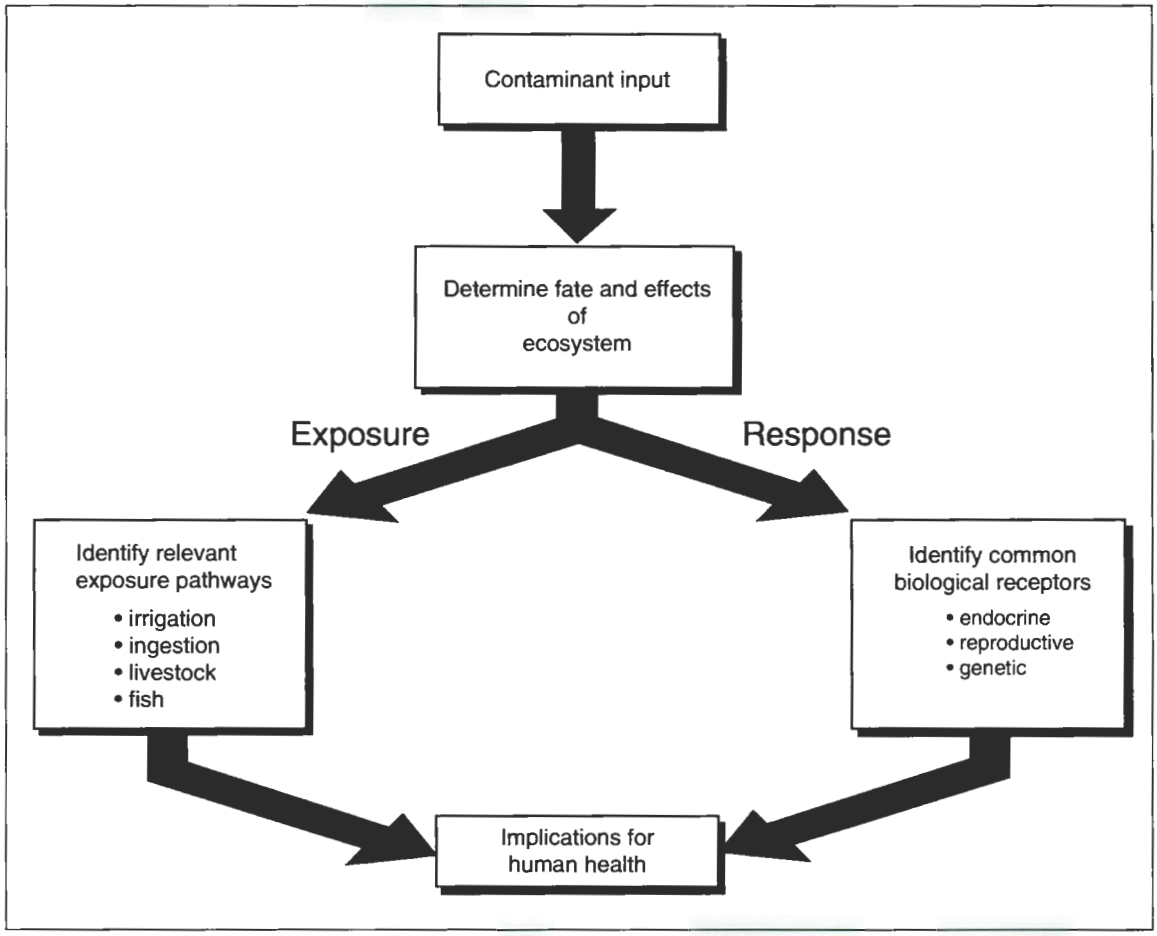
When we examined sunfish from the Pigeon River, we found problems with their endocrine, reproductive, and metabolic systems. We detected altered hormone levels, metabolic and nutritional imbalances, and changes in the normal population and community dynamics. We also observed DNA damage and cancerous lesions in these fish. Such effects were attributed to chemicals released from the mill.

In addition, we found that people in the area could have been exposed to contaminants not only by eating fish but also by using water from the Pigeon River to irrigate crops and water livestock. Thus, some of their sources of food may be contaminated with dioxins.

Is there a link between impaired fish health and a potential threat to human health? Recent studies show that dioxin and other environmental

When sunfish from the Pigeon River were examined, we found problems with their endocrine, reproductive, and metabolic systems.

We found evidence of altered sexual development in fish from the Pigeon River.



In the case of the contaminated Pigeon River, humans are exposed to dioxin and other paper mill contaminants in several ways.

chemicals can disrupt the hormonal system by mimicking or inhibiting estrogens in organisms. Estrogens and other hormones are chemical messengers that regulate various processes in the body. Hormones act on parts of the body by sending chemical signals through receptors on or inside cells. This action can be blocked by chemicals that mimic a hormone and attach to its receptors. Because hormones regulate growth and reproduction, it is believed that hormone-disrupting chemicals could interfere with these processes, possibly leading to reproductive and developmental problems in humans.

Estrogens are known to play critical roles in the development of breast cancer. In fact, hormones are believed to be indirectly responsible for 40% of all cancers in women. Thus, the recent rise in environmental chemicals, including estrogenlike compounds, has increased exposure of body tissues to estrogen, possibly accounting for the 1% annual increase in U.S. breast cancer deaths since the 1940s.

We found evidence of altered sexual development—possible sex changes, impaired gonad development, and reduced steroid hormone concentrations—in fish taken from the upper and most contaminated section of the Pigeon River. Interestingly, breast cancer incidences are higher in the two counties downstream of the paper mill than in surrounding counties. There is only about a 1 in 500 probability that the observed incidences of breast cancer in these two counties

Scott Niemela processes fertilized fis
on board the sampling boat to determ
reproductive condition.

This field laboratory on the Pigeon River was used for on-site processing of fish samples.

ESD researchers Don Harris, Marshall Adams, and Scott Niemela collect a fish sample for bioindicator studies using an electroshocking boat on Watts Bar Reservoir.

are due to random chance alone. This example suggests that bioindicators could provide a reliable early warning that human health may be potentially endangered by increasing levels of environmental pollution.

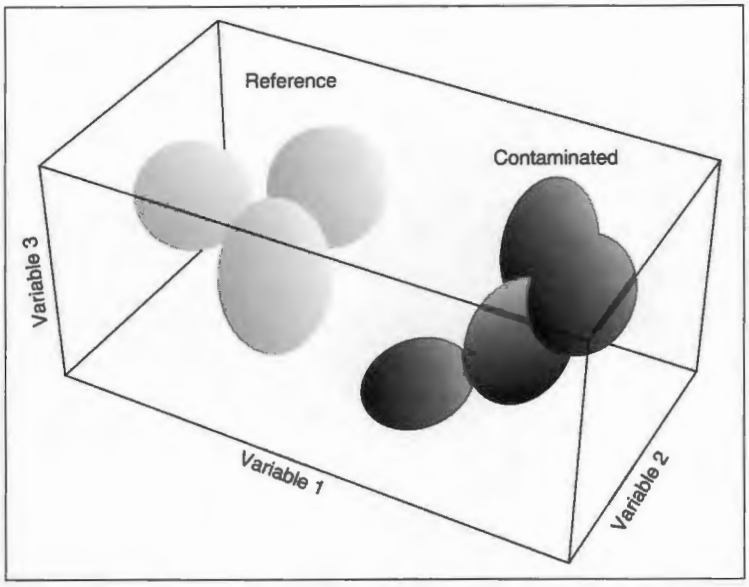
In a project coordinated with Andy Gilman of the Great Lakes Health Effects Program, we are examining the implications of ecosystem health indicators for human health. We are using data supplied by Gilman to write a paper on this subject. In the Great Lakes area in the late 1980s, Theodora Colborn, a zoologist with the World Wildlife Fund, discovered problems with the offspring of 16 predator species, including fish, birds, reptiles, and mammals. Many of the young failed to survive to adulthood or to reproduce. These animals experienced these problems apparently because their parents ate fish from the Great Lakes, which were contaminated with hormone-disrupting chemicals. These wildlife species provide one of the first models for the transfer of hormone-disrupting chemicals from one generation to the next.

Such responses in wildlife can provide models for predicting responses of humans to the same environmental pollutants. However, it is difficult to prove that declines in wildlife populations are attributable to certain suspect chemicals. It is even more difficult to prove that these chemicals are affecting human fertility in the United States. These difficulties can be addressed only through multidisciplinary research linking ecological, wildlife, human, and laboratory animal research and by building bridges among the human, veterinary, and environmental health sciences.

Environmental Restoration

Since 1942 research and production activities on the Oak Ridge Reservation have resulted in occasional spills or discharges of hazardous materials, including radioactive cesium, PCBs, and

mercury into various waterways. Recent environmental laws and regulations such as the Clean Water Act; the Resource Conservation and Recovery Act, and the Comprehensive Environmental Response, Compensation, and Liability Act impose limits on releases of these materials and require that these materials be properly treated, recovered, and isolated from the environment. They also require cleaning up waterways and land contaminated by discharges of hazardous materials.



The ellipsoids represent the integrated health of fish populations at various sites in East Fork Poplar Creek (darker ellipsoids) and in three reference sites (lighter ellipsoids). Intersecting dark and light ellipsoids that indicate the health status of the sites are statistically similar.

In the Biological Monitoring and Abatement Program directed by Jim Loar of ESD, bioindicators are being used to evaluate the short-term and long-term effectiveness of remedial actions on aquatic systems receiving discharges from ORNL, the Oak Ridge Y-12 Plant, and the Oak Ridge K-25 Site. These remedial actions are being taken to comply with environmental regulations.

Biological indicator studies on East Fork Poplar Creek since 1986 have shown marked improvements in the health of fish populations in the stream at several levels of biological organization. In fact, several pollution-sensitive species of fish that have been missing from the creek for years are now beginning to flourish there (see sidebar "East Fork Poplar Creek: Signs of Ecological Recovery" on p. 54).

Bioindicators are also being used to evaluate both the need for and potential effectiveness of remedial actions on the Oak Ridge Reservation. The reservation has been a source of pollutants to off-site waterways—Poplar Creek, the Clinch River, and Watts Bar Reservoir. As part of the Clinch River Environmental Restoration Project directed by Bob Cook of ESD, we are assessing the health of important wildlife species, such as several fish species (largemouth bass, bluegill, catfish, and striped bass) and waterfowl (blue herons and ducks) living in or near these waterways. In addition, the levels of contaminants—PCBs, heavy metals, and radionuclides—are being measured in animals (by ESD's Marshall Adams and Mark Bevelhimer), sediments (by ESD's Dan Levine), and the water (by ESD's Clell Ford) of the Watts Bar system.

An unusual aspect of this project is that both the bioindicators and contaminant data will be used for human health and ecological risk assessments (by ESD's Glenn Suter and Larry Barnthouse). These assessments will guide regulators in determining the extent of environmental restoration required in the Clinch River–Watts Bar system. Additional bioindicator and contaminant data will be obtained later from this system to determine the effectiveness of any reservation-wide cleanup.

Bioindicators are an excellent tool for monitoring the health of biological populations, assessing the potential hazards of environmental pollution to human health, determining if industry is complying with regulations, and evaluating the effectiveness of remedial actions. ornl

East Fork Poplar Creek: Signs of Ecological Recovery

Because of new facilities that remove chlorine and pollutants from wastewater at the Y-12 Plant before it is discharged to East Fork Poplar Creek (shown here), the number of fish species in the creek has risen.

"We are seeing an increase in the number of fish species in East Fork Poplar Creek."

East Fork Poplar Creek is on the road to recovery, ecologically speaking.

So says Jim Loar, an ecologist in ORNL's Environmental Sciences Division who has spearheaded the Biological Monitoring and Abatement Program (BMAP) for the Oak Ridge Y-12 Plant. BMAP was established in 1985 so that the Y-12 Plant could receive a National Pollutant Discharge Elimination System permit for releasing effluents to East Fork Poplar Creek.

According to Loar, since 1985 the Laboratory has gathered "evidence of recovery in stream communities and in the health of individual species in East Fork Poplar Creek." The evidence includes decreasing differences in various biochemical, physiological, and other indicators of fish health between the polluted creek and several reference sites—"clean" creeks that meet acceptable water quality criteria.

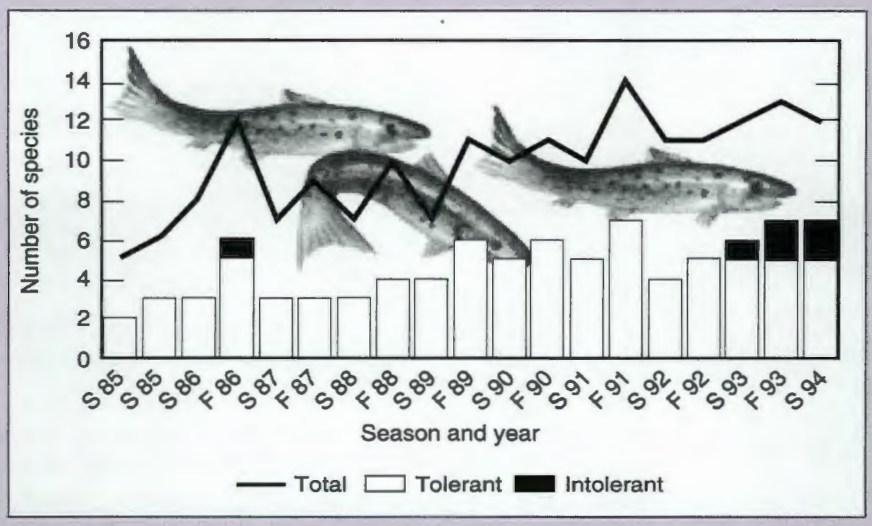
When DOE revealed in 1983 that large amounts of mercury had been released to the creek from the Y-12 Plant, very few species of fish and other aquatic organisms inhabited upper and lower East Fork Poplar Creek inside the plant. Today several pollution-tolerant fish species—striped shiner, blacknose dace, central stoneroller, and redbreast sunfish—have returned to these waters.

Since 1985, ORNL researchers Jim Loar and Mike Ryon have observed more than a tenfold increase in fish abundance in East Fork Poplar Creek, just below Lake Reality at the Y-12 Plant. They have observed an increase in the number of pollution-tolerant fish species, such as striped shiners, green sunfish, and central stonerollers. "Also," says Loar, "we are seeing an increase in the number of species from 5 to 14, including such new inhabitants as northern hog suckers and snubnose darters."

Although these changes in the fish communities of East Fork Poplar Creek provide strong evidence of ecological recovery, the stream still has a way to go before it could be considered a reference creek. "For example," Loar says, "what is missing is the presence of pollution-sensitive fish species. However, a few individuals of some pollution-sensitive fish species—bigeye chub, redline darter, and greenside darter—have been observed in the creek for the first time."

Growing evidence shows that the health of fish populations in the polluted creek is improving. This improvement may be attributed to several factors: the implementation of measures to reduce the levels of mercury and chlorine in the stream and the completion of new wastewater treatment facilities since 1985.

Mercury has been discharged into the creek since the early 1950s as a result of separations of lithium isotopes at the Y-12 Plant in support of the hydrogen bomb project. Process water used at the Y-12 Plant and then released to the creek contained chlorine because its source has been the water-treatment plant that provides Oak Ridge's drinking water. Successful efforts have been made to remove chlorine from and keep mercury out of water leaving the plant for the creek.

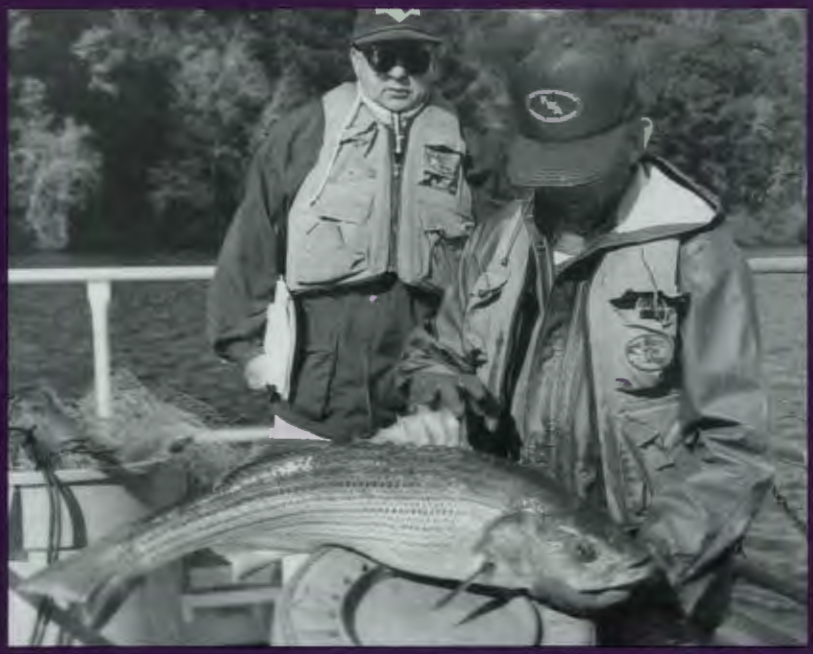


The number of pollution-tolerant fish species in East Fork Poplar Creek just below Lake Reality at the Y-12 Plant has varied from 1985 through 1994. In the past three years, species of intolerant, or pollution-sensitive, fish have been living in the creek, indicating an improvement in its water quality.

Loar says that ORNL researchers have been measuring mercury concentrations in fish at five sampling sites along the creek. "There has been a decrease in the concentration of total mercury in redbreast sunfish at the site just below Lake Reality," he notes. "This decrease coincides in time with the draining of New Hope Pond and filling of Lake Reality at the Y-12 Plant in November 1988."

ORNL scientists have compared the health of individual redbreast sunfish from East Fork Poplar Creek, other polluted streams on the Oak Ridge Reservation, and three reference streams. They have examined indicators of nutritional status, such as fat reserves and levels of liver detoxification enzymes, which are elevated when the fish is exposed to contaminants. With the help of scientists at the University of California at Davis, they have quantified tissue abnormalities in the fish. They have even counted DNA strand breaks, a biological marker for genetic toxicity.

Statistical analyses of all these indicators show that the differences between the health of individual fish from polluted sites and the health of those from clean sites have diminished over the past several years. These changes at the molecular, physiological, and histopathological level, when coupled with those observed at the fish community level, are clearly a sign that East Fork Poplar Creek is on the road to ecological recovery.—*Carolyn Krause*



Biographical Sketch

S. Marshall Adams (right), a research staff member in ORNL's Environmental Sciences Division, directs the division's biological indicators research programs. He also serves on the adjunct faculty at the University of Tennessee and Duke University. He received his Ph.D. degree from the University of North Carolina. His recent studies have included effects of various types of contaminants on key fish populations and the significance of these effects on stream, river, and reservoir ecosystems. He has published scientific reports on predator-prey interactions in aquatic systems, health indicators of aquatic organisms, and the effects of environmental stress on fish. He has served as an associate editor for the *Transactions* of the American Fisheries Society and is a book editor for the Ecological Society of America. Adams was recently awarded the annual prize from the Association of American Publishers for co-editing the outstanding book of the year in biological sciences, *Biodiversity of the Southeastern United States: Aquatic Communities.* Currently, he is an associate editor for the International Society of Aquatic Ecosystem Health. He has recently completed a book entitled *Biological Indicators of Stress in Fish.* He is a fellow of the American Institute of Fishery Research Biologists.

Liane Russell Wins Fermi Award

Liane B. Russell received the Department of Energy's Enrico Fermi Award from President Clinton "for her outstanding contributions to genetics and radiation biology, including her discovery of the chromosomal basis for sex determination in mammals and her contributions to our knowledge of the effects of radiation on the developing embryo and fetus. Her findings have been the benchmark for the study of mutations in mammals and genetic risk assessment worldwide." Russell is the second woman to win the Fermi Award (the first was Lise Meitner, a co-discoverer of the fission reaction). Of the 22 Fermi Award winners, 6 are current or former ORNL staff members. They are Liane Russell and her husband Bill Russell, Alexander Hollaender, Richard Setlow, Alvin Weinberg, and Eugene Wigner.

Richard Sincovec

Gene McNeese

Richard F. Sincovec has been named director of the Engineering Physics and Mathematics Division.

L.E. (Gene) McNeese has been named director of the Chemical Technology Division.

Virginia H. Dale has been appointed associate director of the Environmental Sciences Division.

Fred Bertrand has been named acting director of the Physics Division, replacing **James D. Ball** who has been appointed acting associate director for Physical Sciences and Advanced Materials.

Edward Oliver has been named associate director for Computing, Networking, Informatics, and Education. **Robert C. Ward** will serve as deputy associate director.

Sylvester Scott has been named director of technology licensing and cooperative research agreements in the Office of Technology Transfer.

S. Marshall Adams has been appointed to the adjunct faculty at Duke University.

Lawrence W. Barnthouse has been appointed a member of a National Research Council committee that will review the Department of the Interior's newly established Biomonitoring of Environmental Status and Trends Program.

R. J. Michael Fry was selected to be the 18th Lauriston S. Taylor Lecturer at the 1994 meeting of the National Council on Radiation Protection and Measurements.

R. H. Gardner was presented with the Distinguished Landscape Ecologist award by the U.S. Chapter of the International Association for Landscape Ecology.

The YWCA's 1994 Tribute to Women honored ORNL staff members **Linda L. Horton, Monica Turner, Nermin A. Uckan, Barbara G. Ashdown, Margaret W. Terrell, Robin L. Graham,** and **Patricia F. Daugherty.**

Charles D. Scott received the 1994 David Perlman Lecturer Award from the American Chemical Society's Biochemical Technology Division.

Deborah R. Huntley has been named to the Executive Board of the Tennessee Valley Chapter of the American Vacuum Society.

Virginia Dale

Larry Barnthouse

Robert Roussin

Alvin W. Trivelpiece has been named to serve on the state of Tennessee's Science and Technology Advisory Council.

Robert W. Roussin has been named a fellow of the American Nuclear Society.

Ralph G. Gilliland has been named a fellow of the American Society of Metals International.

D. L. Williams has been named a member of the Executive Standards Council of the American National Standards Institute.

Lee Shugart has been appointed to the Organizing Committee for the National Institute of Environmental Health Sciences.

Glenn Suter has been named a fellow of the American Association for the Advancement of Science.

John B. Caughman has been elected vice president of the Tennessee Valley Chapter of the American Vacuum Society.

G. D. Kerr has been named to serve on the Health Physics Society's Committee on Accuracy in External Dosimetry.

David N. Braski has been named to the Executive Board of the Tennessee Valley Chapter of the American Vacuum Society.

Louis K. Mansur has been named chairman of editors for the *Journal of Nuclear Materials*.

James R. Beene has been named a fellow of the American Physical Society.

Steven M. Gorbatkin has been named to the Executive Board of the Tennessee Valley Chapter of the American Vacuum Society.

Ralph M. Moon has been named a fellow of the American Association for the Advancement of Science.

Sybil Wyatt, Jon Jefferson, Cindy Robinson, and **Tom Cerniglio** have received awards of Excellence, Merit ,and Honorable Mention in various categories of the International Association of Business Communicators' regional publications competiton for both *Bringing Science to Life* and *ORNL '93*.

Van D. Baxter, James R. Sand, and **Edward A. Vineyard** have received a 1993 ASHRAE Best Symposium Paper Award.

The **ORNL Steam Plant** has received a Solid Waste Recycling Award from DOE for diverting six million pounds of fly ash from the landfill for use in manufacturing cement.

Gary K. Jacobs has been appointed to the technical advisory panel for the Hanford Low-Level Waste Disposal Program.

Patricia D. Parr has been elected vice president of the Association of Southeastern Biologists. She also has been appointed area manager for the Oak Ridge Reservation.

Carolyn T. Hunsaker has been named to the board of trustees for the Institute of Professional Environmental Practice and the Advisory Council to the Committee for the National Institutes for the Environment.

Philip M. Jardine has received the Scientific Achievement Award of ORNL's Environmental Sciences Division.

The following ORNL employees and contractors have won awards in the Society for Technical Communication's 1994 Technical Publications

Glenn Suter

Jim Beene

Ralph Moon

Competition: (Distinction) **Amanda Renshaw, Walter Koncinski, S. Marshall Adams, W. D. Crumby, M. S. Greely, Jr., Jim Pearce, Carolyn Krause, Vickie Conner,** (Excellence) **Sybil Wyatt, Jon Jefferson, Margaret Nestor, Darcus Johnson, Brenda Smith, Mickie McBee, Carolyn S. Cain, D. L. Selby, Judy H. Campbell, Larry W. Davis, Carolyn Krause, Jim Pearce, Vickie Conner, Frederick M. O'Hara, Jr., Frederick W. Stoss, Gloria Caton, Tim Elledge, Tifini Cox, G. K. Jacobs, N. W. Dunbar, R. T. Williams, Glenn W. Suter II, Robert J. Luxmore, Ellen D. Smith, Michael A. Huston,** (Merit) **Thomas A. Boden, Tommy R. Nelson, Frederick M. O'Hara, Frederick W. Stoss, Cheryl Koski, Bob Samples, Sandra Schwartz, Tim G. Elledge, Felicia M. Foust and HTML staff, Judy M. Wyrick, Jacqueline T. Miller, Janice M. Asher, Lisa K. Sellers, Gay Marie Logsdon, Delores H. Ogle, Linda J. Jennings, Gloria Caton, Ceramic Technology Project Staff, Kenneth Rose, James H. Cowan, Jr., P. J. Hanson, S. D. Wullschleger, D. E. Todd, Richard S. Halbrook, Lee R. Shugart, Nancy B. Munro, Jim Pearce, Carolyn Krause, Vickie Conner, Denise K. Casey, Anne E. Adamson, Betty K. Mansfield, F. J. Peretz, Deborah M. Counce, Judy H. Campbell, Glenn W. Suter II,** (Achievement) **Cheryl Koski, Bob Samples, Sandra Schwartz, Richard Genung, Robert Jolley, John Mrochek, Martha McReynolds, Paul Greenberg, Bill Gunter, Jr., Anne E. Adamson, Judy M. Wyrick, Shelia Poligone, Ken Davis, Marvel Burtis, Robert Cushman, Frederick M. Stoss, Donna R. Reichle, Jonathan Woodward, D. K. Solomon, S. L. Schiff, R. J. Poreda, Robert J. Luxmoore, Maureen Cunningham, Linda K. Mann, Cynthia Southmayd, ET/FE electronic publishers, ET/FE graphics team, Po-Yung Lu,** and **John S. Wassom.**

The following ORNL employees or contractors have won awards in the Society for Technical Communication's 1994 Art Competition: (Excellence) **Vickie Conner, Robert A. Hawsey,** (Merit) **David Cottrell, Wayne Griest, Renee Balogh, Allison Baldwin, Judy Wyrick, DOE Human Genome staff, Thomas A. Boden, Tommy R. Nelson, Frederick W. Stoss,** (Achievement) **Curtis M. Boles, Thomas G. Cerniglio, Frederick W. Stoss, Frederick M. O'Hara III,** and **Frederick M. O'Hara, Jr.**

Puerto Rico Students Here Last Summer

Topics included statistics, overcoming obstacles to a career in science, navigating on the Internet, and genetic research and ethics.

Inda Rodriguez from Puerto Rico is one of 15 students who participated in ORNL's Summer Educational Experience for the Disadvantaged. The program is designed to encourage students to pursue careers in math or science. Here, she tests the ability of bottles to contain hazardous gases without leaking.

Fifteen high school students from Tennessee and Puerto Rico participated in an eight-week program at ORNL to encourage minority and economically disadvantaged students to pursue careers in math and science.

The Summer Educational Experience for the Disadvantaged (SEED), sponsored by the American Chemical Society (ACS), was in its sixth year. The students—ten from Puerto Rico and five from Wartburg, Tennessee—studied several different scientific disciplines at ORNL, including engineering, biogenetics, chemistry, the information superhighway, and environmental studies. The program is coordinated through ORNL's Office of Science Education and External Relations.

"This program has helped me to focus on what I want to study in college," said Dustin Harris of Central High School in Wartburg. This was Harris' second summer in the Applied Systems Technology Section in ORNL's Engineering Technology Division. As part of his research, Harris, a senior who wants to major in engineering, estimated the damage an explosion might create inside an airplane.

To qualify for the SEED program, economically disadvantaged students must have at least one year of high school chemistry, a strong academic record, and a recommendation by a faculty member.

Applications go to all schools within driving distance of the laboratory and to participating programs in Puerto Rico. The students from Puerto Rico came from the Comprehensive Activities for Upgrading Sciences Achievement (CAUSA) program and the preengineering program of the Ana G. Mendez University System. Both programs host Saturday classes for students in math, science, and languages.

CAUSA also selects two teachers from Puerto Rico to participate in ORNL faculty programs for the summer and to chaperone the students. This past year, CAUSA chose Josi Rivera Acosta, a returning participant and secondary-school math teacher working in the Computing Applications Division, and Sonia Garcma Hernandez, a chemistry teacher working in the Environmental Sciences Division.

SEED students participated in special weekly seminars in addition to their research initiatives. This past summer, lecture topics included statistics, overcoming obstacles to having a career in science, navigating on the Internet, and genetic research and ethics.

Inda Rodriguez, a student from Puerto Rico. who would like to study chemical engineering, said, "I enjoyed working here because I learned

about chemistry and because the people are so nice."

DOE's High School Honors Program

Fifty-seven students from 48 states, the District of Columbia, and Puerto Rico and from France, Germany, Italy, Mexico, and Northern Ireland participated in the Department of Energy's seventh annual High School Honors Program July 22 through August 5, 1994, at ORNL.

The program provided a summer research experience for high school juniors and seniors and college freshmen who exhibit outstanding academic records. Each state and participating foreign country selected one student to participate in a two-week research experience in ORNL's Environmental Sciences Division (ESD).

The focus was on small-group, "hands-on" laboratory and field research to encourage students to pursue careers in math and science, especially environmental sciences disciplines. All expenses, including travel, were paid by DOE.

Students, working with research staff scientists, investigated issues related to the theme of environmental impact. Student teams of two to six members researched topics such as neutron activation analysis of trace elements in soil, evaluation of habitat for wildlife, DNA studies of environmental samples, development of a surface-water hydrology monitoring plan, and bioabsorption and fermentation as a remediation technology. Each team prepared a written and oral report to present their research findings.

"Theme Groups" in which students studied all sides of an issue of national or global importance, were a second component of the program. This activity was designed to model a public forum where students participate in role-playing opposing factions. Some of the issues that students explored included environmental deficits, toxicants in the environment, deforestation and sustainable agriculture, obligations to future generations, the role of computer networks, data sharing, and ethics in scientific data sharing and publication.

The DOE High School Honors Program encourages students to return to ORNL for summer or semester internships during their college career. "For the past few years, we have averaged a return of five to eight students per year," says Julie Watts, ESD coordinator for the program. "We now have a 1988 high school honors graduate working full time with ESD. This program has been a real success."

Students were housed at Maryville College. Four area teachers served as residential supervisors and coordinated social activities.

Other activities included tours of the ORNL facilities, seminars, and opportunities to talk with scientists working in areas of special interest to students. The program is coordinated through ORNL's Office of Science Education and External Relations.—*Kimberly Baker*

Each state selected one student to participate in a two-week research experience in ORNL's Environmental Sciences Division.

Superconducting Motor Spins for Students at EnvironMENTAL Fair

A new demonstration motor based on commercial high-temperature superconducting wire was unveiled by ORNL at the recent EnvironMENTAL Fair, held October 6, 1994, at the American Museum of Science and Energy in Oak Ridge. The motor was developed to demonstrate electric power uses of new superconducting wires. Designed primarily for educational use at area schools and museums and for visitors to ORNL, the motor is the size of a two-pound coffee can and uses liquid nitrogen to cool the superconductor.

The heart of the motor is a coil of high-temperature superconducting wire made of BSCCO, an oxide consisting of a mixture of bismuth, strontium, calcium, copper, and oxygen. This coil was supplied by one of ORNL's partners, American Superconductor Corporation (Westborough, Massachusetts) as part of an ongoing collaboration to develop electric power applications of high-temperature superconductors. American Superconductor produces flexible high-temperature ceramic superconducting wires for coils and systems such as motors and current limiters.

The superconducting coil produces a magnetic field that interacts with electric current flowing in a

ORNL has produced guides to superconductivity and cryogenics for high school and middle school students.

Middle school students meet the future in the form of a superconducting motor being demonstrated by developer Bill Schwenterly of ORNL's Fusion Energy Division.

copper armature to produce the force that causes the armature assembly to rotate. The armature current is switched using a brush and commutator assembly available from a local hobby shop. When fully cooled, the motor rotates at 300 to 500 revolutions per minute. The armature assembly is constructed from flat-wound copper coils, provided by Advanced Sound, a Knoxville, Tennessee, firm.

This portable, educational tool operates using a few dry cell batteries and, of course, the liquid nitrogen coolant. Liquid nitrogen boils at 77 K (–321° F), a temperature that is much colder than the lowest temperature ever recorded at the South Pole. Electric motors and generators using this new technology will be more efficient than conventional machines. They will consume fewer of the earth's natural resources such as iron because they are smaller than conventional motors with the same power.

The motor demonstrator was developed as part of the educational activity of ORNL's Superconductivity Program for Electric Power Systems. This program is funded as part of DOE's national effort to develop the technology necessary for U.S. industry to proceed to commercial applications of high-temperature superconductivity.

In addition to the motor demonstrator, the ORNL program has produced a "Teacher's Guide to Superconductivity for High School Students" and "An Introduction to Cryogenics and Superconductivity for Middle School Students." These guides were produced by teachers who participated in the Teacher Research Associates program, a program funded at ORNL by DOE's

Office of Science Education and Technical Information.

Oak Ridge Science Semester Is 25 Years Old

ORNL's Oak Ridge Science Semester Program is entering its 25th year. The program involves undergraduate participants from colleges of the Great Lakes College Association (GLCA) and the Associated Colleges of the Midwest (ACM).

Deans from the 12 GLCA colleges came to ORNL on November 3, 1994, to get a first-hand look at the program, which has served as a model for the other DOE laboratories. They also attended the annual poster session, highlighting the students' research projects.

In this program, students perform research at the cutting edge of science; learn to operate sophisticated, state-of-the-art equipment and instruments; and supplement their laboratory research experience with seminars, workshops, and courses under the direction of ORNL staff scientists. Three resident faculty members from colleges of the consortium also are assigned to the Laboratory to do research, teach courses, and counsel the students.

"This is a very rich program that has grown substantially over the past 25 years," said George Gilbert, director of the Oak Ridge Science Semester Program. The program has been a wonderful experience for the students to work with top-notch scientists and has provided an excellent educational opportunity for the laboratory."

The 16-week science semester provides opportunities for student research and advanced study in energy-related areas of science and technology, including the biomedical, environmental, and physical sciences; nuclear and engineering technologies; applied mathematics; and advanced energy systems.—*Jennifer Ball* ornl

Students perform research at the cutting edge of science.

ORNL Method Removes Ink from Waste Paper

The ORNL technology is environmentally friendly because cellulase is produced naturally by a fungus.

Jonathan Woodward drops shreds of newspaper into the bioreactor system that uses an enzyme to separate inked newspaper fibers from de-inked fibers. This environmentally friendly, energy-saving technology helps turn waste newspaper into recycled paper as well as egg cartons, insulation, and combustible fuel.

An environmentally friendly, energy-saving technology for removing ink from waste newspapers to make them recyclable has been developed by researchers at ORNL.

The technology was developed by Jonathan Woodward of ORNL's Chemical Technology Division and two contractor employees from Midwest Technical, Inc.—Lynette M. Stephan and Laurence J. Koran, Jr. The new technique resulted from a discovery made in 1992. At that time, the researchers were trying to use a protein—an enzyme called cellulase—to convert waste paper to sugar for fermentation into a liquid fuel called ethanol.

"We were surprised to find that cellulase easily digests and removes ink from newspapers under certain experimental conditions," says Woodward. "We found our technique separates high-quality ink-free pulp fibers from ink-covered fibers, creating a whitish recyclable paper product and a gray product that could be used to make egg boxes, insulation, or combustible fuel."

The enzyme, or biocatalyst, technology has three advantages over the traditional de-inking technology. First, it works on old newspapers that use water-based ink as well as oil-based ink, without releasing ink to the environment.

Second, because it requires no de-inking chemicals, it uses much less energy than traditional methods—as much as 2.3 million British thermal units less per oven-dried ton of paper. If the technique were used on the 8 million tons of newspapers collected annually for recycle, 0.018 quads of energy, or 13 million barrels of oil per year, would be saved.

Third, the ORNL technology is environmentally friendly because cellulase is an enzyme produced naturally by a fungus that is used in washing powders such as those for stone-washing jeans. Traditional de-inking technologies

use potentially harmful chemicals, such as caustic sodium hydroxide, sodium silicate, and hydrogen peroxide.

The new biocatalytic technique uses the enzyme cellulase to treat cellulose fibers making up more than half of waste paper. Cellulase can completely break down cellulose into glucose sugar. However, under certain conditions discovered by the researchers, the action of cellulase results only in the desired separation and pulping of the fibers with little cellulose breakdown.

The apparatus used for the process is simple. It consists of two cylindrical glass containers, or bioreactors, connected by a tube through which water circulates. In each container is a cylindrical strainer made of 20-mesh plastic canvas, the porous material used for needlepoint.

Waste paper and cellulase are mixed together in the strainer in the first bioreactor. The mixing of the cellulase with the waste paper separates its large and small pulp fibers and triggers the release of ink from the paper surface. The released ink tends to stick to the small pulp fibers.

As water flows at 40°C between the two containers, the small inked fibers pass through the pores of the plastic strainer and end up in the other bioreactor outside its strainer. The larger ink-free pulp fibers remain inside the strainer of the first container because they are too large to pass through the strainer pores. In this process, ink is almost completely removed from paper.

Woodward says that several paper companies that have shown interest in the new ORNL technique. Funding for the work that resulted in the discovery came from DOE's Office of Basic Energy Sciences. The development of the separation technology was supported by internal funding through the Laboratory Director's Research and Development Fund. — *Carolyn Krause*

Mike Ramsey shows a "chemistry laboratory on a chip" that he helped develop. This miniature, micromachined device will offer rapid, inexpensive analysis of liquid droplets for environmental monitoring, industrial process control, and medical diagnosis.

Chemistry Lab on a Chip

A "chemistry lab on a chip" might seem like just a researcher's dream, but recent successes at ORNL suggest it could become a reality.

A postage-stamp–size instrument for efficiently separating and identifying chemicals in liquids is being developed by ORNL scientists. Such a device could have widespread use in the environmental, manufacturing, health care, and pharmaceutical industries.

The ORNL researchers have also shown that microscopic devices can be used to carry out chemical reactions. They have used the device to separate chemicals in a liquid droplet in only 150 milliseconds. The work suggests that an entire chemical laboratory, including chemical containers, "beakers" for mixing chemicals, and analysis instruments, can be placed on a microchip.

The "chip" is a glass plate as thin as a microscope slide and about the size of a postage stamp. A winding, hairlike capillary channel, covering an area the size of a dime, is etched in the glass using standard micromachining techniques. The etched channels are closed by bonding a thin plate of glass over the top.

"Such a microchip laboratory could provide faster, cheaper, and more reliable chemical analyses for environmental monitoring, industrial process control, and medical diagnosis," says J. Michael Ramsey, one of the developers of the

The device can separate chemicals in a liquid droplet in only 150 milliseconds.

"A miniature chemical device, much like a microelectronic device, can achieve greater speeds than devices of conventional size."

technology. "It could also be used by unskilled personnel to perform sophisticated chemical analyses in remote locations."

The laboratory on a chip offers several potential advantages over conventional approaches to chemical analysis. Preparation of chemicals for analysis is automated, saving labor and protecting humans from unnecessary chemical exposure. Also, the amount of chemical reagents needed to stimulate chemical reactions on a chip is a millionth of the typical volume used in a laboratory setting, thus minimizing chemical waste. Finally, because the miniaturized device has no moving parts, it should be more reliable and inexpensive enough to be disposable.

Thanks to its greatly reduced size and weight, the microchip laboratory could be incorporated into hand-held devices for surveying waste sites and diagnosing a patient's disease in a physician's office. It could also be part of a small gadget that would be used in chemical process pipes to monitor and control production in a factory.

"One of our goals is to develop microdevices for chemical analysis that demonstrate the same advantages as microelectronics, including small size, low cost, high speed, reliability, and operational simplicity," says Ramsey. "We have designed and tested several types of microfabricated chemical separation devices. Our results show that it is possible to reduce instrument size from a few cubic feet to several cubic centimeters and that the performance of the miniaturized instruments is equivalent to or better than the conventional laboratory versions.

"We have also shown that chemical reactions can be performed rapidly in a very small volume using micromachined devices," Ramsey continues. "At ORNL results of a chemical analysis on a chip were obtained in 5 minutes using reagents in an amount equal to about 1/250 of a drop of water. In general, such a device would consume about 1 milliliter of reagent, or the equivalent of 20 drops of water, per year of operation.

"Engineers have not been able to design microscopic pumps and valves that work well enough for these applications," says Ramsey. "We do fluid pumping and valving using electric fields and osmotic forces to induce liquid to flow through a microscopic channel etched in glass. Charged molecules of different chemicals move at different speeds based on differences in charge and size. Uncharged molecules of different chemicals move at different rates based on differing attractions for material dispersed in the liquid or coating the channel walls.

"With electric field strengths as high as 1500 volts per centimeter, we have separated chemicals in liquids in as few as 150 milliseconds, which is one of the fastest speeds ever," Ramsey adds. "This demonstration shows that a miniature chemical device, much like a microelectronic device, can achieve greater speeds than devices of conventional size."

Ramsey says that chemistry labs on chips could be integrated into a miniature chemical factory. Just as several computers can work at the same time on different parts of a complex problem, chemical analysis microchips could work in parallel to synthesize and test new drugs.

"Test results might be used to influence the next sequence of compounds that is synthesized for tests," he says. "This approach could speed up the discovery of new drugs that are effective against disease."

Besides Ramsey, the developers of the microchip laboratory include Stephen C. Jacobson, Roland Hergenroder, Lance B. Koutny, and Alvin W. Moore, all of ORNL's Chemical and Analytical Sciences Division. This work has been funded by the ORNL Director's Laboratory Directed Research funds and by the Department of Energy's Office of Nonproliferation and National Security.—*Carolyn Krause*

ORNL Designs Radiation-Hardened Memory Chip

Researchers at ORNL have designed semiconductor chips for collider physics experiments that may someday be used to help operate robots in high-radiation environments and to make sharper, clearer, and steadier television pictures.

Charles L. Britton, Jr., and Alan Wintenberg, both of ORNL's Instrumentation and Controls Division, have designed a radiation-resistant chip for storing information resulting from particle collisions measured in a high-energy physics experiment planned for the recently closed Superconducting Super Collider (SSC) project. They are now designing radiation-resistant circuits for robots that may someday be used to clean up contaminated tanks at DOE waste sites.

For this work in collaboration with Ken Read of ORNL's Physics Division and Lloyd Clonts, a University of Tennessee at Knoxville (UTK) graduate student, Britton and Wintenberg recently received a Technical Achievement Award from Martin Marietta Energy Systems, Inc., which manages ORNL for DOE. They were cited for "superior contributions to the experimental physics community by developing the world's first radiation-hardened analog memory unit."

Chuck Britton shows the radiation-hardened memory chip that he, Alan Wintenberg (center), and Lloyd Clonts (left) designed at ORNL for manufacture by Harris Semiconductor, Inc. Radiation-hardened circuits may be used in robots designed to perform cleanup operations in high-radiation zones.

Researchers at ORNL have designed semiconductor chips for use in high-radiation environments.

The researchers have also designed a less expensive chip not hardened against radiation for use in collider physics experiments at other accelerators. "Chips like these," Britton says, "could be used for storing television signals long enough to process them into improved TV images. By processing the stored signals in a few millionths of a second, TV pictures could be made clearer, sharper, and steadier."

The radiation-hardened chip was made by a special process for manufacturing complementary metal oxide semiconductor (CMOS) chips. Harris Semiconductor, Inc., of Melbourne, Florida, developed this process to meet military needs. Britton and his colleagues developed circuits using computer-aided design and drafting tools and sent the designs to Harris by electronic mail. Harris then manufactured about 200 chips to meet ORNL's specifications.

To determine each chip's resistance to radiation damage, the ORNL researchers subject them to gamma radiation from a cobalt-60 source. "These chips are supposed to be able to withstand as much as 10 million rads of radiation," Britton says. "By contrast, ordinary chips would be destroyed by about the same amount of radiation that kills a cockroach—20,000 to 30,000 rads, about 50 times as much as would kill a human."

The SSC, which was terminated by the U.S. Congress in 1993, was being designed to accelerate protons to extremely high energies traveling in opposite directions around a 54-mile ring in Texas. One object of research using the machine was to understand the most basic particles of matter and the glue that holds them together.

The proton beams were to be slammed together in the central tracker system of the eight-story-high gamma-electron-muon (GEM) detector being designed for the SSC. ORNL was asked by DOE to develop radiation-hardened chips to store information about the particles shooting out in all directions during head-on collisions of protons 62 million times a second in the opposing beams.

Radiation-hardened chips may be used in a planned Swiss accelerator.

"The chips had to be hardened against radiation because of the highly energetic gamma rays and neutrons produced from proton collisions and other particle interactions," Britton says. "They should be able to operate even with a little radiation damage by recalibrating their memories."

"There was no practical way for the SSC to immediately process information on all the particles, their energies, and the directions and distances they travel," Wintenberg says. "A lot of the information would be of no interest because it would result from protons passing by each other or glancing off each other rather than directly colliding. So analog memory chips were needed in the SSC to store all electrical information as voltages until computers decide which information might be significant to reconstruct particle tracks, for example. Such voltages would then be converted to numbers for computer processing."

The ORNL chip consists of many capacitors, transistor switches, amplifiers, and associated circuitry. In the SSC the capacitors would have stored electrical signals as voltages from charged wires in gas-filled detectors. These wires would have picked up electrical charges produced when particles from proton collisions passed through each detector, stripping electrons from gas molecules. The voltages of interest stored on the chips would have been turned into numbers for computer use by analog-to-digital converters.

"Radiation-hardened chips will not be needed for the SSC now because of its demise," Read says, "but they may be used in a somewhat smaller collider to be constructed in Switzerland for experiments in which U.S. scientists will participate. Other uses would be for robots that work in high-radiation environments such as nuclear power plants or waste sites."

The ORNL researchers are now working with ORBIT Semiconductor to produce CMOS chips that have similar circuit designs but are not radiation hardened. These chips can be made for a much lower cost than the radiation-hardened ones.

These memory chips will be used for relativistic heavy-ion physics experiments involving ORNL physicists. Several applications are planned for the PHENIX experiment at the Relativistic Heavy Ion Collider Center under construction at Brookhaven National Laboratory in New York and an existing accelerator at the European Center for Particle Physics (CERN) in Geneva, Switzerland.

The CERN experiment is the WA98 experiment, one in a series of experiments aimed at creating a plasma of free quarks, the basic constituents of particles in atomic nuclei, and gluons, the particles that bind quarks together. It is believed that a superhot quark-gluon plasma was first formed during the Big Bang that created the universe and that, within several millionths of a second, the plasma cooled into the atoms making up the universe. Glenn Young, Frank Plasil, and others in ORNL's Physics Division have worked on these experiments since 1986.

"In the past," Britton says, "they have used conventional electronics developed at ORNL for these experiments. But for these new experiments they will use custom chips from ORNL for the first time."

The funding for developing radiation-hardened analog memory chips for the SSC came from DOE through the SSC Laboratory in Dallas, Texas. DOE's Office of Energy Research also has been supporting development of the other chips for the Brookhaven and CERN accelerator experiments.

Gas from Grass? A Promising Biofuel

The automobile engine of the future may be grass-powered, not gas-powered. Wouldn't that be a switch?

Environmental scientists at ORNL are working to develop a fast-growing grass as a source of liquid fuel. The Biofuels Feedstock Development Program at ORNL has selected a native grass species for further studies in alternative-fuel development. The species is called switchgrass.

Scientists and politicians alike realize the importance of developing clean, renewable sources of energy. Today, much of the world depends on oil reserves that are concentrated in a handful of nations. Another problem is pollution, much of which stems from fossil-fuel use. Conversion of woody and herbaceous plants into

clean-burning fuel offers an attractive possibility for meeting future energy demands, researchers say.

Switchgrass is a perennial warm-season grass that grows well in many areas of the country—even on fairly dry, nutrient-deficient land of marginal quality—and it has positive environmental attributes. Its natural range extends from Quebec through Mexico and into Central America.

Switchgrass has two growth forms. One is a leafy, thicker-stemmed variety common to lowland sites in the Southeast. The second form is shorter, fine-bladed, and more typical of grass in the western plains. Both were abundant on the native prairie when American pioneers arrived.

The ORNL program emphasizes the need for high-yield crops that can be grown economically over a wide area and with minimum impact on the environment. Switchgrass was selected as a model herbaceous crop because it has high, stable yields and relatively low production costs. Its other positive environmental attributes include relatively low need for pesticides and fertilizers and excellent soil conservation potential. These features could make switchgrass tremendously beneficial to owners of small farms in a depressed agricultural industry.

"One reason switchgrass was selected as a fuel alternative is that it is very similar to hay in the way it is raised, making its production compatible with traditional agricultural practices," says Sandy McLaughlin, an ORNL senior research staff member and a task leader in the ORNL biofuels program. "In fact, the equipment used for harvesting hay can also be used for switchgrass, helping to lower the front-end costs for farmers who want to grow switchgrass and sell it to conversion facilities."

McLaughlin says that 100 gallons of fuel could be produced per dry ton of harvested switchgrass. The amount of fuel produced per acre of harvested switchgrass could be as high as 500 gallons.

Research on developing fast-growing grasses and hardwoods for the ORNL program is paralleled by research at DOE's National Renewable Energy Laboratory in Golden, Colorado. There engineers work to develop more efficient ways to convert biomass to liquid and gaseous fuels. By the 21st century, energy crops could yield more than 230 million gallons of ethanol annually, or about 650,000 gallons of ethanol every 24 hours.

Sandy McLaughlin examines switchgrass on the Oak Ridge Reservation. Such grass shows promise as a feedstock for producing fuel.

One acre of harvested switchgrass could produce as much as 500 gallons of fuel.

The research at ORNL is supported by DOE's Office of Transportation Technologies through the Energy Efficiency and Renewable Energy Program.

Research at Virginia Polytechnic Institute and State University has shown that deep switchgrass rooting patterns improve soil quality by increasing soil carbon content. This ability to transfer carbon dioxide from the air to the soil will help offset carbon dioxide emissions to the atmosphere, a significant global pollution problem.

Switchgrass protects against erosion, has low fertilizer and pesticide requirements, and provides cover for wildlife. But someday it may have a new claim to fame. Americans may eventually be talking about making gas from grass.—*Angela Swatzell and Wayne Scarbrough*

Revolutionary Auto Engine Conceived

"The LM engine can adjust its output to suit different driving requirements, ensuring maximum fuel efficiency at any speed."

An ORNL researcher has designed a revolutionary "liquid-metal" automobile engine that can change size, depending upon acceleration requirements. No prototype is yet available, but detailed schematic drawings have been made.

As conceived, the engine could provide high-level performance when desired, would cost less than conventional automobile engines, and should offer economy-minded drivers the possibility of 38 kilometers per liter, or 80 to 90 miles per gallon, of gasoline, for a lifetime mileage of at least 805,000 kilometers.

Carsten M. (Kit) Haaland of ORNL's Engineering Physics and Mathematics Division has invented a magnetohydrodynamic liquid metal (LM) engine that can "shrink" the engine combustion volume down to around 0.06 liters, which is much smaller than that found in existing commercial automobiles. The engine volume can expand by a factor of 10 to 0.6 liters in about one second when needed. The smaller engine volume will burn just enough fuel at high-efficiency steady cruising, whereas the larger engine volume will take a lightweight vehicle to 96 kilometers per hour, or 60 miles per hour, in just seven seconds.

Martin Marietta Energy Systems, Inc., has applied for a patent for the magnetohydrodynamic engine. Magnetohydrodynamics is the science of magnetic fields combined with the motion of liquids that conduct electricity, such as mercury or liquid sodium.

The output of the LM engine is electric power in the form of alternating current (ac) at variable frequencies that match the variable rotational frequencies of car wheels. The electrical output of the LM engine is fed by wires directly to ac motors that provide rotation in the driving wheels. Unlike a conventional electric generator or auto engine, the LM engine has no rotating parts.

The electric power is generated by the back-and-forth motion of the LM engine in a strong magnetic field. The driving force for this motion comes from the same force that drives a conventional auto engine—the expansion force that results from burning fuel.

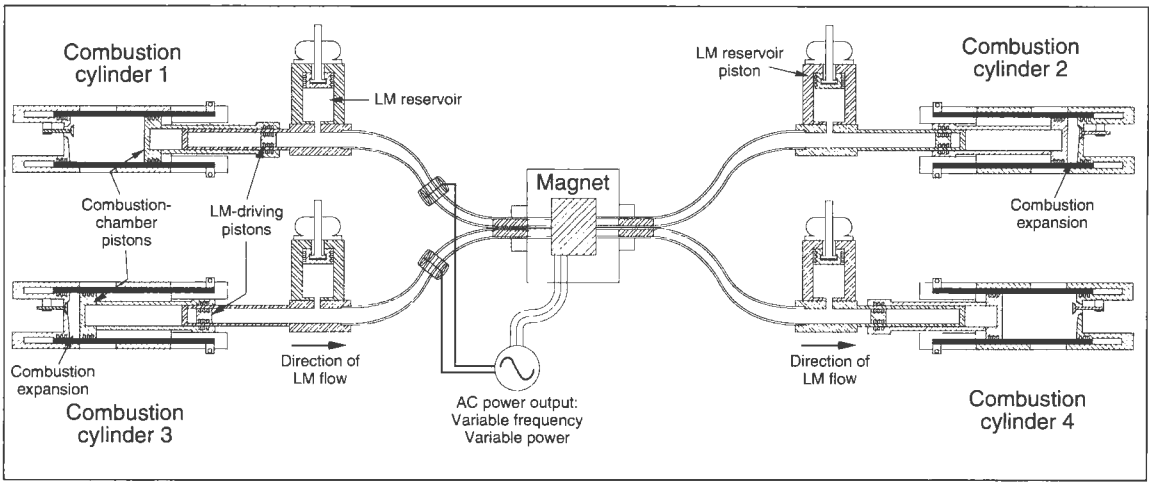
However, in the LM engine, the connection from expansion force to electric power generation is made without any mechanical devices such as connecting rods, crankshaft, pulleys, or belts. Thus, the engine has fewer moving parts and problems with friction.

"The LM engine can adjust its output to suit different driving requirements, ensuring superb vehicle performance and maximum fuel efficiency at any speed," Haaland says. "Because there are fewer moving parts in the engine, and because an auto powered by it won't need a clutch or transmission, the initial vehicle costs should be lower and the frequency of repairs should be greatly reduced.

"Because the engine displacement volume can expand quickly," Haaland says, "a driver will be able to push the accelerator pedal to the floor and get an exciting response from an engine that has suddenly increased its available power up to 10 times. The driver could then let up on the gas pedal to shrink the LM engine volume when the desired speed is reached. The LM engine could provide the driver up to 80 miles per gallon of fuel at a constant speed of 65 miles per hour, and up to 100 miles per gallon at a steady 55 miles per hour on a smooth level surface."

Haaland's part of a 1990 study supported by the Laboratory Director's Research and Development Fund resulted in the variable-size LM engine. He conceived the idea for a four-piston double-duct LM engine in 1992. The four-piston setup is used to drive the LM engine back and forth in opposite directions in two separate ducts. This arrangement eliminates vibration and instabilities in the LM motion that result from strong magnetic fields. It also allows a transformer to be conveniently connected to one side of the double-duct to step up voltages and step down currents to practical levels. A specially designed computer chip would control the operation of the LM engine and the vehicle.

The variable-size (variable-displacement) LM engine uses free pistons, with no connecting rods or solid metal attachments. The pistons are driven by combustion of a liquid fuel, such as gasoline,



This revolutionary magnetohydrodynamic liquid metal (LM) engine conceived at ORNL should achieve a fuel efficiency of at least 80 miles per gallon. In this variable-size LM engine, the distance the gasoline-driven pistons travel is limited by the quantity of liquid metal in the ducts. If the liquid metal is pumped out of the duct back into the reservoir, the piston stroke gets longer, resulting in more flow of the liquid metal through the magnetic field from the nearby magnet; as a result, more electricity is produced to power the wheels. This arrangement allows the LM engine size to vary according to need.

diesel fuel, liquid propane, or some combination. Each pair of pistons is linked by a duct containing liquid metal, the source of which is a nearby reservoir. The distance the pistons travel is limited by the quantity of liquid metal in the operating ducts: the more liquid metal, the less piston movement.

If the liquid metal is pumped out of the duct back into the reservoir, the piston stroke gets longer, resulting in more movement of the liquid metal through the magnetic field produced by nearby magnetic material; as a result, more electricity is produced to power the wheels. This arrangement allows the LM engine size to vary according to need.

Such an engine requires liquid metals that have high electrical conductivity, low density, and low viscosity. The most favorable liquid metals for this purpose are members of the alkali metal family, such as liquid sodium, liquid potassium, or a combination of these. Because they will burn spontaneously in air or water, the ducts carrying liquid metal in the engine must be designed to remain sealed against the chaotic forces of collision. To prevent any contact with air or water, the liquid metal is sealed permanently in two channels. Approximately two liters (slightly more than two quarts) of liquid metal would be used in a typical LM engine.

"There are no load-bearing sliding surfaces in the LM engine. The sideward push of pistons against cylinders in the usual engine is eliminated, and no crankshaft, connecting rods, wrist pins, and their associated bearings are required," Haaland says. "Thus, the engine will experience less load from internal friction. Stress points on connecting rods and wrist pins are eliminated.

"Because of these features, the LM engine could operate up to 300 cycles per second in a two-cycle mode with greatly improved scavenging, resulting in much smaller engine size per kilowatt. All these factors, including the use of air cooling instead of water cooling, result in less weight, improved fuel efficiency, lower cost, and longer life for the LM-engine–powered vehicle.

ORNL Wins Two R&D 100 Awards

Two R&D 100 awards in 1994 bring Oak Ridge's total to 84.

Tuan Vo-Dinh conducts a test to determine if a liquid sample is contaminated with PCBs. Vo-Dinh and his research associates received an R&D 100 Award for developing the PCB test.

Two of the top 100 new technologies recognized in 1994 by *R&D* magazine were developed or co-developed by ORNL researchers. The total number of R&D 100 awards for Department of Energy plants in Oak Ridge is 84.

The winning ORNL technologies are an improved method of testing for polychlorinated biphenyls (PCBs), a significant environmental contaminant, and a computer software package that virtually turns computer workstations into supercomputers.

The developers of the PCB test strip are Tuan Vo-Dinh, Anjali Pal, Lorna Ramirez, and Tarasankar Pal, all of ORNL's Health Sciences Research Division. The ORNL co-developer of "parallel virtual machine" (PVM) software is Al Geist of the Engineering Physics and Mathematics Division. Collaborating with him on this development were V. S. Sunderam of Emory University in Atlanta, R. J. Manchek and J. J. Dongarra, both of the University of Tennessee at Knoxville, and A. L. Beguelin of Carnegie-Mellon University in Pittsburgh.

R&D magazine has annually honored inventors and scientists around the world since 1963 by selecting the 100 most technologically significant new products and processes.

* * *

The newly developed PCB test uses strips of chemically treated paper that glow under ultraviolet (uv) light if the environmental sample being tested is contaminated with PCBs. The improved process saves money by eliminating costly laboratory procedures and extra work time. Before Vo-Dinh's innovation, researchers had to collect samples on site and then transport them to a laboratory for chemical analysis to determine whether they were contaminated.

"The PCB strip test will cost ten times less than previous methods because it uses a simple process called photoactivated fluorescence, allowing quick analysis at the site," says Vo-Dinh, leader of the Advanced Monitoring Development Group at ORNL. "A user of the test can rapidly screen samples for PCBs and even measure the level of contamination."

When the patented process is developed fully for large-scale field use, testing a sample could cost only a few dollars. "However," Vo-Dinh notes, "the raw material for each sample run—the

chemically treated paper test strip—costs less than a penny."

The research project was sponsored by DOE's Office of Health and Environmental Research, the Environmental Restoration and Waste Management Office of Technology Development, and the Environmental Protection Agency's Environmental Monitoring Systems Laboratory in Las Vegas.

PCBs were manufactured in the United States from 1929 to 1977. They were used in electrical equipment, such as transformers and capacitors, and in hydraulic fluids and lubricants for industrial equipment. Through such products, PCBs made their way into the environment.

The disposal of PCBs was not regulated until the late 1970s, when studies first showed that these toxic compounds persist in the environment and may cause cancer.

In the new test, a drop of liquid from an environmental sample is applied to a paper test strip coated with special chemicals that are activated by uv light if exposed to PCBs. UV light is then shone on the strip. If PCBs are present, the activator molecules on the test strip will absorb the uv energy, interact with the PCBs, and glow. The intensity of the glow is measured in a luminescence analyzer, which indicates the level of PCB contamination.

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The PVM computer software package developed by ORNL's Al Geist and others virtually turns computer workstations into supercomputers. The software allows organizations and individuals with computers to tap the power of several workstations simultaneously, thereby solving problems that would be too large or complex for a single workstation.

PVM is one of the first software systems to allow computers with widely different architectures and data formats to cooperate simultaneously on a single computational task. Their combined power can equal that of multimillion-dollar supercomputers, at a fraction of the cost.

PVM is particularly useful in linking several computer workstations during off hours to solve problems that normally would be submitted to a more powerful mainframe computer. Perhaps best of all, says Geist, the software is available free through an ORNL electronic mail network. "It's an example of your tax dollars at work," he says. (The Internet address to access PVM is http://www.netlib.org/index.html.)

Geist notes that the PVM system could be viewed as "a poor man's supercomputer." By using it to tap the aggregate power of computer workstations whose combined cost is roughly $250,000, researchers have achieved computing speeds that rival those of $20 million supercomputers. The package has been applied to as many as 125 workstations. It can even be used to link supercomputers.

"The workload achieved," Geist says, "is limited only by the number and power of computers to which you have access."

The software also allows linking of several computer networks, such as Ethernet and Token Ring, to form a single PVM configuration.

PVM will be particularly beneficial to universities, most of which cannot offer courses in supercomputing because of the high cost of the hardware. "With PVM," Geist says, "universities can teach students how to write parallel programs that apply to supercomputing even though they could never afford a supercomputer."

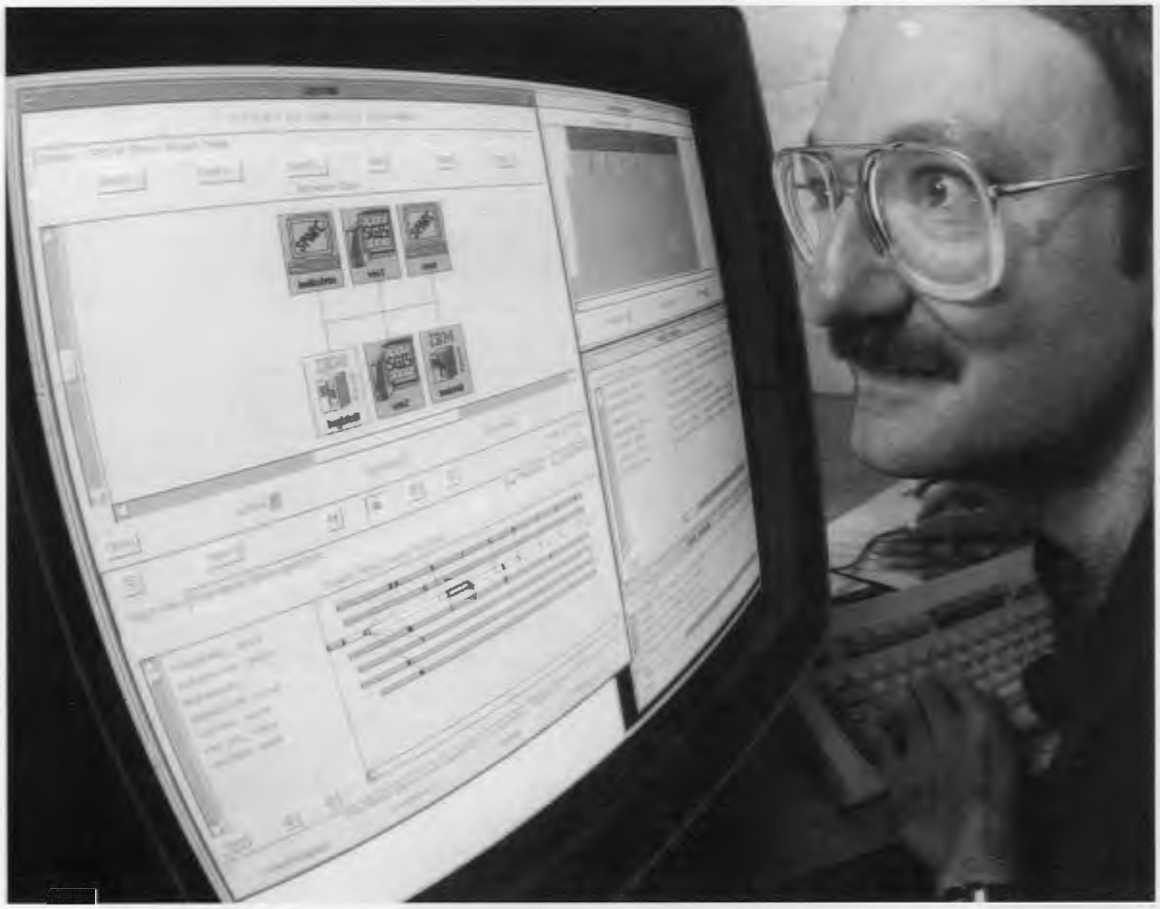
PVM is being used at hundreds of sites worldwide by companies whose business ranges from aerospace, automotive, and chemical research to medicine and the environment. PVM is supported on more than 30 different types of workstations and supercomputers, including those manufactured by IBM, Hewlett Packard, DEC, Sun, Cray Research, Convex, Silicon Graphics, and Intel.

Parallel computing using the PVM system may be the key to solving so-called computational grand challenges, such as modeling of the global climate, groundwater transport of hazardous waste, and the structure of superconductors.

"At this time, these problems can't be solved because of a lack of computer power," Geist notes. "One computer, even a supercomputer,

PVM is particularly useful in linking several computer workstations during off hours to solve problems.

Parallel computing using the PVM system may be the key to solving so-called computational grand challenges.



Al Geist, co-developer of "parallel virtual machine" software and a winner of an R&D 100 Award, explains that several computers linked together (shown as icons) can work on different parts of the same problem.

simply has physical limitations. Parallel computers will be required to solve these problems."

PVM research is sponsored by the Applied Mathematical Sciences Research Program of DOE's Office of Energy Research.

Nuclear Physics Device for ORNL Accelerator Arrives from England

Although the Daresbury Laboratory in England was closed on March 31, 1994, one of its nuclear physics instruments will have a second life at ORNL. The large, multimillion-dollar instrument will be used with ORNL's upgraded heavy-ion accelerator facility to study nuclear reactions predicted to occur during the birth and death of stars.

On October 20, 1994, the Daresbury Recoil Separator, which has been donated to the Laboratory, was delivered to ORNL for use in its new Holifield Radioactive Ion Beam Facility (HRIBF), now being constructed and expected to begin operation in the fall of 1995. HRIBF will be the only U.S. facility dedicated to producing and accelerating intense beams of radioactive nuclei.

The two accelerators that formed the heart of the Holifield Heavy Ion Research Facility from 1980 to 1992 are being reconfigured. One will be used to produce radioactive nuclei that do not occur naturally, and the second will be used to accelerate them. When radioactive nuclei

bombard a target, particles called recoils are produced. The Daresbury Recoil Separator will direct these recoils to detectors while steering away radioactive beam particles.

"The ability of the Daresbury Recoil Separator to separate recoil products from projectile particles makes it a tremendous addition to our research program," says Jim Ball, acting ORNL associate director for Physical Sciences and Advanced Materials. "Combining this instrument with ORNL's unique radioactive beams will enable pioneering advances in our understanding of the explosive events that create and destroy stars."

Physicist Michael S. Smith (pointing) and engineer Don Pierce admire a 19-ton velocity filter magnet. It is one of 14 magnets in the Daresbury Recoil Separator, which was sent from a closed facility in England to be an important part of ORNL's Holifield Radioactive Ion Beam Facility. The magnet will separate by velocity the heavy ions leaving targets bombarded by radioactive ion beams.

"This instrument will enable pioneering advances in our understanding of the explosive events that create and destroy stars."

The recoil separator came to ORNL from the Nuclear Structure Facility of the Daresbury Laboratory in Warrington, England. The facility was closed because of budget cutbacks in the United Kingdom. The Physics Division staff of the Holifield Heavy Ion Research Facility, which faced budget cutbacks of its own in 1992, was successful in securing a new role for the Holifield facility. Approved for construction in 1992, the new HRIBF will begin operating in 1995. The physicists will use these capabilities to study nuclear structure and to conduct nuclear astrophysics research.

"Radioactive beams at ORNL will be used to study nuclear reactions occurring in exotic stellar explosions such as novae, supernovae, and X-ray bursts," says Michael Smith of the Physics Division. "These incredibly energetic astrophysical events produce the majority of heavy elements in the universe and mark the dramatic end of the life of massive stars.

"Sophisticated computer models of these explosions," Smith continues, "require precision measurements of nuclear reactions involving radioactive nuclei like those that will be produced in our new radioactive ion beam facility. Such important measurements would not be possible without instruments such as the Daresbury Recoil Separator."

This separator generates magnetic and electric fields that selectively focus the recoil products onto detectors while steering away the projectile beam particles. The detectors generate information on the arrival time, position, and energy of the recoil products; these data are processed electronically and sent to a computer for storage and analysis. The information obtained may help scientists understand the structure of some 100 nuclei that cannot be produced with nonradioactive beams and targets.

The Daresbury Recoil Separator is 13 meters long and weighs about 90 tons. Its components include two 18-ton dipole magnets surrounding vacuum chambers containing high-voltage electrostatic plates. These components form two velocity filters that separate the radioactive beam

particles from the recoil products based on differences in their direction and speed.

"The transfer of the Daresbury Recoil Separator from England to ORNL required the cooperation of researchers and technical staff from both laboratories," says Jerry Garrett, scientific director of HRIBF. "We anticipate that this cooperative spirit will continue through research collaborations between ORNL physicists and those from Daresbury Laboratory and sites throughout the United Kingdom. Such collaborations will greatly benefit research efforts in nuclear astrophysics, nuclear structure physics, and radioactive beam physics on both sides of the Atlantic Ocean."

Now, in a reversal of roles, ORIC will produce the radioactive beams and the tandem accelerator will accelerate them.

Cyclotron Reaches Goal for Radioactive Beam Facility

The Oak Ridge Isochronous Cyclotron (ORIC) has proven that it can still carry out its original mission—produce intense beams of light ions, such as charged atoms of hydrogen and helium. The difference today is that ORIC, the Laboratory's only cyclotron, is being used to produce radioactive rather than stable ion beams. A cyclotron is an accelerator in which charged particles are propelled, often in a circle, by an alternating electric field in a constant magnetic field.

On March 10, 1994, an important milestone toward developing ORNL's new Holifield Radioactive Ion Beam Facility was achieved. ORIC produced a 75-million-electron-volt beam of alpha particles (helium nuclei).

"This is the first time since 1983 that a beam was extracted from ORIC using the internal ion source," says Fred Bertrand, acting director of the Physics Division. "This achievement marks a major milestone in the Physics Division's development of a radioactive ion beam facility."

ORIC was built in 1964 to produce intense light-ion beams. But its mission changed in 1970 to the production of heavy ions, which were needed for nuclear physics experiments. From 1980 to 1992, the 25-million-volt tandem accelerator, the workhorse of the Holifield Heavy Ion Research Facility, took up the burden of producing heavy ions at ORNL. ORIC was used part-time to boost the energy of the heavy-ion beams emerging from the tandem accelerator.

Now, in a reversal of roles, ORIC will produce the radioactive beams and the tandem accelerator will accelerate them.

Just as many people switch careers at least twice, a cyclotron's role can also change more than once. —*Carolyn Krause*

Greenhouse Gases and Forests

Researchers at ORNL have created an experiment to test the effects of regional precipitation changes on forests. In the experiment, an oak forest is being manipulated to show the effects of drought, normal precipitation, and heavy precipitation on different tree species.

Scientists worldwide predict that the greenhouse effect will increase global temperatures and alter regional levels of precipitation. Temperature increases of approximately 3 to 5°C (5 to 10°F) could occur in 60 to 70 years—a short time compared to a mature tree's life span, which can be several hundred years.

The projected change in precipitation has led researchers in ORNL's Environmental Sciences Division to ask a key question: With some change in precipitation, will current forests be able to maintain current levels of growth and ecological diversity? Determining the sensitivity of forests to changes in soil moisture will provide information on one of the effects of increasing atmospheric concentrations of greenhouse gases.

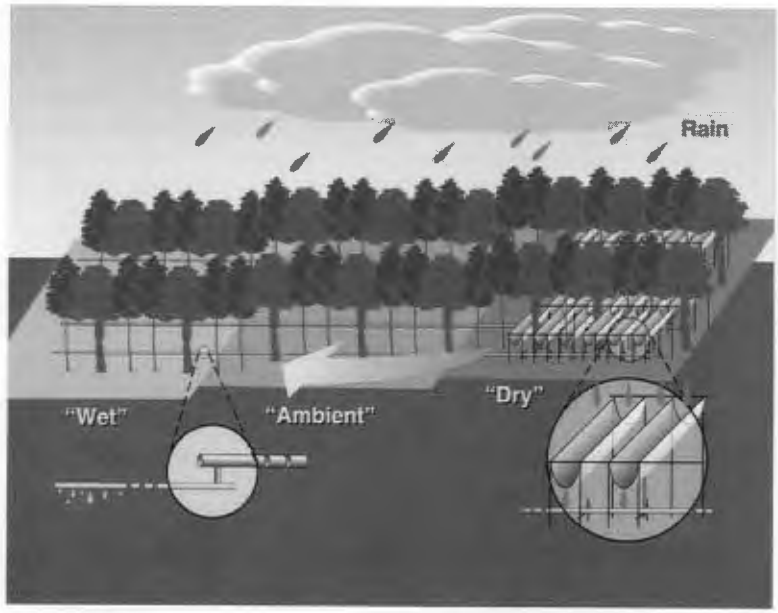
The experimental site for the precipitation studies is a part of the Walker Branch Watershed on DOE's Oak Ridge Reservation, which has been used for ecological research for more than 25 years. The site was chosen for this experiment because the forest has not been disturbed by other experiments or heavy use. According to Paul Hanson, a project researcher, this project is the largest experimental manipulation of an oak forest.

The site, which is approximately the size of three football fields, consists of a wet plot, a control plot, and a dry plot of equal length and width. The amount of precipitation distributed to

the wet and dry plots is controlled by a series of plastic, gutterlike troughs. Each trough is 0.3 meter (1 foot), and they are spaced 0.6 meter (2 feet) apart.

Approximately 2000 troughs intercept about 33% of precipitation falling onto the dry plot—a level chosen to reflect drought levels from the mid-1980s. The intercepted rainwater then flows to the wet plot. The control plot receives natural precipitation.

Trees are unlikely to die during the current three-year experiment, but researchers hope to see trends that will help them predict the plight of forests in several years or decades to come.



The Walker Branch Watershed is the site of a "throughfall displacement experiment" designed to test the effects of regional precipitation changes on different tree species.

One prediction is that tall trees with deep roots may buffer themselves against short-term droughts because their roots will be able to reach deep water supplies. For example, oaks are considered to be more tolerant of droughts than are maples.

The data gathered by this experiment will be applied to other types of trees. However, the experiment cannot be generalized to all regions in the United States because each region's plant life is specifically adapted to that region's climate.

The precipitation experiment is composed of four studies funded through the Program for Ecosystem Research, Office of Health and Environmental Research, DOE. These four studies examine the ability of deciduous forest species to tolerate and survive periods of drought, observe changes in below-ground processes, and quantify alterations in forest productivity and water use under the manipulated conditions of changing moisture levels.

Several collaborators are conducting complementary research on the experimental site. Ted Leininger, U.S. Forest Service, and Johann Bruhn, University of Missouri at Columbia, compose one team studying how *Armillaria*, a pathogenic fungus, will affect oaks when precipitation levels change. Don Shure of Emory University is studying changes in insect feeding patterns in forests in response to precipitation changes.

Researchers hope that the watershed experiment will provide several ecological scenarios on which to base further research, and an understanding of how climate change, influenced by increasing atmospheric concentrations of greenhouse gases, will affect forests before the effects are irreversible.—*Kimberly Baker*

Researchers hope the watershed experiment will provide an understanding of how climate change will affect forests before the effects are irreversible.

ORNL-Produced Isotope Used in Recently Approved Bone Pain Treatment

A therapeutic radioisotope recently approved in the United States for relieving cancer-induced bone pain is produced from a material enriched in a stable isotope by ORNL. The treatment, called Metastron, is manufactured and marketed by

We continue to support Amersham in providing certified, high-quality strontium-88.

Amersham International in England. The company's division Medi-Physics, Inc., in Arlington Heights, Illinois, is distributing Metastron throughout the United States, where it is expected to have widespread use.

In the past seven years, Metastron has been used worldwide for more than 6000 patients to reduce metastatic bone pain—pain caused when breast and prostate cancer spreads, or metastasizes, to bone. Metastron was not employed in the United States for managing metastatic bone pain until recently, following its June 1993 approval by the U.S. Food and Drug Administration (FDA).

Metastron, which consists of strontium-89 chloride, is used to treat bone pain because strontium-89 localizes in bone as a result of its chemical similarity to calcium and because its radioactivity reduces tumor growth in bone. Its effectiveness reduces or eliminates the need for chemotherapy or addictive narcotics to relieve pain. This nonsedating drug eliminates bone pain for up to six months with a single injection. It improves patient quality of life, especially mood, mobility, appetite, and sleep patterns.

According to the December 1993 issue of *Reader's Digest*, Metastron leaves patients alert, allowing them to participate in normal activities. "Dr. Ralph G. Robinson at the University of Kansas Medical Center has studied Metastron in more than 600 patients," the magazine states. "About 80% get relief," he says. "And for some, pain disappears completely."

The strontium-89 in Metastron is produced in five European reactors by neutron irradiation of targets enriched in strontium-88 by ORNL. The source of the strontium-88 is a set of calutrons at the Oak Ridge Y-12 Plant operated by ORNL's Isotope Enrichment Group headed by Joe Tracy. The calutrons, which separate isotopes electromagnetically, were originally used to produce enriched uranium for the Manhattan Project during World War II.

"Since the early 1980s," Tracy says, "ORNL's Isotope Enrichment Program has collaborated with Amersham in development of the Metastron product, and we continue to support Amersham in providing certified, high-quality strontium-88.

"The ORNL group does not certify isotopes for human consumption," Tracy says. "However, our quality-assurance documentation and certification of the starting strontium-88 played an important role in Amersham's obtaining FDA approval for Metastron."

By electromagnetically separating the isotopes of naturally occurring strontium in a single pass, an ORNL calutron produces materials enriched in more than 99.8% strontium-88 for fabricating strontium-88 carbonate targets. After neutron irradiation, these targets are converted to a strontium-89 chloride solution, which is injected into patients.

Tracy says the enrichment process almost completely eliminates the strontium-84 contaminant from the enriched target. Exposure of strontium-84 to neutrons in a reactor yields strontium-85, which emits penetrating gamma rays that could harm patients. Strontium-89, which has a half-life of 51 days, emits pure beta radiation, energetic electrons that have a very short range.

Predicting Properties of Chemicals Using Neural Networks

Bobby G. Sumpter (sitting) and Don Noid have helped develop MOLDESIGN, a "neural network" computer program that can predict properties of almost any chemical, based on its structure and elemental composition.

ORNL researchers have developed a computer program that can predict physical properties of some classes of chemical compounds based on their chemical names. The inexpensive personal-computer software relies on a neural network, a "learning computer" that can be trained to recognize patterns and make associations. It is fast, accurate, and easy to use.

Already ORNL researchers have used the program, called MOLDESIGN, to address the recent ban on the production and use of common Freon™ in heat pump compressors and car air conditioners. MOLDESIGN has the capability of evaluating numerous possible Freon™ substitutes and determining the best candidates that could be used in existing equipment without changing its design and parts. The best compounds would have the desirable properties of Freon™ but would not destroy earth's protective ozone layer and increase the likelihood of skin cancer and cataracts caused by ultraviolet radiation from the sun.

The computational approach was developed by Andre Gakh (a postdoctoral scientist), Bobby Sumpter, and Don Noid, all of ORNL's Chemical and Analytical Sciences Division.

MOLDESIGN can screen present and predicted compounds to identify materials with desired properties. This capability could save U.S. industry millions of dollars in testing costs as it searches for more effective drugs, explosives, and metallic alloys and plastics.

"MOLDESIGN's ability to predict physical, chemical, and mechanical properties of compounds before they are synthesized can be very useful," Sumpter says. "It can guide a material's design and processing to get the best product.

MOLDESIGN, Noid says, is particularly useful for polymers, the large molecules formed from chains of smaller molecules that make up plastics. MOLDESIGN can be used to predict the properties of different blends of polymers. Sumpter adds that it has the capability to identify the best processing technologies for making polymers that have desired properties such as increased hardness or stiffness.

MOLDESIGN can predict physical, chemical, and mechanical properties of compounds before they are synthesized.

The key to developing crash-avoidance systems for cars and trucks is to understand the detailed behavior of drivers and vehicles.

"A neural network," Sumpter says, "can be constructed to predict correctly the properties of chemical compounds based on structural features and elemental compositions. This capability provides the foundation for designing new compounds or for predicting properties of existing compounds that have not been previously characterized."

MOLDESIGN was developed at the Laboratory as part of a 1992 cooperative research and development agreement (CRADA) between Martin Marietta Energy Systems, Inc., which manages ORNL for the Department of Energy, and Hoechst Celanese Corporation, an international manufacturer of fibers, chemicals, plastics, and pharmaceuticals, which is headquartered in Germany and has an office in Summit, New Jersey. The development was supported by Y-12 Plant funds obtained from DOE's Defense Programs.

This CRADA, called Atomistic Simulations of Materials: A Neural Network Approach, is part of a larger CRADA called Materials by Computational Design involving DOE's Oak Ridge Y-12 Plant, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories.

Avoiding Car Crashes Subject of CRADA

ORNL is collaborating with Scientific-Atlanta, Inc., on research that could reduce the number of deaths and injuries from vehicle collisions. The partners will develop a device to study both driver and vehicle behavior, and the information could aid in the design of crash avoidance systems for cars and trucks.

ORNL and Scientific-Atlanta will develop a portable automotive data acquisition system for crash-avoidance research (DASCAR). The goal is to apply technologies developed for defense to the reduction of human suffering and financial losses resulting from vehicle collisions on U.S. highways.

The effort is receiving U.S. Department of Transportation (DOT) funds designated for development of the Intelligent-Vehicle Highway System (IVHS). The nation's first IVHS CRADA is supporting the crash-avoidance research project.

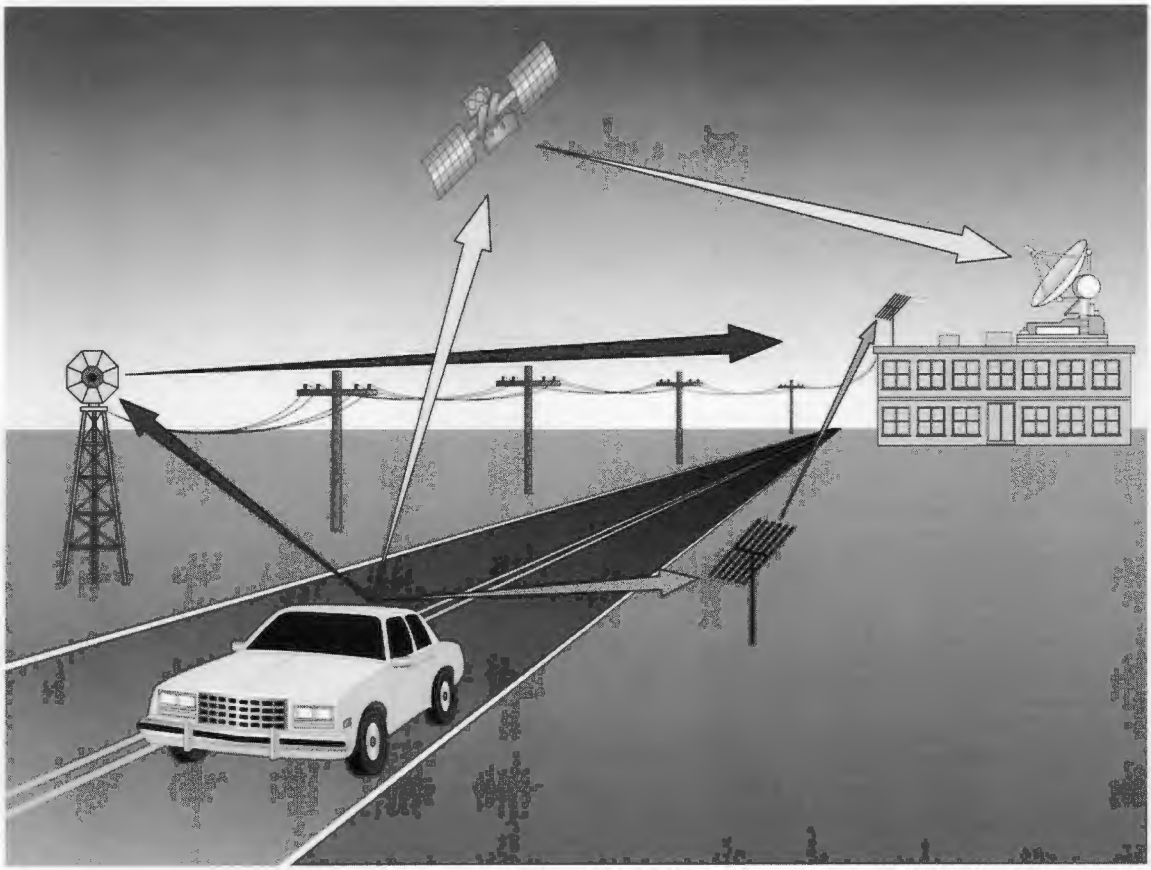
Scientific-Atlanta is a communications company whose task is to develop and provide an automotive data processing unit, compressed video digital storage and retrieval system, and communications equipment. ORNL's expertise in human factors research (e.g., identifying the most effective ways to display and communicate reactor control information to human operators), advanced technology, and instrumentation and controls will be called upon in the CRADA.

Richard J. Carter is ORNL's principal investigator for the CRADA and a psychologist in the Engineering Physics and Mathematics Division (EPMD). Working with him on this project at ORNL is Frank Barickman, a senior at Gannon University in Erie, Pennsylvania, who is participating in a program sponsored by the Oak Ridge Institute for Science and Education and DOE. Another collaborator on the project at ORNL is Philip F. Spelt of EPMD.

Carter says the key to developing crash-avoidance systems for cars and trucks is to understand the detailed behavior of drivers and vehicles under a variety of road and traffic conditions.

"We are primarily interested in the changes that occur right before an accident or near miss, such as an increase in speed," Carter explains. "These specially equipped vehicles will be used on a test track and the open road to test the effects on driver performance of various conditions ranging from the weather to traffic congestion."

Using high-speed digital data processing equipment and specially developed software, Scientific-Atlanta and ORNL will develop a prototype system that will consist of four video cameras, each the size of a thumb; sensors strewn along the car's bottom and under the hood; and an on-board computer system. The computer system, which is small enough to fit in the trunk of almost any car, collects, records, processes, compresses, and transmits data from the sensors and cameras. The processed data will be transmitted to a control center by cellular telephone and microwave communications with a satellite (for cars on the



Schematic of Data Acquisition System Crash Avoidance Research (DASCAR) car showing its communication links with the central computer control station through (clockwise from car) cellular telephone, microwave (to and from satellite), and radio signals.

"An intelligent cruise control could be developed to respond instantly to shrinking distances between cars to avoid a potentially deadly crash."

open road) and by radio telemetry (for cars on a test track).

"Sensors will record all driver actions, such as braking, steering, turning on the wipers, and tuning the radio, as well as data on the driver, such as heart rate and brain waves," Carter says. "DASCAR will gather near real-time information on the car's speed, pitch, roll, yaw, lateral position within the lane, and distance from cars ahead and behind. DASCAR will also record information on characteristics of the road, changes in the weather, and traffic and sign density that could affect driving."

ORNL has completed a study to determine the parameters and measures that should be recorded, identified available state-of-the-art hardware and software to record the parameters and measures, and estimated the costs of developing a DASCAR system.

"We were asked to conceive of an unobtrusive data recording system that wouldn't be noticed by the outside world," Carter says. "We couldn't have a satellite dish on the car roof, gadgets hanging from the bumper, or a fifth wheel behind the car. We will have electrodes on the driver because it is too expensive to sense driver physiology and behavior remotely."

The heart of the DASCAR system will be Scientific-Atlanta's data processing unit, which collects data from all the sensors and cameras. For this system, Scientific-Atlanta also will contribute a radio telemetry system and satellite link for two-way communications with the INMARSAT satellite. The Global Positioning System will help

Rhenium-188 is expected to play an important role in treating the pain of bone cancer.

determine where the car is on the road and within its lane. In addition, the company will provide a compressed video digital storage and retrieval system, which rapidly retrieves and integrates compressed video data with other digitized information for analysis and transmission by DASCAR.

ORNL's role in the CRADA will be to incorporate hardware supplied by Scientific-Atlanta into the other components of the data acquisition system. ORNL will then install and calibrate the DASCAR within five vehicle types and will evaluate and pilot test the data acquisition system.

"Our goals are to procure, develop, test, and validate this hardware and software on a car. We will put the first DASCAR system on a car driven by the director of ORNL's Robotics and Process Systems Division," Carter says. "We will drive this car around the Oak Ridge area this year. In 1995 we will test some DASCAR systems on cars on a 7.5-mile test track in East Liberty, Ohio. Then 15 DASCAR cars will be tested by volunteers throughout the nation."

Carter says ORNL also has been asked to develop software for the data processing center to make sense out of data sent there from all the test cars. Such software will seek out meaningful data from the cars, such as a significant sequence of events occurring within one second of a car crash. It will present the data as easy-to-interpret graphics on a display screen.

"Most vehicle crashes could be prevented if the correct action were taken within a half second to a second before the collision," Carter says. "If the car can sense that it is too close to another car, it could be programmed to take over steering and braking from the driver at a certain point to avert the collision. DASCAR should demonstrate that a car's lateral position in the lane and distance from cars ahead and behind can be recorded. If so, an intelligent cruise control could be developed to respond instantly to shrinking distances between cars to avoid a potentially deadly crash."

ORNL research for the CRADA will be supported by $205,000 from the National Highway Traffic Safety Administration (part of DOT).

Medical Isotope Generator Licensed to California Firm

A new ORNL-developed device that produces an inexpensive radioisotope for treating patients with cancerous tumors, cancer-induced bone pain, or arthritis may become a commercial product for hospitals by the end of the decade.

Through a licensing agreement, Martin Marietta Energy Systems, Inc., has granted exclusive rights to Isotope Products Laboratories, Inc. (IPL), in Burbank, California, to manufacture and market the tungsten-188/rhenium-188 generator. The device was developed by F. F. (Russ) Knapp and colleagues in the Nuclear Medicine Group in ORNL's Health Sciences Research Division.

IPL, which was founded in 1967, produces radioisotopes used in environmental measurements, analytical instruments, and nuclear medicine. IPL's new nuclear medicine subsidiary, IPL Imaging and Therapeutics, Inc., will manufacture the generator and seek U.S. Food and Drug Administration approval to market it to hospitals.

"We hope to build upon the solid development work of Dr. Knapp's group," says Len Hendrickson, IPL president. "Much clinical development work remains to be done before the rhenium generator can benefit patients worldwide. We look forward to completing the work necessary to bring the product to market. The rhenium generator is an important addition to Isotope Products' growing line of nuclear medicine products. Our new subsidiary will be responsible for manufacturing and marketing the product."

The source of the tungsten-188 for the generator is ORNL's High Flux Isotope Reactor. As the radioactive tungsten decays in the generator, it forms radioactive rhenium-188, which can be used for medical treatment. "Because half of tungsten-188's radioactivity disappears in 69 days," Knapp says, "the shelf life of the generator is at least two months. Rhenium is constantly being supplied for several weeks.

"The radioactive rhenium produced in the generator," he adds, "emits energetic electrons called beta radiation and short bursts of light called photons as half of its radioactivity decays in about 17 hours. After injection into the patient, the

distribution in the body of rhenium-188–labeled agents can be monitored with photon-sensitive cameras. More importantly, the beta radiation, which can kill cancer cells, can penetrate a third of an inch into tumor tissue, suggesting that it can be used to reduce large tumors."

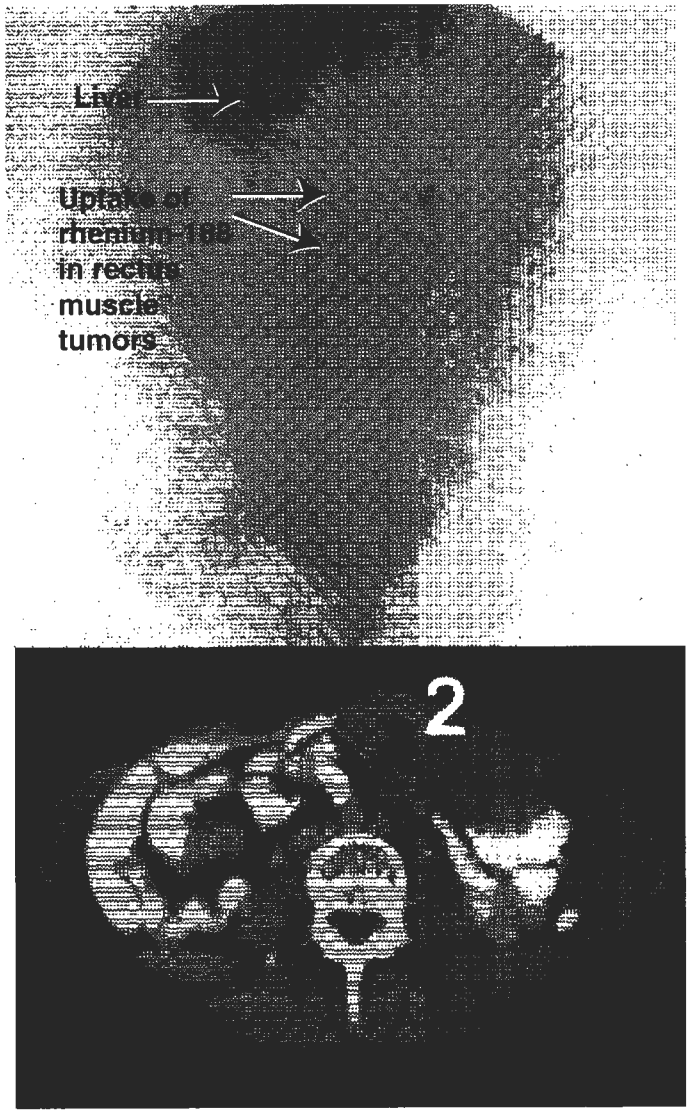
Researchers at the Center for Molecular Medicine and Immunology at the University of New Jersey developed a procedure for chemically linking rhenium-188 to an antibody that homes in on colon cancer cells. Studies of 12 patients with colon tumors showed the ability of this therapeutic agent to concentrate in these cells.

Rhenium-188 is expected to play an important role in treating cancer-induced bone pain. The rhenium can be attached to certain compounds that tend to settle in bones. "The treatment is expected to be considerably less costly than using strontium-89, rhenium-186, and other radioisotopes that are currently used to treat bone pain," Knapp says, "and studies are in progress to verify this prediction. If the rhenium-188 treatment is found to be less expensive, it could help reduce health care costs."

Patients having cancer of the breast or prostate often experience bone pain when cancer cells migrate from the primary tumor to the skeleton. The cancer cells can penetrate tissues surrounding the bone. It is believed that increased pressure on nerves in this tissue from both tumor cells and inflammation causes bone pain. The energy of the beta radiation reduces inflammation, thus relieving bone pain.

For treatment of arthritis, the rhenium can be attached to compounds that are injected into the fluid of inflamed knees and other fluid-filled joints. According to Knapp, the energy released as the rhenium decays helps relieve the painful swelling and inflammation of arthritic joints.

"The use of radioisotopes for arthritis treatments is very common in Europe," Knapp



Gamma camera image (upper panel) shows two rectus muscle tumors in a patient's peritoneal region near the liver obtained after intravenous administration of rhenium-188–labeled antibody. The tumors can also be seen in a computerized tomographic image (below). *Courtesy of D. M. Goldenberg, M.D., M. Juweid, M.D., R. Sharkey, Ph.D., and colleagues at the Center for Molecular Medicine and Immunology in Newark, New Jersey.*

"ORNL is helping develop processes for producing super-conducting wire for electrical conductors and energy storage devices."

says. "Such treatments are expected to be used more widely in the United States on an aging population."

Superconducting Wire Technology CRADA

ORNL and Oxford Superconducting Technology of Carteret, New Jersey, are jointly developing technology needed to produce long lengths of bismuth-2212 wires that can carry useful amounts of electrical current when chilled to low temperatures. The wires will be made of silver tapes coated with thick bismuth films.

Superconducting films and wires of short lengths have been fabricated, but few long wires that have high critical current density have been reliably reproduced. ORNL is collaborating with industrial partners to develop reliable processes for fabricating long superconducting wires for use in bulk electrical conductors and energy storage devices.

In a CRADA signed earlier this year, Oxford is developing a dip-coating process for coating silver tapes with long, thick films of bismuth. Oxford has the primary responsibility for all powder and slurry preparation; for preparation, heat treatment, and evaluation of longer lengths of prototype conductors; and for actual manufacturing of the wires.

Oxford is choosing appropriate powders, solvents, binders, and dispersants that make possible uniform and homogeneous coatings over a long length. Oxford will also produce samples of dip-coated bismuth-2212 wires.

In the CRADA, ORNL researchers led by Robert K. Williams of the Metals and Ceramics Division evaluate the microstructure of powders and wires and perform other analytical characterizations. For example, they will determine the sizes of crystalline grains making up the wire and the chemistry in the areas between the grains, known as grain boundaries. For this work, they are using X-ray diffraction, thermogravimetric and differential thermal analysis, metallography, and electron microscopy.

ORNL also is engaged in developing or selecting lower-cost alloys that could replace the silver now used for tapes on which the bismuth is deposited. In addition, ORNL and Oxford will jointly measure wire performance such as critical current density, critical temperature, and magnetization as a function of magnetic field.

The one-year CRADA is valued at $125,000; DOE will fund $50,000 of the project. All of the work at ORNL is funded by DOE's Office of Energy Management's Superconductivity Program for Electric Power Systems. The program is developing with industry the technology necessary for commercial development of electric power applications of high-temperature superconductors.

Oxford Superconducting Technology is a leading producer of low-temperature superconductors used in magnets for magnetic resonance imaging (MRI) scanners, nuclear magnetic resonance spectroscopy, particle accelerators, and other applications. The company has recently completed delivery of nearly two million feet of superconducting cable to DOE's Brookhaven National Laboratory for the Relativistic Heavy Ion Collider.

Next Issue

The Oak Ridge Reservation has evolved into a valuable natural resource over the past 50 years. More than 1000 plant species and more than 300 animal species, like this young osprey nesting in the Clinch River adjacent to the reservation, now call the reservation home.

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Tuan Vo-Dinh, a leading photonics expert at ORNL, developed a method for on-site detection of PCBs. See photonics articles beginning on p. 4.