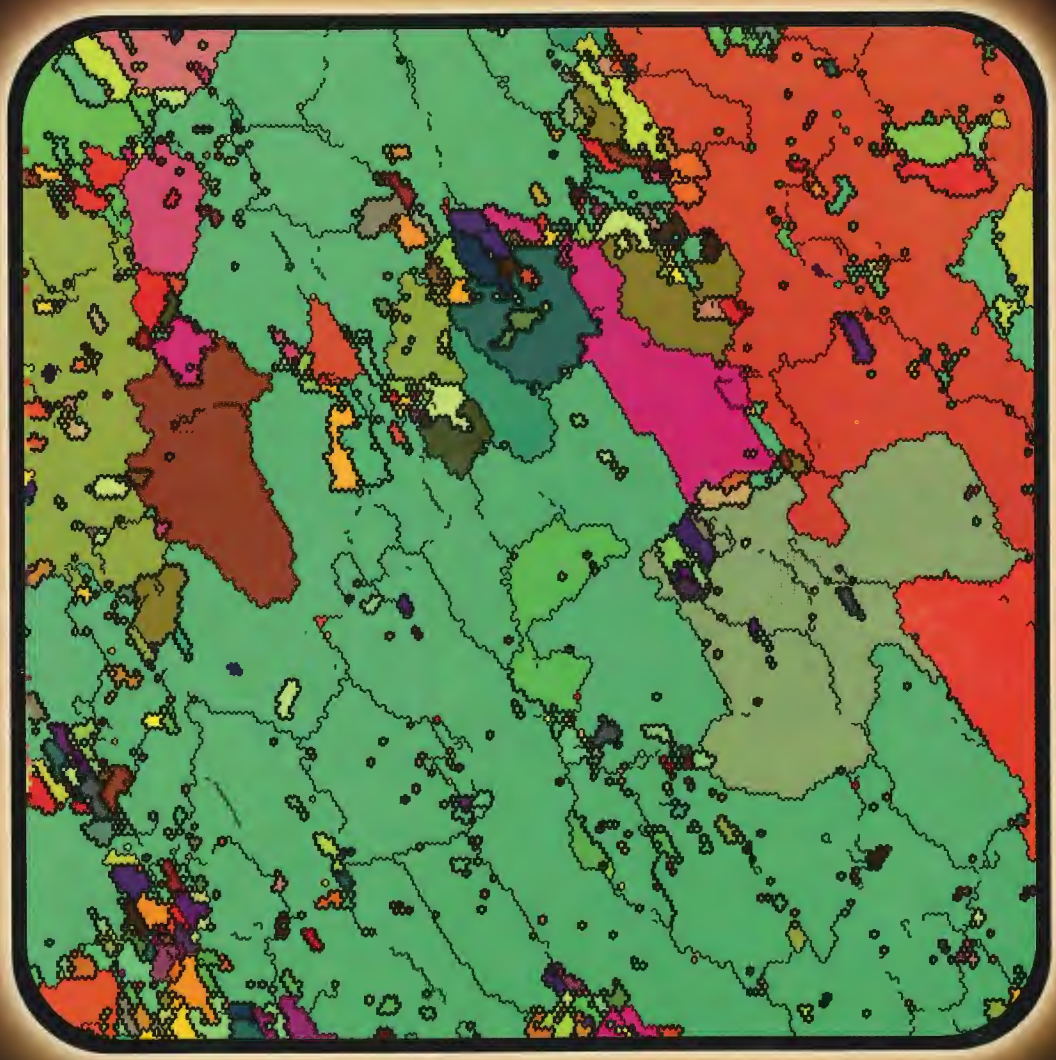
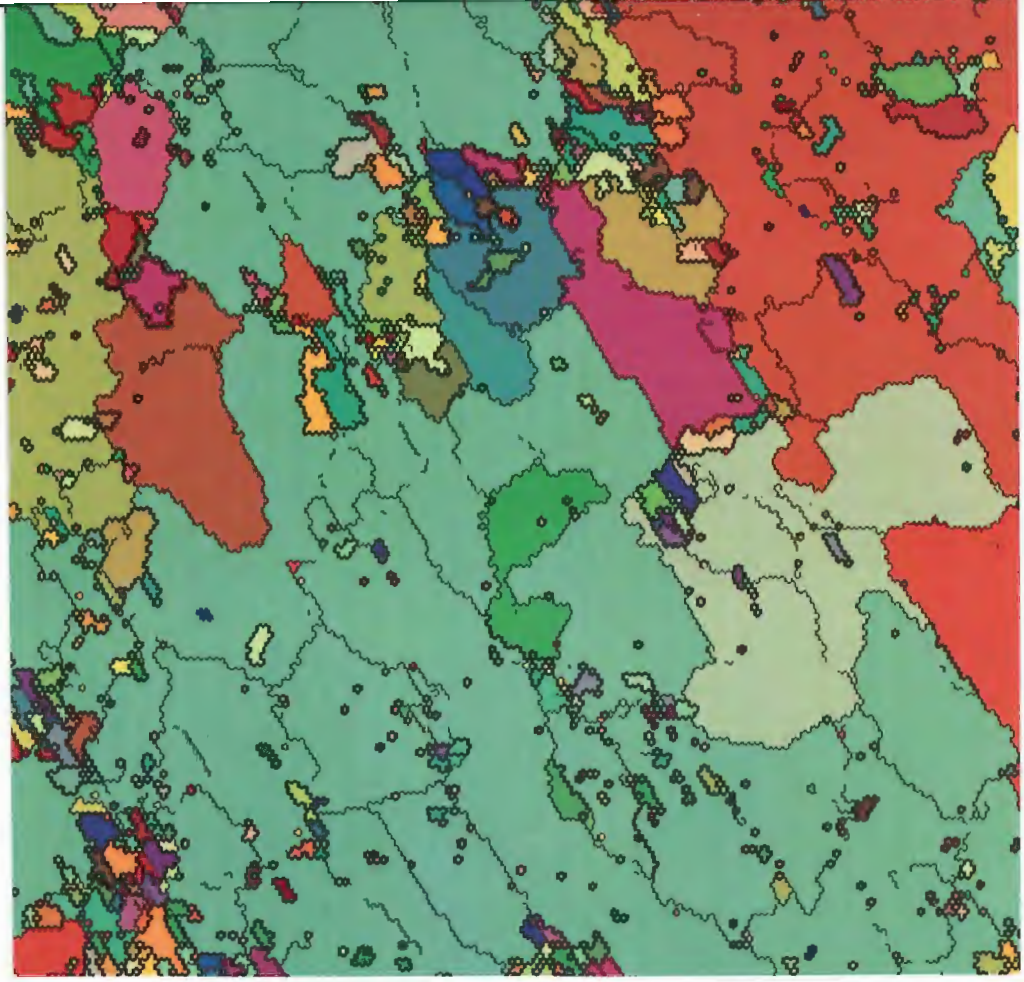
Department of Energy/Lockheed Martin Energy Research Corp.

Oak Ridge National Laboratory REVIEW

Vol. 29, Nos. 3 & 4, 1996



Next Generation of Superconducting Wire



COVER CAPTION

This colorful map of texture in a substrate for a superconducting film was produced by ORNL's computerized field-emission-gun scanning electron microscope, which analyzes patterns of electrons backscattered from crystalline planes of atoms. This capability was essential to understanding the grain-boundary structure of bismuth- and thallium-based superconductors that carry large amounts of current and to optimizing the texture of buffered nickel and copper substrates for superconducting tapes. See articles beginning on p.2 and p.8 for a discussion of ORNL's exciting development of short superconducting tapes using textured substrates, which recently received a NOVA Award for Teamwork from Lockheed Martin Corporation. The cover was designed by Dave Cottrell, graphic artist in the Computing, Information, and Networking Division.

The *Oak Ridge National Laboratory Review* is published two to three times a year and distributed to employees and others associated with or interested in ORNL. The address of our editorial office is Building 4500-South, M.S. 6144, Oak Ridge, TN 37831-6144; telephone: (423) 574-7183 or (423) 574-6974; FAX, (423) 574-1001; electronic mail, krausech@ornl.gov.

If you have changed your mailing address and want to remain on the mailing list, please notify the editorial office.

Internet users can find the *Review* at: http://www.ornl.gov/ORNLReview/

The *Review* is also available on microfiche at the ORNL Central Research Library.

The *Review* is printed in the United States of America and is also available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

ORNL is managed by Lockheed Martin Energy Research Corporation for the Department of Energy under contract DE-AC05-96OR22464.

ISSN 0048-1262

Editor
Carolyn Krause

Assistant Editor
Deborah Barnes

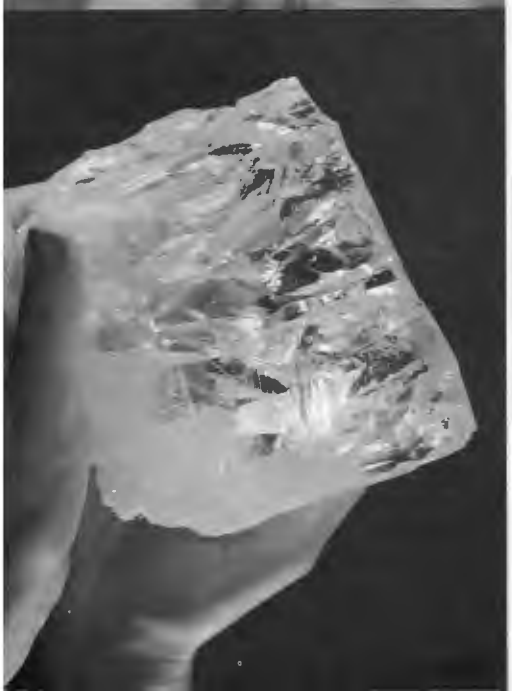
Consulting Editor
Bill Appleton

Designer
Linda Dickert

Technical Editor
Charlene Horak

Photographer
Tom Cerniglio

Produced by ORNL's office of Communications and Public Affairs and the Computing, Information, and Networking Division.



Oak Ridge National Laboratory

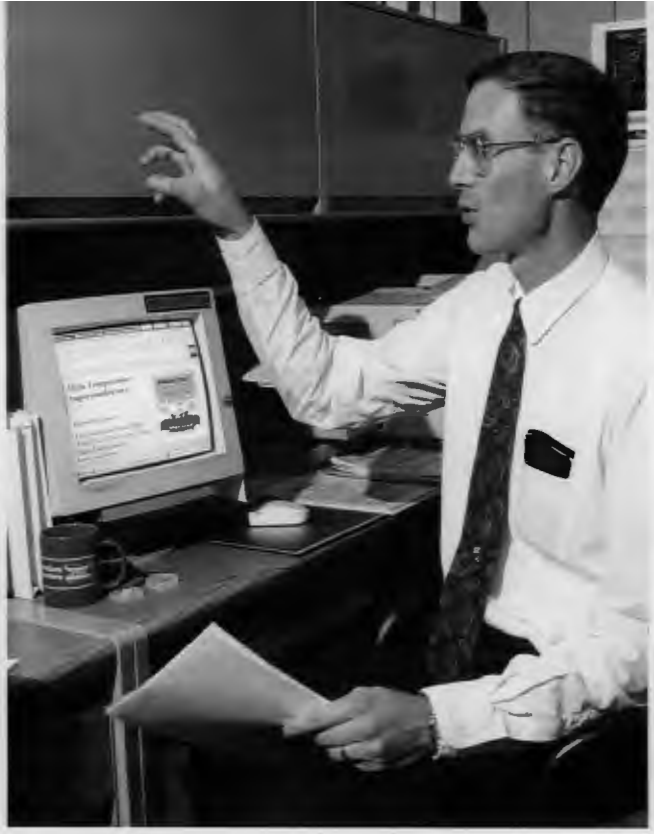
REVIEW

Vol. 29, Nos. 3 & 4, 1996

FEATURES

DEPARTMENTS

Oak Ridge National Laboratory is a multiprogram, multipurpose laboratory that conducts research in energy production and end-use technologies; biological and environmental science and technology; advanced materials synthesis, processing, and characterization; and the physical sciences including neutron-based science and technology.



Hot Wire: ORNL's Promising Route to Superconductivity

By Carolyn Krause

Electrons, like people, like to go with the flow. As they travel the electrical highway, they try to avoid electromagnetic roadblocks and get in the fast lane. Easing the flow of electron traffic has been a goal at ORNL since 1986 when high-temperature superconductivity was discovered. But, like electrons, ORNL, researchers have encountered roadblocks. They have found it exceedingly difficult to develop a high-temperature superconducting wire. After much persistence, secrecy, team work, and just plain hard work over the past seven years, ORNL scientists have found a promising new route to forming a superconducting wire.

On April 10, 1996, at the spring meeting of the Materials Research Society in San Francisco, ORNL researchers rolled out a new superconductor—a tape 3 millimeters wide and 15 millimeters long, and it became a hot item. They announced the development of a process for making the backbone of superconducting wire using a pair of rollers, heat, and thin crystalline films. The rolling-assisted biaxial textured substrates (RABiTS) process generated excitement among researchers in the electrical industry because it represented a leap forward in the race to develop fabricable superconducting wire. RABiTS is faster and probably cheaper than the ion beam–assisted deposition (IBAD) process perfected in 1995 by DOE's Los Alamos National Laboratory (LANL).

Considered a cornerstone technology in high-temperature superconducting wire, the ORNL process conditions the substrate, or template, upon which a superconductor can be formed. The substrate, which is made of nickel covered with thin buffer layers, provides the underlying foundation for the superconducting wire. The superconducting material, called YBCO for short (for yttrium-barium-copper oxide, or $YBa_2Cu_3O_{7-x}$), is made of crystalline grains. Each grain is a homogeneous region in which atoms are lined up in fixed directions. In materials available before the RABiTS or IBAD processes were developed, the grains pointed in different directions, like cars at a very busy intersection. RABiTS gives the YBCO grains a consistent orientation, like cars whizzing by on an interstate highway, unlocking electronic gridlock. A high degree of grain alignment in all directions is the key to more efficient electrical current flow through the superconductor.

Efficient current flow is the Holy Grail of the electrical industry. Today electricity is delivered by copper wire. But atomic bumps in the unpaved copper road slow the flow, and electrons pay tolls in the form of energy loss. The copper's resistance

Our substrate process will pave the way for the future manufacture of the next generation of high-temperature superconducting wires.

causes the wire to heat up and dissipate energy. Superconductors avoid this wasteful process. Because superconductors have no resistance to the flow of electricity, electrons get a free ride in the interstate's fast lane.

"Our substrate process will pave the way for the future manufacture of the next generation of high-temperature superconducting wires," says Robert Hawsey, director of ORNL's Superconductivity Technology Center. "These wires will be the first to conduct electricity efficiently in the presence of high magnetic fields at liquid nitrogen temperatures.

"If these wires can be made long enough and strong enough, they can be used in transmission cables, transformers, current limiters, and motors and generators—anywhere large amounts of electricity are produced, transmitted, or distributed to customers. They can be used in devices that contain magnets, such as particle accelerators for research and medical diagnostic machines. They may also be used in large motors used in heavy industry, such as paper or steel mills."

YBCO: Stands Up to Fields But Is Out of Line

Hawsey knows all about the struggle to make a YBCO-based wire (the name YBCO inspires the question, "Why be so out-of-line?). "Before I became the center's director in 1991, many groups had tried in vain to put YBCO coatings that were superconducting on standard silver wire. We lost interest in YBCO after it was shown that bismuth-based wires could carry a lot of current in low magnetic fields."

A compound containing some of the YBCO ceramic was first produced in January 1987 by Paul Chu of the University of Houston and M. K. Wu at the University of Alabama in Huntsville. They had substituted yttrium for the lanthanum in lanthanum-barium-copper oxide, the first high-temperature superconductor, discovered in January 1986 by J. Georg Bednorz and K. Alex Müller of the IBM Zurich Research Laboratory in Switzerland.

Bob Hawsey, director of ORNL's Superconductivity Technology Center, discusses the bright future he sees for ORNL's work with industry to develop a commercializable superconducting wire. On the computer screen is the World Wide Web site that contains information on the development of ORNL's superconducting wire (http://www.ornl.gov/HTSC/htsc.html). *Photographs by Tom Cerniglio.*

If it's kept cold enough and if its atoms are properly aligned, YBCO can conduct electricity without resistance, unlike copper metal used in conventional conductors. As a superconductor, YBCO has two important properties. First, it can conduct electricity in the presence of a relatively strong magnetic field, making it potentially useful for motors, generators, and other devices that have magnets, such as accelerators and medical diagnostic machines. Second, it superconducts if chilled to 77 K by liquid nitrogen, making it a high-temperature superconductor. Alloys of niobium and titanium (NbTi) and of

So the big challenge has been to fabricate wires and tapes coated with properly aligned YBCO. After such coated conductors were made finally at ORNL, the next … hurdle … was to improve the YBCO coating's ability to carry large amounts of current.

niobium and tin (Nb_3Sn) conduct electricity with zero resistance when chilled to 4.2 K by liquid helium, making them low-temperature superconductors. High-temperature superconducting materials like YBCO are preferred because they are far more economical: liquid nitrogen is 50 times less expensive than helium (10 cents a liter instead of $5 a liter).

The problem with YBCO has been the difficulty of aligning its grains and incorporating it into a long flexible wire. It is possible to make small-area (<1 in.), high-quality YBCO films on single crystals, but they are too short for use as wire and easily break when bent like wire. It is also possible to make thick YBCO conductors, but these "bulk conductors" superconduct as well as films only if chilled to 20 K by liquid helium. So the big challenge has been to fabricate wires and tapes coated with properly aligned YBCO. After such coated conductors were made finally at ORNL, the next big hurdle on the road to a practical superconducting wire was to improve the YBCO coating's ability to carry large amounts of current (critical current density).

"Normally, YBCO's crystalline grains are randomly oriented, so we tried various ways to align them to get good current flow," Hawsey says. "In 1989 our researchers, working with Georgia Tech scientists, tried coating flat silver tapes and round silver wires with YBCO using a metal organic chemical vapor deposition process. We were not successful in making a good superconductor this way. At that time, a bismuth-based material called BSCCO looked more promising than YBCO for making superconducting cables."

BSCCO (pronounced "bisco") is shorthand for bismuth-strontium-calcium-copper oxide. Several domestic and foreign companies are now fabricating BSCCO tapes and wires in lengths of kilometers. They pack BSCCO in silver tubes and draw the tubes into wires or flatten them into tapes. "BSCCO performs well in underground transmission cables and transformers at temperatures of 65 to 77 K and in higher magnetic fields at 20 to 30 K," says Hawsey. "BSCCO's grains are platelike, so when the material is rolled, they tend to line up in one direction more easily than YBCO grains. But unlike YBCO at 77 K, BSCCO's performance drops like a rock in the presence of a magnetic field."

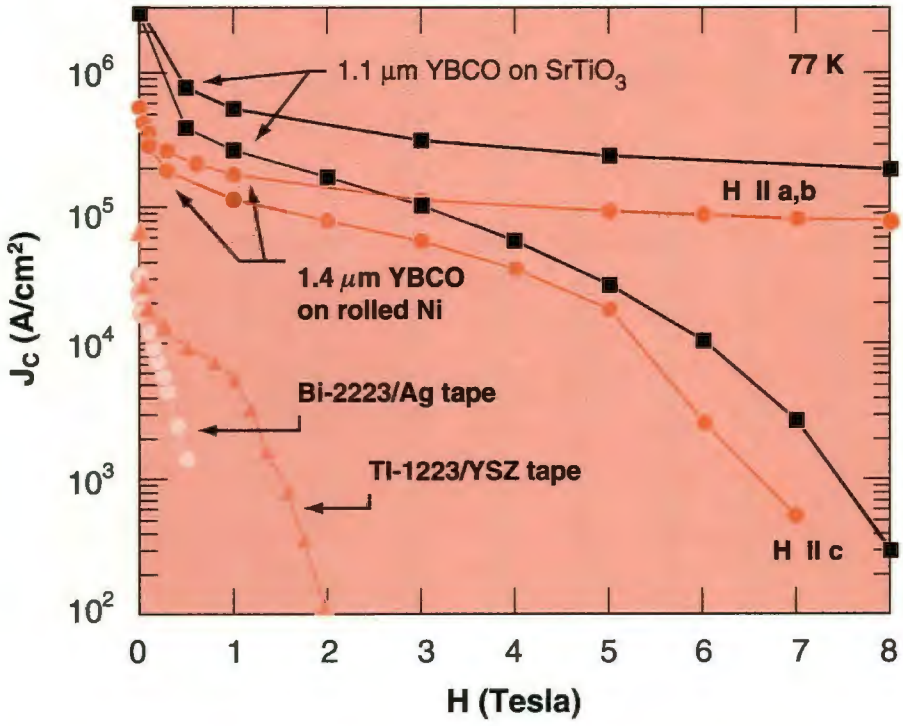
In 1990, ORNL researchers took a completely different approach to aligning grains in YBCO films. They first examined YBCO films deposited onto metal tapes by pulsed laser ablation. In initial work using silver sheets as substrates, they noticed that even metal sheets obtained from the stockroom possessed a certain useful degree of grain alignment. Metallurgists have known for many years that grain alignment, called "texture," is often introduced into metals when they are rolled to form thin sheets or foils. The ORNL researchers realized that, if they could intentionally roll highly textured metal foils and then transfer this alignment to a deposited YBCO film, they should be able to make high-current wires that could operate in high magnetic fields at 77 K.

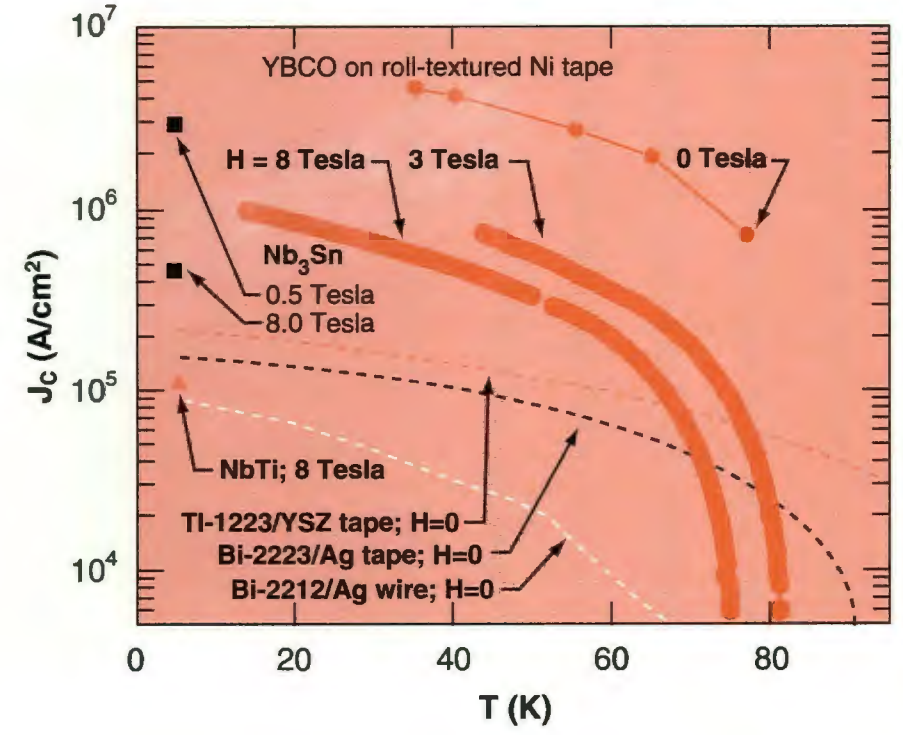
The many steps needed to roll metal tapes and to deposit high-quality buffer layers and YBCO turned out to be much more challenging than researchers first envisioned. However, five years after they first began working on this alternative approach, YBCO was no longer on the back burner. Some 15 ORNL researchers from three different divisions, along with five students and postdoctoral researchers, had teamed to solve a series of problems. They found a way to roll nickel to make a flexible textured tape coated with YBCO and three buffer layers—palladium, cerium oxide, and yttrium-stabilized zirconia. The pattern on the nickel template forced the alignment of the crystalline grains of the buffer layers and the YBCO on top.

"In the summer of 1995," Hawsey says, "we had low critical current densities. So we figured out how to improve the architecture of the buffer layers after Christmas to raise the critical current density to 300,000 amperes per square centimeter from January through March 1996. By late April, we had simplified the architecture by eliminating the palladium and raised the current density to 710,000 amperes per square centimeter in zero applied field. On April 10 we announced our development of a process to make a practical superconducting wire at a Materials Research Society meeting and in a news release. We caught the Japanese by surprise with our announcement of RABiTS. That was pretty darn exciting."

ORNL and LANL Processes Compared

Hawsey said that the development of a YBCO superconducting wire earlier at LANL was encouraging to the ORNL group. "They used a similar architecture and similar materials like cerium oxide, yttrium-stabilized zirconia, and nickel, except they use





The magnetic field and temperature dependence of the critical current density for short-sample YBCO conductors produced using ORNL's RABiT substrates. These data are compared with typical values of both high- and low-temperature superconductors (such as niobium-tin and niobium-titanium).

Hastelloy nickel alloy and we use rolled pure nickel. These material similarities gave us the confidence our materials would work."

How do the two processes differ? ORNL relies on a high degree of alignment of atoms in the substrate, which propagate through the buffer layers to the YBCO. LANL starts with Hastelloy nickel alloy that is not well aligned and deposits an yttrium-stabilized zirconia (YSZ) layer on it as a buffer. LANL uses IBAD to align the YSZ layer under the YBCO film. The ion beam selectively removes the YSZ atoms not aligned at certain orientations biaxially. This is the limiting step that slows up the process and makes it potentially more costly than the RABiTS process for roll-texturing nickel.

Los Alamos has made impressive improvements over the IBAD process invented in the late 1980s in Japan. So far, Los Alamos has achieved 1 million amps per square centimeter in zero applied field at 75 K. The Japanese achieved a half-million amps per square centimeter using IBAD. Los Alamos broke the million mark by careful tuning of the process and careful attention to detail for depositing buffer layers.

Why must critical current density be so high in superconductors? Says Hawsey: "A lot of supercurrent must flow in the superconducting YBCO film to make up for the fact that the substrate, which is just a building block, is not carrying any current. The YBCO superconductor in thickness represents only a couple percent of the actual wire. Unless the current density is extremely high in the YBCO, the tape or wire won't have the overall current density of 50,000 to 80,000 amps per square centimeter required in a conductor. Standard household wires typically carry less than 1000 amperes per square centimeter. The higher the current density, the smaller the wire can be. That's important because engineers want wires used in motors,

High-temperature superconducting wires, says Hawsey, offer the possibility of fabricating new electric power devices that are more compact, cost less to operate, and use less energy.

transformer coils, and transmission lines to be as small as possible."

High-temperature superconducting wires, says Hawsey, offer the possibility of fabricating new electric power devices that are more compact, cost less to operate, and use less energy. U.S. electricity demand is expected to double by the year 2030, so energy-efficient systems are needed to reduce requirements for costly new power plants.

Industrial Strength

"What Oak Ridge has done," Hawsey says, "is to come up with an industrially scalable way to get the alignment needed to ensure efficient electrical current flow. However, a few technical issues must be addressed before this technique is commercialized. Industrial partners must help us address the technical challenges of developing an industrial process of reproducing a reliable long-length superconducting wire."

YBCO surface-"coated conductor" architecture uses RABiTS to achieve a well-textured superconductor.

One challenge is to determine the best way of chilling the wires to make them superconducting. Should the wire be wrapped around a hollow tube containing liquid nitrogen? Or, should it be conductively cooled by putting a cryocooler in contact with part of the wire?

Can the length of the superconducting wire be extended from a few centimeters to a kilometer? "The longest textured nickel tape we have produced is about a meter in length," Hawsey says. "The question is, can a uniform texture be reproduced along a wire hundreds of meters long? Industrial partners such as the Westinghouse Science and Technology Center will help us address this technical issue."

Hawsey also expressed concerns about buffer layer continuity and mechanical integrity of the substrate. "Will the buffer layers consistently have the desirable mechanical properties when the wire is wrapped around a tube or made into a coil?" he wonders. "Will superconducting properties hold up under the strain experienced by film wrapped around a tube? What happens to the superconducting properties if the wire is chilled to cryogenic temperatures 100 times? If a RABiTS superconductor is coated with a passivation layer, can it sit on a shelf in East Tennessee humidity all summer and still function when built into a device?"

The fact that nickel is magnetic may also be a problem. "The electrical energy in the superconductor could dissipate in the presence of an alternating magnetic field, causing unacceptable alternating-current losses," Hawsey says. "Also, if you wind a magnet with nickel wire, the magnetic nickel may distort the magnetic field of the magnet by sucking in the flux lines. Such an effect could make it difficult to predict the shape of the magnetic field, which may be essential in magnetic resonance imaging (MRI) and accelerator magnets. But, if this turns out to be a problem, it may be overcome by good engineering."

There are also economic issues. Can a substrate be produced that is economically attractive to industry? How will the cost of making a RABiTS wire compare with the cost of fabricating a wire using the Los Alamos IBAD process or the current BSCCO processes?

One of ORNL's industrial partners is Midwest Superconductivity of Lawrence, Kansas, the first company to license the RABiTS technology. It uses metal organic chemical vapor deposition to grow YBCO on single-crystal ceramics. "Their process is scalable," Hawsey says, "but we want to know if it will work on the nickel substrate. They wanted to work with us on this question under a cooperative research and development agreement (CRADA). If their process is scalable for making commercial wires from nickel and YBCO, that may bring costs down. They've already duplicated ORNL's results on short samples."

Midwest Superconductivity has teamed with Westinghouse Science and Technology Center, and the two partners are collaborating with ORNL. "We will work with both partners to get them in position to produce buffered textured metals in long lengths," Hawsey says. He notes that Westinghouse is a potential purchaser of wire for use in their new generation of motors, transformers, generators, and energy storage systems.

"Westinghouse will tell us what the wire will have to do to work in new applications," Hawsey says. "We will try to solve problems to make sure the wire performs as needed."

Southwire, another CRADA partner of ORNL, will work as an adviser to Midwest Superconductivity on the use of RABiTS wire in transmission cables. On April 3, 1997, ORNL signed a four-way CRADA with 3M (a Fortune 100 company), Southwire Company, and LANL to further develop the RABiTS and IBAD substrates. 3M will use its expertise in electron beam deposition, laser control, and process modeling. Southwire will apply its expertise in thermomechanical processing of metals and underground cable product definition.

"We will continue to do research to develop a more economical process," Hawsey says. "One way to save money is to avoid using expensive laser deposition systems because they require high-power lasers and a vacuum, which are costly to produce and maintain. We are looking at solution-based techniques like sol-gel processes. We have experience in ceramic sol gel processes that we have patented. A number of people have demonstrated that sol-gel processes can deposit a superconductor that grows epitaxially on single-crystal substrates such as magnesium oxide or lanthanum aluminate. We are proposing to develop a way to use sol-gel processes to deposit YBCO and buffer layers, avoiding the cost of vacuum techniques and lowering the manufacturing cost.

"I'm not ready to call a winner between ORNL or LANL but I hope one or both of these two DOE-funded processes will work for industry," Hawsey adds. "A nickel-YBCO wire could finally kick off some of these applications that have never been possible in the electric industry because of the high cost of cooling metallic superconductors such as niobium-tin and niobium-titanium. To make BSCCO work for a motor or generator, it must be cooled to 20 K by expensive helium or a helium-gas cryocooler.

"If this YBCO wire works when chilled by much cheaper liquid nitrogen, all of a sudden we're talking about cost-effective electric power applications that hadn't been possible before. Underground cables that carry twice the power as conventional cables will be available within the next five years, and superconducting transformers that can be installed inside office or apartment buildings without concerns about fire or oil leakage may be developed. Other, non-utility applications are on the horizon.

"For example, superconducting magnets in MRI machines in hospitals are cooled by liquid helium. If we can replace them with magnets that can be cooled by liquid nitrogen, then these machines' cooling systems will be simplified. One result may be lowered health care costs. In addition, high-temperature superconducting wires would enable less expensive operation of superconducting accelerator magnets and fusion magnets at DOE research laboratories."

Hawsey says that the development of the RABiTS wire has several interesting aspects. "We kept quiet for five years and published no papers. Our effort was highly multidisciplinary. The development required staff from three ORNL divisions and funding from two DOE sources—the Office of Energy Efficiency and Renewable Energy and the Office of Energy Research."

The DOE laboratories should be "big players" in superconducting research, he says. "The fact that DOE laboratories have gone this far is testimony to the value of our partnerships with industry."

In the quest to pave the way for the efficient flow of electrons, ORNL researchers have taken a long, tortuous route that has proved also to be an exciting intellectual journey. ornl

Chemical and Analytical Sciences	David Beach, M. Paranthaman, Shara Shoup
Metals and Ceramics	Amit Goyal, Ed Hatfield, Don Kroeger, Dominic Lee, Fred List, Patrick Martin, Vinod Sikka, Eliot Specht
Solid State	John Budai, David Christen, Ron Feenstra, Qing He, Charlie Klabunde, David Norton, Bernd Saffian, Brian Sales
Central Management Offices	Bob Hawsey

List of contributors by ORNL division to the development of the superconducting wire.

Unlocking Electronic Gridlock: ORNL's Search for the Winning Combination

By Carolyn Krause

John Budai sets up an X-ray diffractometer. He used this instrument to analyze the structure of substrates and thin films for superconductors. He first demonstrated that rolled pieces of silver could provide sufficient texture to increase the superconductivity of an overlying film of yttrium-barium-copper oxide (YBCO) and proposed that this approach

high TEMPERATURE

In 1996 the spotlight on high-temperature superconductivity applications suddenly shifted. It had shone on AT&T Bell Laboratories, DOE's Los Alamos National Laboratory, and research groups in Japan. Its new target was ORNL. The reason: ORNL researchers had found a combination of materials and methods that attracted the attention of the electrical industry and the scientific world. Here's the story.

YBCO's Silver Lining

In 1990 Rosa Young, a researcher with Energy Conversion Devices, Inc., visited ORNL's Solid State Division (SSD), where she once had worked. She met with Jim Roberto, SSD director, and explained to him that she had been growing yttrium-barium-copper oxide (YBCO) on silver foils using pulsed laser ablation. She brought samples with her because she needed measurements of the amount of current that the YBCO superconducting material can carry—that is, the critical current density. Roberto asked her if she had the capability to study the sample structures to determine which structures give the highest critical current density. When she said no, Roberto suggested that she talk to SSD's John Budai about doing X-ray diffraction studies on her coated silver foils.

Young took her samples to Dave Christen (also in SSD) for measurements of critical current

We found that the critical current densities of Rosa's samples were better than those of YBCO on a polycrystalline substrate.

Dave Christen measures the amount of electrical current that can be carried by a YBCO film deposited on a buffered metallic template, or substrate. ***Photograph by Tom Cerniglio.***

density. Christen placed the samples in a magnetic field cryostat containing a conventional superconducting magnet and a digital voltmeter. With this apparatus, Christen could chill the sample to 77 K, apply a strong magnetic field to it, and measure the voltage of a direct current passed through the sample. "We found that the critical current densities of Rosa's samples were better than those of YBCO on a polycrystalline substrate (the underlying template in which the various crystalline grains point in many different directions) but worse than those of YBCO on a single-crystal substrate."

Budai then analyzed her samples using X-ray diffraction in which X rays are directed at and scattered by the electron clouds of atoms in a crystal; the scattered X rays are captured as a pattern that yields information about the structure of the crystal. A native of Burlington, Vermont, Budai came to ORNL in 1984 as a Eugene P. Wigner Fellow after earning his Ph.D. degree in physics from Cornell University and working for two years at Bell Labs at Murray Hills, New Jersey. Budai was surprised to find that the YBCO film showed signs of texturing—that is, many crystalline grains mimicked the orientations of the grains in the textured metal, or substrate. He realized that textured growth of YBCO was possible on a rolled piece of metal, such as foils of stockroom silver used by Young. Further investigation in November 1990 showed that YBCO grows epitaxially on single-crystal silver with a much higher degree of alignment than on stockroom silver; this was the first direct proof of epitaxial alignment of YBCO on a metal substrate—the YBCO grains mimicked the alignment of atoms in the silver crystal. (Although YBCO had been found to be epitaxial on many different crystallographic planes of silver, only a certain single plane would result in the desired single orientation of YBCO grains.) It was

also shown in February 1991 that a well-aligned YBCO film could be grown on an epitaxial buffer layer of platinum, the first proof that textured growth of YBCO films is possible on metals other than silver.

As a result of these observations, Budai proposed in late 1990 that rolling may cause enough alignment in silver or other metals to result in textured growth of the film and enhance its superconducting properties. Such alignment in rolled metal, which is often considered undesirable, is called biaxial texture. Thus began the development of a new solution to an alignment problem that had thwarted commercial applications of YBCO for several years.

In 1988, Duane Dimos of IBM determined that two crystalline grains of YBCO must be aligned at an angle of less than 10 degrees to achieve high critical current density in overlying superconducting ceramics. The 1990 ORNL critical current measurements and results from subsequent X-ray diffraction and electron microscope studies would confirm that if two crystalline grains are at a high angle at their boundary, electrons won't be able to hop efficiently from one grain to the other, and current will be disrupted. A high population of small-angle grain boundaries was essential for high current densities in YBCO.

Consider crystalline grains to be tiny cross-shaped tubes, tube walls to be grain boundaries, and electrical current to be BBs. If one tube is precisely lined up in front of the other tube, BBs can be shot through both tubes to the next tube. If the second tube is turned slightly at an angle, BBs could still get through, although they might bounce around inside the tube. But if the second tube is turned at a high angle (greater than 10°, lower than 90°), the BBs will crash into the tube wall (or miss the tube completely) rather than travel from tube to tube. Thus, just as more-or-less lined-up tubes are required for BBs to go a long way, small-angle boundaries are essential to efficient electron flow.

Research Team on a Roll

Amit Goyal of ORNL's Metals and Ceramics (M&C) Division then began an effort to roll-texture silver. Goyal, a native of northern India, earned his Ph.D. degree in materials science and engineering from the University of Rochester before coming to ORNL in 1990 as a postdoctoral researcher. Goyal, coworker Fred List, and their group leader Don Kroeger liked the idea of using silver as a substrate because it is chemically compatible with YBCO and it is lower in cost than some of the alternatives. However, their experience in melt processing YBCO was marred by the fact that it has a higher melting point than silver. Melt processing, which involves heating a material above its melting point and cooling it under controlled conditions, was perceived at the time to be a promising technique for making conductors. So they thought that alloys of silver-palladium, which have higher melting points than silver, could be used for melt processing. Goyal, who had extensive experience with melt processing YBCO-silver composites, experimented with various substrates and determined that silver-palladium alloys containing 10% palladium could be successfully used for melt processing YBCO. On completion of melt processing, the film contained many large crystals of YBCO several millimeters in size; however, they were all unaligned. The researchers were interested in Budai's observations of epitaxial YBCO on silver because they suggested a possible route to aligning YBCO films if the silver-palladium substrate could be textured. Unfortunately, no evidence of epitaxial growth of YBCO on silver-palladium substrates was ever observed.

Despite the promise held by Budai's initial idea, enthusiasm for this approach remained low at ORNL, as well as at most companies working on superconducting wires. Many researchers did not think it possible to build a high-performance wire from a thin film of YBCO. In fact, ORNL was only able to obtain modest current densities of YBCO on the silver foils. Thin-film–deposited conductors were not believed practical because the best films could be grown on only inflexible, short substrates made from ceramics such as magnesium oxide and strontium titanate. M&C Division researchers, however, were enthusiastic about the progress made in the fabrication of polycrystalline bismuth-based, powder-in-tube tapes and bismuth- and thallium-based thick films respectively. These superconducting tapes are formed by flattening silver tubes packed with powders made of bismuth (or thallium), strontium, calcium, and copper oxides (BSCCO). It was commonly observed by researchers worldwide that long lengths of BSCCO tapes could be made and that each tape carries reasonably high currents, although much smaller than those epitaxial thin films carry. These tapes had commercially useful properties, especially in high-background magnetic fields, but only when chilled by gaseous helium, which is much more expensive than liquid nitrogen used for devices formed from high-temperature YBCO films. The thallium and bismuth-based wires had no biaxial texture, so they were expected to contain numerous high-angle grain boundaries. The question was, were the grain boundaries in these materials different from those in YBCO?

Goyal, Specht, and Kroeger studied BSCCO and thallium-based superconductors to determine how they worked. Using a technique called electron backscatter diffraction and a theory called percolation, they observed two things: a wide

Many researchers did not think it possible to build a high-performance wire from a thin film of YBCO.

distribution of grain boundaries (usually detrimental to good current flow) and percolative paths (for improved current flow) that had formed from small-angle grain boundaries. It was just fortunate that the particular processing methods used to make bismuth- and thallium-based materials produced a high population of small-angle boundaries. This discovery was extremely important because it suggested that higher critical current densities can be obtained by increasing the numbers of small-angle grain boundaries. Of course, the next question was, how can the population of small-angle grain boundaries be increased? Goyal determined how degrees of biaxial texture affect the population of small-angle grain boundaries in these tetragonal materials. He then found that an efficient way to achieve the desired high population of small-angle grain boundaries was to produce some biaxial texture in the conductor. However, the processing methods used to make the bismuth- and thallium-based materials were not suitable for producing biaxial texture.

Yet the idea of a YBCO "deposited conductor" remained alive at ORNL. In the fall of 1992, ORNL co-workers Fred List and David Norton proposed the following "future work" for the Laboratory at a DOE Peer Review meeting: "growth of in-plane textured YBCO films on textured metallic substrates (with) epitaxial growth of buffer layers (if necessary) and YBCO." That these buffer layers are a key to success would soon become apparent as a result of laboratory experiments.

In early 1993, enthusiam at ORNL for a "coated conductor" approach was increased when Goyal learned from a scientific conference that thin films could be used as conductors and reported that meter-long tapes had been made in Japan. This new information inspired him to continue his work on texturing silver because it appeared possible to deposit YBCO films using a thin-film process in long lengths, as opposed to a process like melt processing. The big prize lay in making a biaxially textured conductor out of YBCO because it has the best intrinsic superconducting properties at liquid nitrogen temperatures, permitting a range of applications. So Goyal began experiments to produce a sharp, single-orientation texture in silver but found it difficult. Moreover, additional orientations were present, resulting in many undesirable high-angle boundaries.

Goyal realized that producing a biaxial texture of less than 10 degrees in all directions was most likely in a material that had "cube" texture. However, he found it difficult to produce this texture in silver even though most face-centered cubic (FCC) materials are expected to produce a cube texture when deformed in a certain way. He thought his inability to get the desired texture was due to either small amounts of impurities in the silver or an inadequate rolling procedure. So he decided to conduct rolling experiments with other FCC metals like copper and nickel to learn more about texture development in silver.

In a typical experiment, ORNL technician Ed Hatfield inserted a copper or nickel rod between two steel rollers turning in opposite directions as they move closer together. After many passes, the rod is rolled into a thin foil and then is heated so that the material recrystallizes, producing the desired orientation. This rolling procedure aligned the copper or nickel grains at angles as low as 7 degrees.

Further experiments indicated to Goyal that such "hot rolling" would be required to texture silver. Hot-rolling experiments on silver at ORNL showed that, although cube texture could be obtained, it was difficult to control 'twinning," which results in high-angle grain boundaries. Then Goyal decided to test the highly textured nickel and copper samples that had been lying in his office for months. He thought that,

What DOE Says about ORNL's Feat

James Daley, team leader for DOE's Superconductivity Systems Program, praised ORNL's efforts in developing a superconducting wire. "This research innovation has tremendous significance for superconducting wires," said Daley. "We now have a path to the goal we've pursued since the 1986 Nobel Prize-winning discovery—a superconducting wire that can be used in motors, generators, and other energy systems while operating at liquid nitrogen temperatures." William Oosterhuis, chief, Solid State Physics and Materials Chemistry Branch in DOE's Office of Basic Energy Sciences, added, "We are extremely pleased that a combination of fundamental materials science supported by the Office of Basic Energy Sciences, and applied research supported by the Office of Energy Efficiency and Renewable Energy has resulted in the development of materials processing methods for high-temperature superconducting wires that can carry the substantial electric currents needed for practical applications."

Eliot Specht analyzes the quality of palladium-nickel substrates for making superconducting tapes using the X-ray diffractometer. He determined that the first palladium layers deposited on rolled nickel were textured like the nickel. ***Photograph by Tom Cerniglio.***

if he could deposit nonreactive noble metals like silver epitaxially on these reactive base metals using a bulk process, he may have a method of producing textured substrates. Goyal used a simple laboratory flash evaporator to deposit silver at room temperature on the textured copper. He found that the silver was epitaxial on the copper but had a slightly different grain orientation. When the silver-copper samples were heated at low temperatures, he found that the grain orientation switched to the cube texture. When the samples were heated at high temperatures, the silver diffused into the copper, forming an alloy without destroying the cube texture. From these experiments, Goyal produced a description of ways to make aligned, buffered substrates, a description that would become a draft of the first ORNL U.S. patent application for the technology. First was a method to obtain biaxially textured laminated surfaces suitable for growth of YBCO by epitaxial deposition of buffer layers on biaxially textured base metals. Second was a method to obtain biaxially textured alloys by diffusing the deposited material into the substrate without destroying the texture. The third was to realize epitaxial layers of the desired orientation by depositing a material onto the surface of a textured base metal and heating it to induce the desired texture. Goyal also proposed that base metals such as copper and nickel might be preferable to silver because of their lower cost and higher strength.

A major problem in using nickel and copper as substrates is that they react easily with oxygen when heated to higher temperatures, forming oxides that destroy the desired texture. Because nickel is more resistant to oxidation than is copper, the researchers eventually abandoned experiments on copper and silver and focused primarily on nickel and silver as the starting template. To minimize oxidation, they decided to use a film deposition technique rather than a bulk processing technique like melt processing to coat the substrate with YBCO.

Oxides—Good and Bad

In 1993, SSD's Dave Norton, working with Budai, began investigating the deposition of YBCO and other oxides on single-crystal silver foils using pulsed-laser deposition (PLD). Norton had been using PLD for superconductor research since 1989 when he came to ORNL as a Wigner Fellow, after obtaining his Ph.D. degree in electrical engineering

An effort was begun at ORNL to deposit palladium on rolled nickel … to prevent formation of texture-destroying nickel oxide.

from Louisiana State University. In PLD, a pulsed laser beam is focused on a target, causing the material to heat rapidly and vaporize, forming an ejecting plasma or plume of ions, atoms, and molecules. The vaporized material then deposits on an adjacent heated substrate, where it forms a crystalline film.

The growth of YBCO on silver presented a challenge. YBCO must be grown on the substrate at 750°C, a temperature at which silver evaporates. When cooled, the substrate and film don't shrink at the same rate. This difference in thermal contraction can lead to cracking of the film.

A rolled nickel substrate for YBCO also has limitations. Nickel atoms have an irritating tendency to swap places with copper atoms in YBCO, ruining the superconductor. A buffer layer was needed to serve as a chemical barrier to the diffusion of nickel atoms to YBCO. Such a layer should also be able to transfer nickel's crystallographic alignment to the YBCO film.

In the fall of 1994, Goyal, program manager Bob Hawsey, and Mariappan Paranthaman, a materials chemist in ORNL's Chemical and Analytical Sciences Division, learned at the Applied Superconductivity Conference in Boston that Russian researchers had epitaxially grown YBCO on layers of magnesium oxide, palladium, and single-crystal nickel on rock salt. They were struck by the fact that the Russians had deposited palladium on single-crystal nickel and that the palladium had helped transfer the alignment to YBCO. An effort was begun at ORNL to deposit palladium on rolled nickel. It was believed that coating nickel with a nonreactive noble metal like palladium or platinum would prevent formation of texture-destroying nickel oxide.

At this time, several vapor deposition processes using vacuum chambers were being used at ORNL for this project, including PLD, electron-beam evaporation (e-beam), and a technique called sputtering. At ORNL, important work in sputtering was being done by Qing He, a University of Tennessee (UT) graduate student in Dave Christen's group.

In the fall of 1994, Qing He began sputter-depositing palladium on roll-textured nickel, based upon information in the Russian work that had used evaporative deposition. After he optimized the sputtering process, He soon was able to deposit epitaxially aligned palladium films on the textured nickel supplied by Goyal, as analyzed by Budai and Eliot Specht, an X-ray diffraction expert in the M&C Division. Shortly thereafter, Qing He also was depositing biaxially textured silver films on the palladium-coated nickel substrates. Paranthaman later found a way to use e-beam evaporation to make palladium-nickel samples. These accomplishments caused great excitement, because they pointed to a route for the deposition of chemically compatible, epitaxial buffer layers on textured nickel substrates. Norton pursued the direct deposition of YBCO and various oxide buffer layers on silver-coated nickel substrates in early 1995, but he encountered the same problems experienced with YBCO on crystalline silver.

While holding a textured nickel tape, Amit Goyal (right) watches technician Ed Hatfield insert a nickel rod in an ORNL rolling machine to make another roll-textured tape using a rolling procedure developed by Goyal. Goyal originally performed studies on texturing silver and silver-palladium alloys for use in superconductors. He suggested that the best approach to making a superconducting wire would be to use base metals rather than silver or silver-based alloys for epitaxial deposition of buffer layers. *Photograph by Tom Cerniglio.*

During this time other important factors were recognized from earlier work done in 1993 and 1994. Qing He, who had been depositing oxides on polycrystalline nickel alloys, discovered the importance of surface smoothness in obtaining a single out-of-plane orientation (although no in-plane orientation was ever achieved on these polycrystalline metals). He had found that polished superalloy surfaces yield a much improved buffer layer alignment. Around the same time, Goyal and Paranthaman had observed improved alignment of the thallium-based superconductor T11223 deposited on polished random silver surfaces. Christen and He then polished one half of a rolled nickel substrate and followed its progress through all subsequent processing. In characterizing the structure, Specht found that the palladium buffer layer was much better aligned out-of-plane on the polished half.

Clearly, obtaining a smooth, polished surface was essential to getting good thin films. Mechanical and chemical polishing of the nickel provided one way to achieve this goal. However, Goyal thought these methods would be inefficient for polishing kilometer-long conductors. He then tried to get a good surface on nickel by having the rolls polished before rolling the metal. Because very large deformations of the metal are caused by rolling, it was deemed possible that the surface features of the rolls could be replicated on the nickel. After several experiments, Goyal was successful in obtaining a highly smooth surface in rolled nickel, as smooth as that obtained by mechanical and chemical polishing.

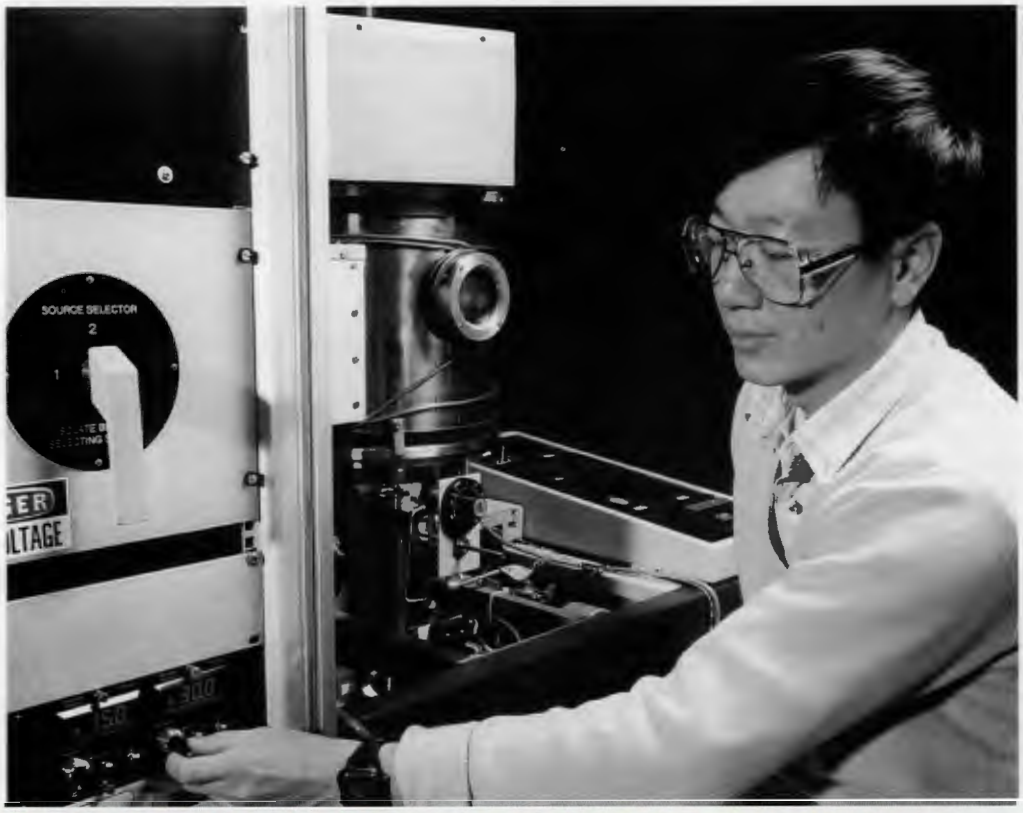
Paranthaman later found a way to use e-beam evaporation to make palladium-nickel samples. Norton pursued the direct deposition of YBCO on silver.

Using this pulsed laser deposition system, Dave Norton and Chan Park deposit buffer layers of cerium oxide and yttria-stabilized zirconia and the superconductor YBCO on a rolled nickel substrate for making a high-temperature superconducting tape. ***Photograph by Tom Cerniglio.***

Quite by chance, He and Christen found that palladium could be deposited epitaxially on nickel even at room temperature.

These meter-long, well-textured, 125-micrometer-thick nickel tapes are smoother, thinner, and shinier than aluminum foil; in each one you can see your reflection.

More detective work lay ahead for the ORNL team. By May 1995, Christen had acquired a cerium oxide sputtering target and began depositing cerium oxide as a YBCO-compatible buffer layer on palladium-nickel substrates. Although epitaxial cerium oxide could be obtained, the buffer layers had poor structure—they were laced with many cracks, holes, and blisters. The X-ray measurements of Budai and Specht also showed that, during the high-temperature deposition of cerium oxide, atoms in the palladium layer were diffusing into and mixing freely with atoms of the nickel substrate. Electron microscopy observations of the samples by Goyal and by postdoctoral researcher Dominic Lee revealed a rough, coarse, cracked substrate surface.



Qing He, a University of Tenneessee graduate student who has been working in the Solid State Division, used sputtering to show that palladium could be deposited on textured nickel and that cerium oxide could be deposited on palladium-nickel at room temperature. ***Photograph by Tom Cerniglio.***

In early 1995, Christen and He conducted high-temperature, high-vacuum annealing studies of as-rolled nickel. They found evidence of gas evolution at the high temperatures at which the buffer layers were being deposited. Better coverage and smoother, blister-free buffer layers resulted from depositions on nickel that had been heat treated in high vacuum at high temperatures. But this approach did not solve the problems of palladium-nickel interdiffusion at the high deposition temperatures. Quite by chance, He and Christen found that palladium could be deposited epitaxially on nickel even at temperatures as low as room temperature, using ideas they had gathered from earlier work of depositing the oxide yttria-stabilized zirconia (YSZ) on polycrystalline superalloys. Even though early attempts had failed, He and Christen realized that it might also be possible to deposit cerium oxide at low temperature, although published work of others had succeeded only at high temperatures. The process worked. Later, detailed studies showed that the optimal deposition temperature was about 300°C, which was adequate to solve the palladium-nickel interdiffusion problems.

Breaking the Silence

In early 1995, the ORNL team thought they had come up with a layered superconductor that could give a respectably high critical current density. Measurements by Charlie Klabunde in Christen's group showed that a layered structure consisting of YBCO, cerium oxide, silver, and palladium on the textured nickel had a critical current density of 80,000 amperes per square centimeter.

At a workshop on thallium-based superconductors in 1995 in Breckenridge, Colorado, Goyal, Hawsey, Kroeger, and Paranthaman

felt frustrated. They knew that Hitachi researchers would be announcing their process for roll-texturing silver for use in a thallium-based superconductor. The ORNL researchers felt the "Oak Ridge" process, which also produced biaxially textured silver on which YBCO grows epitaxially, was very promising and should be mentioned at the meeting. But they wanted to give it a distinctive name with a memorable acronym. Because it was the Easter season, Goyal thought of bunnies and came up with the RABiTS acronym for rolling-assisted, biaxially-textured, substrates. The RABiTS process for making textured silver was announced as an important aside during Goyal's invited paper on thallium-based superconductors. A week later, Goyal mentioned the process during a presentation of another paper on grain boundary effects in superconductors at the Materials Research Society (MRS) meeting in San Francisco. The April 29, 1995, issue of *Science News* reported on ORNL's development of a process of "depositing the superconductor onto a carefully chosen substrate so that the crystal grains fall into alignment." (A patent on RABiTS has been applied for in the United States and certain foreign countries.)

Persistent difficulties in growing oxide buffer layers and YBCO films on silver-coated textured nickel encouraged ORNL researchers to eliminate this noble metal from the structure. Unfortunately, Norton and UT researcher Bernd Saffian discovered a new problem when depositing a film of YBCO on a buffer layer of cerium oxide on a palladium-nickel substrate. The YBCO, although seemingly well aligned, had cracks. The source of these flaws turned out to be cracks in the underlying cerium oxide. The cracking could make cerium oxide less effective in preventing the substrate's nickel atoms from trading places with copper atoms in the YBCO film, as well as introducing electrical discontinuity in the superconductor.

Norton proposed depositing YSZ on the cerium oxide because YSZ had been used successfully with other substrates, such as sapphire and silicon, for the semiconductor industry. He found that YSZ is a crack healer. It either grows across cracks arising in cerium oxide or it is structurally stronger and doesn't crack even if cerium oxide does.

Shortly after Christmas 1995, ORNL researchers had solved the seemingly intractable problems of thermal contraction, volatility, and oxidation in coated superconductors. A workable buffer layer architecture seemed at hand.

Keeping Industry in Mind

From January through March 1996, the ORNL team made superconducting tapes of YBCO on YSZ on cerium oxide on palladium-nickel. Critical current measurements showed that the team's best samples achieved 300,000 amperes per square centimeter.

Because it uses conventional rolling, the RABiTS process was thought to be of great interest to industry. Since ORNL's critical current was considered respectably high, it was decided to announce the details of the RABiTS process at the April 10, 1996, annual meeting of the MRS—and in a news release.

In the meantime, Norton, Saffian, and coworkers were looking for a way to simplify the buffer layer architecture. They wanted to minimize layers to reduce manufacturing costs. They knew that palladium could be eliminated if a way could be found to prevent nickel oxide from forming on the rolled nickel substrate. The key was to sweep out the oxygen in air that leaks into the chamber and reacts with the nickel substrate before it is coated with cerium oxide. Several ORNL researchers independently suggested introducing hydrogen gas into the chamber to reduce nickel oxide. The idea worked well the first time.

After the April 10 announcement, the ORNL team began making palladium-free superconducting tapes. Measurements of short nickel tapes on which the buffer layers and YBCO have been deposited showed that the critical current density of these tapes had doubled—from 300,000 amperes per square centimeter to 710,000 amperes per square centimeter. So in late April, the current-doubling feat was revealed in follow-up news bulletins. In June 1996, ORNL applied for a patent on the simpler buffer layer architecture for RABiTS substrates. Recently, the researchers raised the critical current density of RABiTS tapes to 900,000 amperes per square centimeter.

Work on deposition of oxide buffer layers continues at ORNL. Research is focused on reducing the number of buffer layers between YBCO and the substrate to just one. Using sputtering, Fred List prepared samples of YSZ on cerium oxide (that was grown by Paranthaman using e-beam evaporation) in which the cerium oxide has two different thicknesses in angstroms. X-ray diffraction and scanning electron microscopy analyses showed that cerium oxide cracks if it is 500Å thick but not if it's 50Å thick, suggesting that YSZ might not be needed to prevent cracking if the cerium oxide layer is very thin.

PLD is the best available technique for growth of oxide layers for research, but industry is more likely to use e-beam evaporation to make coated superconductors because it has experience with this technique and it may be more easily scalable than PLD.

ORNL researchers have optimized e-beam processes for depositing silver on palladium-nickel, cerium oxide on nickel (using cerium metal, not cerium oxide as a target, as in PLD), YSZ on cerium oxide on nickel, magnesium

Additional Reading

For more information on research on high-temperature superconductivity, consult the following Internet home pages and publications.

DOE: http:/www.eren.doe.gov/superconductivity/

ORNL: http://www.ornl.gov/HTSC/htsc.html

"High Critical Current Density Superconducting Tapes by Epitaxial Deposition of $YBa_2Cu_3O_x$ Thick Films on Biaxially Textured Metals," A. Goyal et al., *Applied Physics Letters*, 69 (12), p. 1795, 16 September 1996.

"Epitaxial $YBa_2Cu_3O_7$ on Biaxially Textured Nickel (001): An Approach to Superconducting Tapes with High Critical Current Density," D. P. Norton et al. *Science*, Volume 274, p. 755 1 November 1996.

Deposition of Biaxially-oriented Metal and Oxide Buffer-layer Films on Textured Ni Tapes: New Substrates for High-current, High-temperature Superconductors, Q. He et al, *Physica C*, vol. 275, p.155, 10 February 1997.

"Growth of Biaxially Textured Buffer Layers on Rolled Ni Substrates by Electron Beam Evaporation," M. Paranthaman et al., *Physica C*, Vol. 275, 1997, p. 266, 20 February 1997.

Mariappan Paranthaman uses e-beam evaporation to make a RABiTS substrate 7 centimeters long. He shows the nickel substrates on which buffer layers are deposited by e-beam evaporation. *Photograph by Tom Cerniglio.*

oxide on silver on palladium on nickel, and magnesium oxide on silver on platinum on nickel. In September 1996, Paranthaman made a 7-centimeter long RABiTS tape using only e-beam evaporation to produce the two ultrathin buffer layers of cerium oxide and YSZ.

Like PLD, the e-beam process is done in a vacuum. Vacuum processing is expensive. What industry may prefer as an alternative for superconducting wire manufacture is a nonvacuum process in which a chemical is spread on a rolled metal that can be heated in a furnace. The spreading process could be spin casting, dip coating, or spraying. The furnace annealing would cause the organics in the solution to boil off and the rest of the material to crystallize as a film. So, to try to meet this need, Paranthaman, his group

What industry may prefer as an alternative for superconducting wire manufacture is a nonvacuum process in which a chemical is spread on a rolled metal that can be heated in a furnace.

leader David Beach, and postdoctoral researcher Shara Shoup have developed sol-gel processes for epitaxially growing buffer layers of lanthanum aluminate, gadolinium aluminate, and barium zirconate deposited on single-crystal strontium titanate. Shoup has shown that sol gel processing can grow epitaxially one buffer layer on a textured metal substrate.

ORNL researchers have also confronted the possibility that nickel's magnetic properties may be a problem. (Nickel's magnetism could distort the shape of magnetic fields needed for accelerators and medical imaging instruments.) The researchers have identified an alternative material that has less magnetism than nickel and can do as good a job as the base metal in a RABiTS substrate.

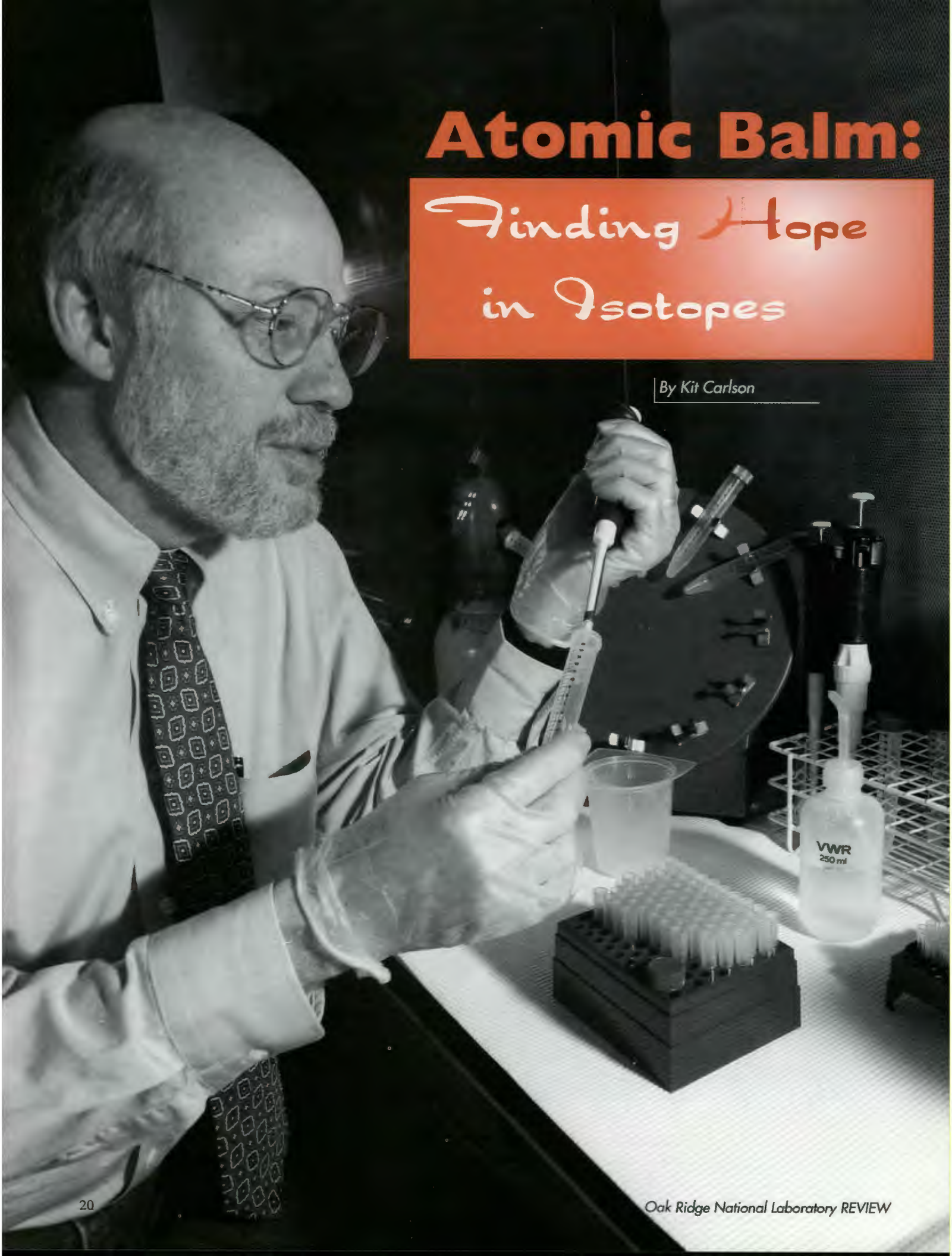
ORNL researchers have searched continuously for combinations of materials and methods to produce wires and tapes with enhanced superconductivity. During the past three years, silver and palladium played important roles in the development of the wire, but as the work progressed and the needs of industry were considered, other materials appeared more economical. A winning combination of researchers in Oak Ridge and in industry will continue the quest for the winning combination of materials and methods for making the best possible superconducting wire. ornl

Shara Shoup, a postdoctoral researcher who works with Paranthaman, uses a sol-gel process to chemically coat a substrate with a buffer layer. Chemical methods for making superconducting wire are expected to have wide industrial appeal. ***Photograph by Tom Cerniglio.***

Atomic Balm:

Finding Hope in Isotopes

By Kit Carlson



On a hospital in Kyoto, Japan, a middle-aged man lies on a hard table, a huge camera suspended over his chest. Something is not quite right with his heart—his doctor has told him that. But his symptoms are subtle, their cause uncertain so far: no clogged arteries, no decline in blood flow, no damage to his heart muscle.

What's wrong? What's wrong? he broods, as a needle pierces a vein in the crook of his arm. *What's wrong with me?*

From the needle flows a solution of fatty acids that have been "tagged" with radioactive iodine-123. His blood washes them into his heart as it flows through coronary arteries, nourishing the heart muscle with oxygen and nutrients. The heart muscle cells extract fatty acids for fuel, even the radioactive ones. All the while, the iodine-123 decays, emitting photons that the hovering gamma camera records, revealing—pinpoint by pinpoint, until a bright galaxy of photons has accumulated—the places in the heart where those fatty acids remain unmetabolized. Such places are regions of dying muscle tissue that are not often identified by the usual blood-flow markers such as thallium-201.

Something is indeed wrong—the man is in the early stages of heart disease; left untreated, eventually it could kill him. Instead, thanks to this early diagnosis, there will be treatment. Instead, there will be hope.

When atomic bombs destroyed Hiroshima and Nagasaki half a century ago, the Japanese people were linked forever to the nuclear researchers at a Manhattan Project outpost in Oak Ridge, Tennessee. Out of the secret installation in the rolling hills had come the uranium to fuel the first bomb as well as the proof that plutonium could be made in sufficient quantities to stoke the second.

Russ Knapp formulates a new pharmaceutical agent for animal testing.

But even a mushroom cloud can have a silver lining. Today, the same technology that begot the atomic bomb brings healing balm, uniting ORNL researchers with hundreds of thousands of Japanese who may be suffering from heart disease. Japan is the first country where this ORNL-developed, radioactive imaging agent called BMIPP—marketed there as Cardiodine®—has won full governmental approval for use in hospitals and clinics.

Call it irony. Call it redemption. Russ Knapp, head of ORNL's Nuclear Medicine Group, calls it "incredible." "Imagine," he says, "more than 100,000 patients have been tested with this agent. It's not just a neat idea in some lab. It's actually useful."

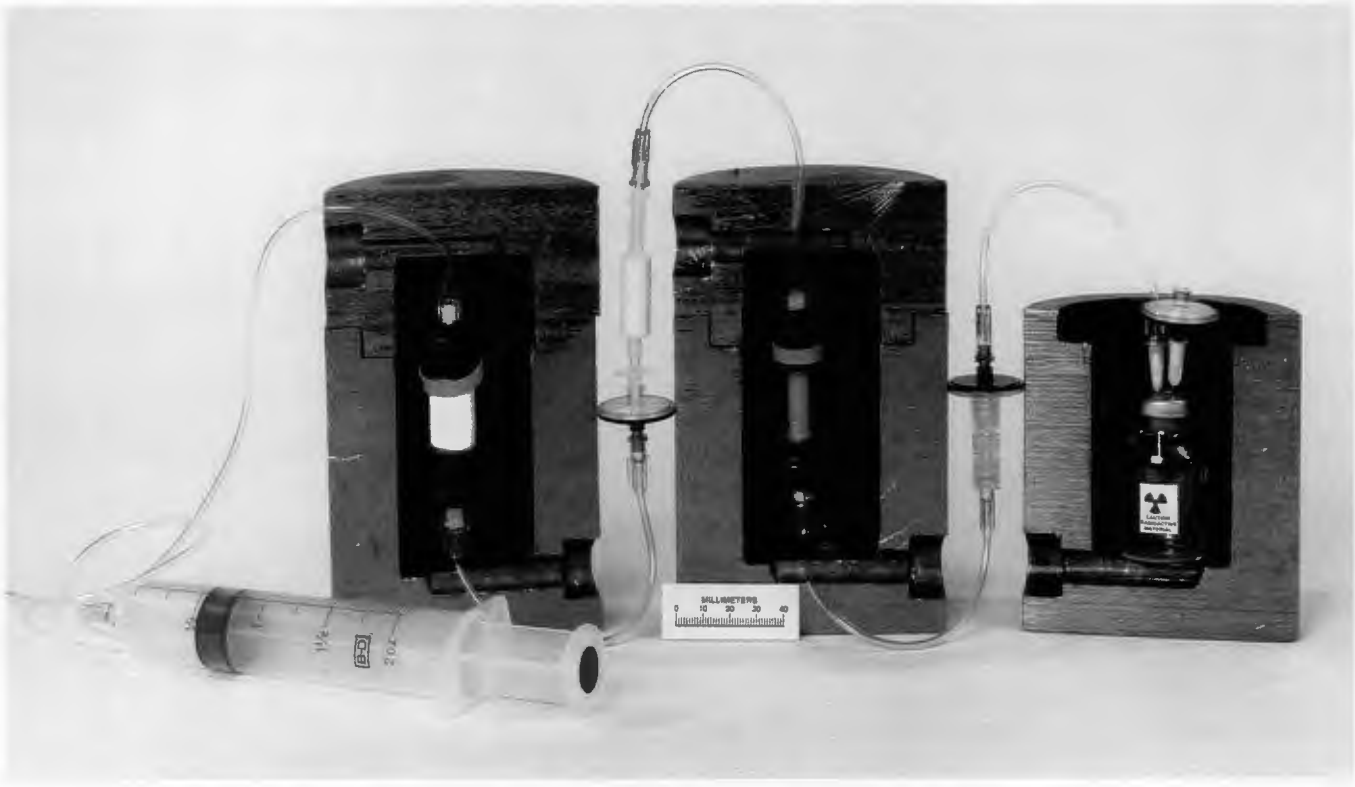
ORNL's nuclear medicine man speaks with an almost parental pride, as well he might. From its birth on Knapp's bench to its introduction into Japanese clinics, Cardiodine® was nearly 20 years in the making. In fact, in the same space of time, Knapp's own children grew from babies to young adults. He hopes to see the agent approved in Europe, and then in the United States, by the end of the decade—but those approvals will take much time and even more money.

An ORNL-developed imaging agent helps diagnose heart disease in Japanese patients.

The tortuous path from idea to actuality is a hard truth for researchers in nuclear medicine—harder, perhaps, than in any other medical specialty. After all, if you're playing with atomic fire, you don't want anyone to get burned. Radiopharmaceuticals must be tested—first in the lab, then in animals, finally in people with real diseases. Regulatory agencies such as the U.S. Food and Drug Administration (FDA) seek to ensure that these substances can be used and disposed of safely.

But the fact that Cardiodine® has left home, as it were—passed beyond Knapp's guiding influence and into clinical life—offers hope that some of his group's many other promising ideas can follow the same path.

Imagine an isotope that could relieve the pain and swelling of rheumatoid arthritis or the agony of end-stage cancer … not the $1800-per-dose version currently used, but one generated right in the hospital for only $40 a dose. Imagine zooming in on a cancer untreatable by conventional radiation or chemotherapy, binding a tiny, well-aimed speck of isotope to the tumor, then burning it away, a millimeter at a time. Imagine lighting up the brain with a radioisotope that binds to receptors in nerve and brain cells—the group of receptors most likely to shut down in Alzheimer's disease—to confirm or rule out that diagnosis with certainty. Imagine.



Prototype of ORNL's tungsten-188/rhenium-188 generator. *Photograph by Curtis Boles.*

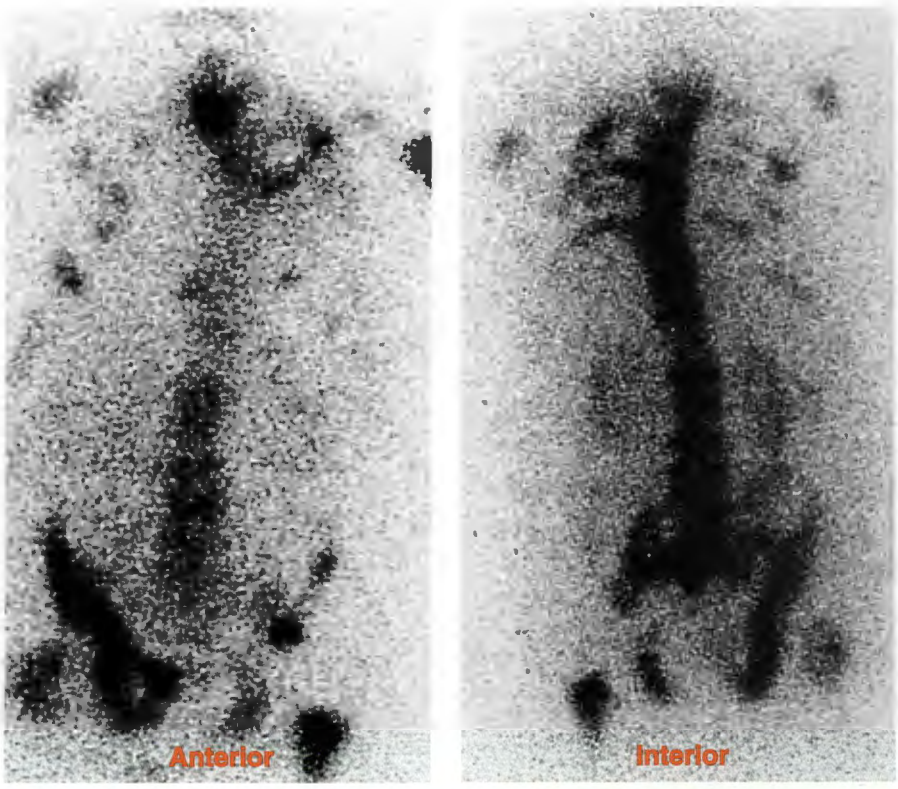
The Importance of Being Collaborative

Imagination is Russ Knapp's business—and so is collaboration. By training he's a biochemist, a basic scientist, a researcher dedicated merely to extending the boundaries of human knowledge. But in practice, the boundaries he pushes against are those that mark the limits of human health, hope, endurance, and courage.

Such boundaries can be found in every branch of medicine—cardiology, oncology, neuropsychiatry, gastroenterology. Working with Knapp at their edges is a small but varied team of scientists—organic chemists, a microbiologist, radiochemists, and always some visiting researchers, who come from every corner of the world to his lab ("There are very few places to get formal training in this kind of research," he explains). In turn, the Nuclear Medicine Group reaches back out to the wide world for collaborators. Researchers are testing ORNL's new nuclear medicine technologies in clinics not only in the United States but also in hospitals in Australia, China, Germany, Italy, Japan, and Uruguay.

"One of my major responsibilities is to establish and manage collaborative programs," Knapp says. "I spend almost one-quarter of my time planning and coordinating joint research projects and writing joint grant applications and papers. This work guides decisions on future nuclear medicine research projects."

However, if the world is Knapp's proving ground, it is not exactly his oyster: in an era of shrinking federal budgets and dwindling research dollars, advancing the frontiers of nuclear medicine has become more difficult. Where ORNL once had four research reactors plus an accelerator to produce radioisotopes, the High Flux Isotope Reactor (HFIR) is now the only source remaining. And a local clinical partner, Oak Ridge Associated Universities, lost its nuclear-medicine funding a decade ago.



Gamma camera images show uptake of a rhenium agent in skeletal tissue for the treatment of cancer-induced bone pain caused by metastases in a 66-year-old patient suffering from prostate cancer. The rhenium agent (Re-188-HEDP) was prepared using Re-188 obtained from ORNL's tungsten-188/rhenium-188 generator. The agent is being tested in patients in Germany. ***Courtesy of H. Palmedo, M.D., S. Guhlke, and H.-J. Biersack, M.D., Clinic for Nuclear Medicine, University of Bonn, Germany.***

Tough times and a tough planning climate have served both to focus and to expand the research of the Nuclear Medicine Group, which is primarily supported by DOE's Office of Health and Environmental Research. "When you're trying to decide what research to do, a key thing is what facilities you have," he notes. "We have a reactor, so we do a lot with reactor-produced isotopes. But we've found that it may actually be an advantage *not* to have a clinical component—if we had clinical colleagues here, they would most probably focus on one area, and it would be hard to be as broad as we are. The fact that we can interact with medical specialists in many areas gives us much more flexibility." In short, where resources are limited, Knapp substitutes resourcefulness. So when Knapp begins to transform ideas and imaginings into doctors' tools, he has to be practical right from the start.

Rhenium-188: An Answer to Cancer

Pain. Phenomenal, excruciating, mind-bending pain. Pain when you

move. Pain when you are touched. Pain when you just lie there, praying to die.

Pain is what you get when you're dying of cancer, including breast or prostate cancer. Quick to metastasize, the primary tumors release cells that often home in on the skeleton and begin boring into bone. These metastases squeeze the nerves and send out chemical by-products that nettle the body's pain receptors. Inflammation brings more pressure. Pressure brings more pain.

At this stage, forget cures. It's all the doctors and nurses can do just to ease the torment.

"These people are often near the terminal stage of the disease, and until the end, their quality of life can be horrible," Knapp says. "They're in great pain, and they can also suffer terrible side effects from the steroids and narcotics they're given for relief."

In Europe, a rhenium radioisotope—rhenium-186—is used to help alleviate bone pain. "But you have to make every dose in a reactor," Knapp notes. "Because it has only a 90-hour half-life, you have to ship it overnight to the hospitals over and over again. These requirements make it very expensive—about $1800 for a single patient dose. Treatment with strontium-89, an FDA-approved agent made from an enrichment product from ORNL calutrons, costs about the same."

Knapp and his colleagues propose a slightly different isotope—rhenium-188, the same isotope that shows such promise for treating primary tumors. As a pain reliever, it could prove just

As a pain reliever for people with cancer-induced bone pain, rhenium-188 is effective and less expensive than other treatments.

Arnold Beets (left) measures the alpha-particle radioactivity emitted by a radioisotope sample held by Saed Mirzadeh. ***Photograph by Tom Cerniglio.***

Rhenium-188 could also relieve inflammation and pain in joints from rheumatoid arthritis. And it costs much less than other therapeutic radioisotopes.

as effective as rhenium-186 and at a cost of only $40 a dose, based on daily use of a generator for several months.

The energetic electrons emitted as rhenium decays don't just burn through tumors; they also reduce inflammation caused by the tiny metastases on the bones. Unlike narcotics, which merely deaden the nerves that feel the pain, rhenium relieves the inflammation that causes the pain.

Knapp and his team have devised a small rhenium generator—about the size of a thick paperback novel—that can produce hundreds of doses of rhenium-188 over several months, right in a hospital. It's a simple thing: a cylinder with rubber tubing at each end, shielded in a small lead box. At the top of the tube, tungsten-188—produced in the HFIR—binds tightly to aluminum oxide powder that has been saturated with acidic saline. As it decays, the tungsten turns to rhenium-188, which lets go of the powder. Wash more saline through the top, and out the bottom comes a solution of rhenium-188. It can then be chemically incorporated into a wide variety of therapeutic agents in forms such as a phosphorus compound (phosphonate) or a dimercaptosuccinic acid compound.

"And all the while, the tungsten's still decaying. You could use this for six months in a hospital—we've used one here for more than a year," Knapp says. "This is in itself a production system, so the costs are much, much less. That's one of our selling points."

"And someday," he continues, "we hope to take the technology a step further—to find ways to administer higher rhenium-188 doses that kill tumors without destroying the immune system's bone marrow."

This same isotope could also relieve inflammation and pain in joints swollen by rheumatoid arthritis. "People who can't even walk because of the pain could start walking again," Knapp predicts. "In the United States alone, there are a hundred thousand people each year who could benefit from this treatment. Their insurance companies should be able to afford it."

Fortunately, rhenium-188 has proved ideal for this sort of application, because it decays quickly and energetically, emitting beta particles that can reduce inflammation. Rhenium-188 was a choice isotope also because it costs much less than other therapeutic radioisotopes. "The price of rhenium-188 for this treatment," Knapp says, "is expected to be just a few percent the price of radioisotope treatments using rhenium-186 or strontium-89, greatly reducing health-care costs."

Others find hope in this isotope. "In 1995 I was invited by Professor L. Troncone, the head of nuclear medicine at Catholic University Hospital in Rome, to give a lecture in Rome as part of our collaboration," Knapp says. "When he had heard about this generator, he came to me and said, 'We have a great financial crisis in our country. I can't afford to pay $1800 a dose to relieve someone's pain. This isotope looks great. Can you help us?" The same need has been expressed in other countries, including Germany, Greece, and Uruguay.

Another of the Nuclear Medicine Group's promising new projects and examples of collaboration is a "magic bullet" designed to lock on to a tumor and burn it away. First came an idea from RhoMed, Inc., in Albuquerque, New Mexico: to use radioisotopes to make a nonradioactive, partially effective cancer treatment more potent. In the original treatment, a patient is injected with a chemical agent called octreotide—a small peptide, or amino acid cluster, synthesized from eight amino acids. In theory, the octreotide binds quickly to a tumor cell and turns off the growth hormones the renegade cell needs to thrive. "Unfortunately, it's only partially useful," Knapp says, "and only in certain situations."

Knapp had found a boundary and wanted to step beyond it by collaborating with RhoMed researchers. "We knew if the right radioisotope could be attached to that binding substance, we'd have a way to deliver radioactivity to that tumor." In fact, that approach had already been used to create a commercially available diagnostic tool that lets a doctor see where the tumor is, how many metastases there are, and how effective radiation or chemotherapy is proving. But researchers wanted to use radioactivity to treat, not just diagnose. And the isotope whose radioactivity they wanted to tap was rhenium-188.

In 1995, a cooperative research and development agreement was signed between ORNL and RhoMed. Researchers with varied backgrounds from both organizations were able to tackle an assortment of basic questions: What is the chemistry of the octreotide? Where can we hang an isotope? Which isotope should we use? Saed Mirzadeh, a radiochemist in the Nuclear Medicine Group, helped probe these particular questions; other team members explored similar questions in their own specialties in collaboration with RhoMed researchers, in particular with B. Rhodes, president of RhoMed, and P. O. Zamora, a cell biologist working at RhoMed on this project. Mirzadeh and Arnold Beets, also of the Nuclear Medicine Group, have worked closely with Knapp on problems related to the HFIR production and processing of the tungsten-188 parent radioisotope.

"The RhoMed researchers have been able to attach rhenium-188 to this octreotide, and they found evidence that

ORNL researchers think the agent might help diagnose Alzheimer's disease.

this Re-188-RC-160 compound binds to tumors," Knapp reports. "They've done some animal studies—implanting small-cell lung carcinoma cells into mice. When the tumors had grown, they've injected the compound and demonstrated that it shrinks the tumors."

For human patients with soft-tissue cancers—cancer of the breast, the prostate, the uterus—this patented agent could offer a new avenue of hope. It has intrigued Knapp's European collaborators, such as Dr. Hans J. Biersack in Bonn, Germany. Biersack, chief of the Clinic for Nuclear Medicine at the University of Bonn, where Knapp worked in 1985–1986 and 1991–1992, expects to begin patient studies soon with the rhenium peptide agent to treat patients suffering from inoperable metastases of breast cancer and with the rhenium-188–labeled phosphorus compound to relieve cancer-induced bone pain.

"Using this binding phenomenon looks like it might be an interesting way to deliver a therapeutic isotope," Knapp says. "It could be an alternative to traditional radiation therapy. We think it has a promising future, and that's pretty neat."

Diagnosing Alzheimer's Disease: A Challenge

To have Alzheimer's disease is to feel like someone is daubing your brain with liquid paper, or a computer virus is erasing your files one by one. Slowly, inexorably, the brain begins to shut down. The most basic memories cease to exist—how to use a spoon, how to sign your name, who your spouse is. As the higher functions fade, emotions run stronger. Agitation builds regularly, culminating in intense rages.

Huimin Luo, organic chemist and Hollaender postdoctoral fellow, synthesized a fluorine-18–labeled compound that may be useful for imaging memory loss using positron emission tomography of the brain.

Russ Knapp and Kathy Ambrose check metabolism cages for studies of the distribution and elimination of radiopharmaceuticals from rats.

At the end, comatose and incontinent, the body still endures, but the person inside has vanished.

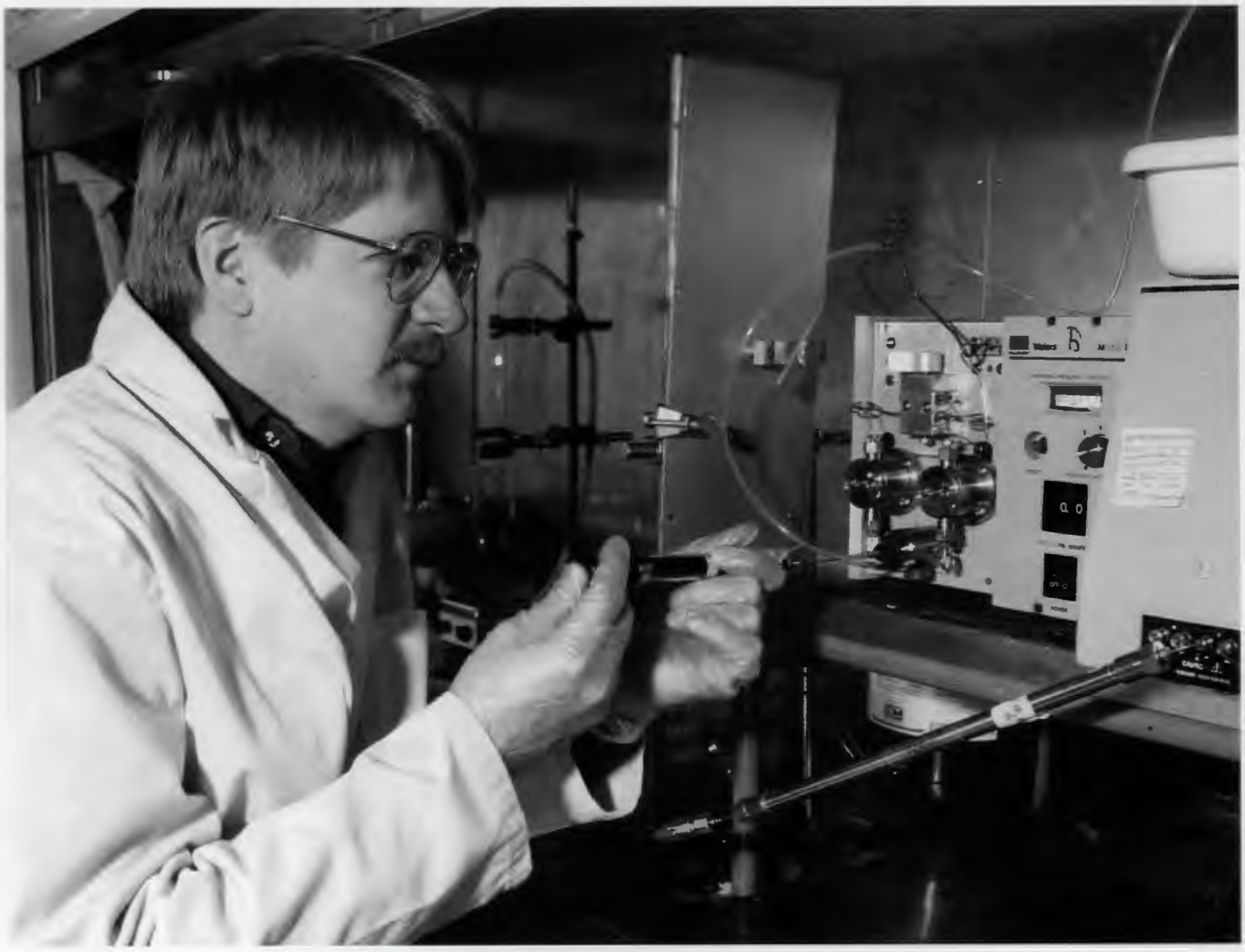
There is no cure for Alzheimer's disease. There isn't even a real diagnostic test for it; only a pathologist can truly confirm it, and only by examining the brain in an autopsy. Knapp and his team can offer no cure, but under the guidance of organic chemist Dan McPherson, they think they're onto a diagnosis. The secret is to know how the brain talks to itself—and where the lines of communication seem most vulnerable to Alzheimer's.

"When you think, when you move, when you experience pain, hunger, or lust, there are many networks of neurons firing in your brain," McPherson explains. "All the time, awake or asleep, the nerve cells in these networks have to communicate in some way. So a little chemical message is produced in this cell, and it travels over and excites the next cell. That's how the nerve impulse is propagated."

A neuron's message-sending equipment is called its neurotransmitter; incoming messages are picked up by the neuroreceptor. It's possible to synthesize a compound that will bind to active receptors; by tagging the compound with an isotope, it's fairly simple to make it visible to a gamma camera. That lets researchers see where receptors are turned on and taking messages.

In practice, of course, it's not quite that simple. Alzheimer's seems to damage one specific kind of receptors, called muscarinic-cholinergic receptors, which make up only 20% of all neuroreceptors. The challenge for McPherson and other members of Knapp's group has been to devise a molecule that binds only to those particular receptors, highlighting

Before it can be tried in humans, IQNP must pass toxicity tests.



Dan McPherson injects a sample into a high-performance liquid chromatography device, which is used to purify compounds being developed to diagnose diseases of the heart and brain.

We think it could possibly be used to monitor the progression of Alzheimer's disease and the effects of therapy.

changes just in parts of the brain affected by the disease.

"It's a real challenge, chemically," McPherson says. Then he smiles. "But we think we have a molecule that will work."

The molecule, dubbed IQNP, was tagged with radioactive iodine-123 (the same isotope used in Cardiodine®). In its first tests, it successfully imaged a normal rat brain: it set the receptor-rich areas aglow, tracing a heart-shaped halo around the cerebrum.

However, it's a long, long road from rats to people, making collaboration crucial. Dr. Joachim Kropp, an associate professor at the Technical University in Dresden and board-certified nuclear medicine physician, was once a visiting researcher with Knapp at ORNL. Kropp hopes to do the first human studies in Dresden once the preliminary work and in vitro studies are done.

But what preliminaries! First, there must be autoradiography studies, tests with normal and Alzheimer's-damaged brain tissue taken from autopsies (the samples have been frozen, so the neuroreceptors will still work). "Our collaborators in Stockholm, Sweden, put IQNP in solution, dip the pieces of tissue in there for awhile, then take them into the darkroom and put them on a piece of X-ray film," Knapp explains. "If the IQNP specifically binds in these regions, the radiation from the iodine exposes the film, producing dark images on a clear background, in the same way that visible light exposes photographic film to make a picture." Barry Zeeberg, at George Washington University Medical School, and R. E. Reba, at the University of Chicago, are collaborating on these studies.

These studies must be coordinated with more animal studies—in this case, on monkeys. Christer Halldin, a radiochemist at the Karolinska Institute in Stockholm, will pick up the task at this stage.

Finally, before it can be tried in humans, IQNP must pass toxicity tests. Two different species of rats and mice must be injected with the agent, blood and urine tests run, autopsies done, and everything formulated and written in a report acceptable to the FDA. Toxicity tests are "*very* expensive," Knapp frets. Fortunately, he has a friend—a very good friend—Jukka Hiltunen, who is managing director of a radiopharmaceutical company in Finland. If the autoradiography looks good and if the primate studies pan out, Hiltunen is expected to conduct the toxicity studies free of charge.

More recently, Huimin Luo, a Hollaender postdoctoral fellow working with Knapp and McPherson has successfully synthesized a new fluorine-18–labeled analog, called FQNP, which may be useful for the same application using positron emission tomography. The result could be tools that may not only give a diagnosis but also show how severe the disease has become and how it's progressing. If the diagnosis is not the inexorable Alzheimer's, treatment may be possible because memory loss can have a number of causes.

Knapp is characteristically hopeful about the technique's future. "I hate to say that this technique could diagnose Alzheimer's disease," he cautions. "But we're really excited about its potential. We think it could possibly be used to monitor the progression of the disease and the effects of therapy."

Meanwhile, because the same receptors affected by Alzheimer's are found in the heart's natural pacemaker, the researchers are also adapting this same tool to unlock more cardiac secrets. It may not happen in matters of romance, but when it comes to neurotransmitters, at least, the head and the heart may prove to have a lot in common.

Epilogue

The ancient Greeks used the myth of Pandora to explain the presence of pain and suffering in the world. In the story, the gods gave Pandora a box but forbade her to open it. Naturally, she could not overcome her curiosity. When she opened it—just for a peek—she unwittingly released all the miseries of the human condition contained inside. Bereft, alone, she stared at the empty box.

But then she noticed that it was not entirely empty. At the bottom remained a tiny but persistent spirit: Hope.

We are no different from the ancients. We, too, suffer the torments of sickness and death; we, too, take heart when we find hope.

Hope is a spirit that infuses Russ Knapp's research. Not just the general hope of every scientist—that all this work will advance human knowledge in some way—but a deeper, more specific longing: that all this work will relieve human suffering.

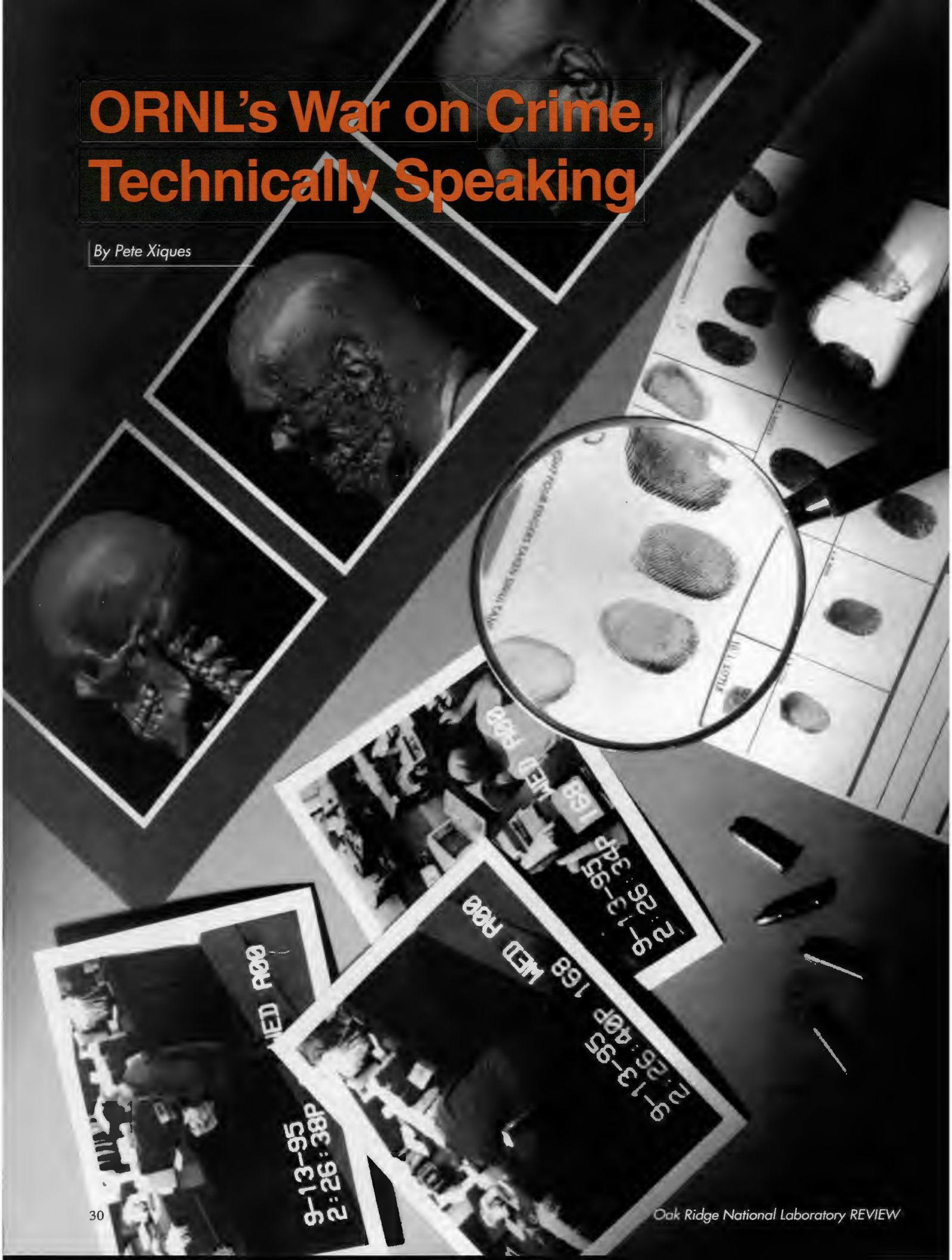
For people with Alzheimer's disease, terminal cancer, and rheumatoid arthritis, hope can seem elusive. But for some, the work of Knapp and his group will bring it within reach once more.

In Japan, tens of thousands of cardiac patients have already grasped it. Already taken it to heart.

Kit Carlson is a freelance writer who lives in Silver Spring, Maryland. ornl

ORNL's War on Crime, Technically Speaking

By Pete Xiques



ORNL's war on crime is being waged not from its ivory tower but from its CASTLE—the Center for Applied Science and Technology for Law Enforcement, which is building a strong case for crime-fighting technology. But before the program tackles a law-enforcement problem, says CASTLE director Scott McKenney, the case must meet several criteria: The problem must require the unique resources of a national laboratory or a university—CASTLE won't compete with private-sector companies. It must be solvable. And the solution must be affordable.

Some projects have yielded crucial evidence for cases that are pending in court. Others have solved cases outright. Some examples.

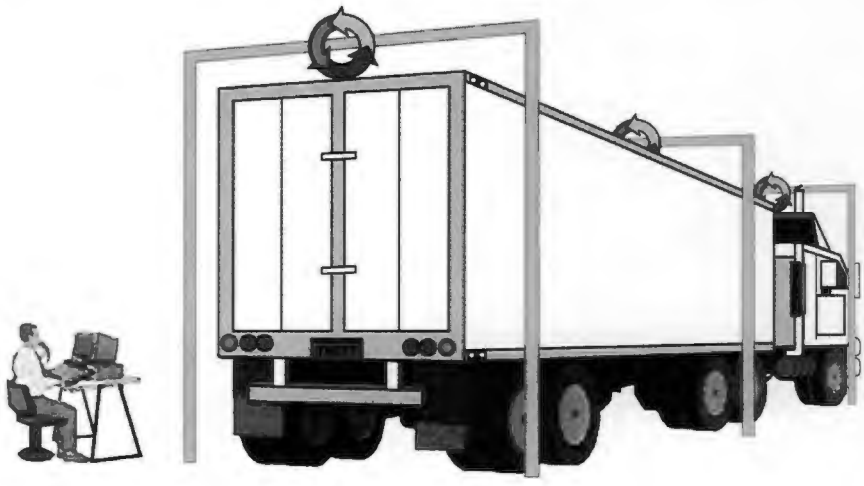
- During a high-profile murder and robbery, a tiny shard of plastic from the dial of the safe was embedded in the suspect's clothing when he tried to shoot open the lock. ORNL scientists used neutron activation analysis and other advanced techniques to link the fragment to the crime scene—without destroying the tiny piece of evidence.

- In partnership with the University of Tennessee, ORNL researchers are developing better ways to determine a victim's time of death. Using advanced analytical chemistry, scientists are seeking chemical signatures in the body that mark precisely how much time has passed since death.

- New instruments developed at ORNL may yield a high-security "portal of the future," which is designed to prevent sabotage, theft, and terrorist activity. Super-sensitive explosives detectors—based on ion-trap mass spectrometry technology developed by ORNL—determine whether samples contain explosives. Another system can detect the heartbeat of a hidden prisoner trying to escape by hiding in a laundry truck. Still another system uses ORNL's fiber-optic weigh-in-motion system that enables operators to weigh vehicles entering and leaving a screening area.

- Miniaturizing complex analytical lab equipment may revolutionize how crime scenes are investigated. ORNL is developing tools investigators can use in the field, such as a small, portable mass spectrometer that can quickly analyze unknown samples at crime scenes. The "lab on a chip" concept promises to give police the ability to analyze even minute samples in real time, with accuracy equal to or better than that of conventional laboratories. For example, ORNL scientists are developing a DNA testing chip that would let police analyze blood at the scene immediately, rather than shipping off samples and waiting weeks for results. Some 20 companies have expressed interest in licensing the new DNA technology.

"Law enforcement professionals are getting smart about what the Lab can do for them," says McKenney, "and we're getting smart about what their needs are. As we better understand one another, we can really make an impact."



If a prisoner is hiding in this truck, ORNL's heartbeat detector can determine if the escapee is present. In the future such an "enclosed space detection system" may be used to detect human presence in hostage situations or collapsed buildings.

That makes sense. You might even say it's elementary.

* * *

"And what do you think of it all, Watson?" asked Sherlock Holmes, leaning back in his chair.

"It seems to me to be a most dark and sinister business."

"Dark enough and sinister enough."

—Arthur Conan Doyle

The Case of the Disappearing Fingerprints

The murder was a detective's worst nightmare. A three-year-old girl had been abducted from her neighborhood, sexually molested, and brutally killed. Police were sure that a family acquaintance was the killer—in fact, initially the suspect had confessed, but later he recanted. Investigators were desperately seeking hard evidence to link the suspect to the dark and sinister crime.

As results came in from the forensics lab, Knoxville Police Department Specialist Art Bohanan felt frustration wash over him. The suspect's fingerprints were all over the inside of the car thought to have been used in the abduction. But there was no trace of the little girl's prints.

It was not the first time Bohanan had run up against this particular brick wall. In a similar case several years earlier, witnesses testified that they had seen the child in the suspect's car—but no prints from the missing child could be found there. What was it about children's fingerprints and cars that conspired against Bohanan?

Checking with others in the department and then with other law enforcement agencies, Bohanan found little to go on. The Federal Bureau of Investigation (FBI) could offer nothing. Scotland Yard had no answers. The Israeli police had not observed it, either. Forensic scientists had done little research on the fingerprints of children, because children were rarely crime suspects.

We think the kids' fingerprints are still there, but the current technologies used by police just don't detect them.

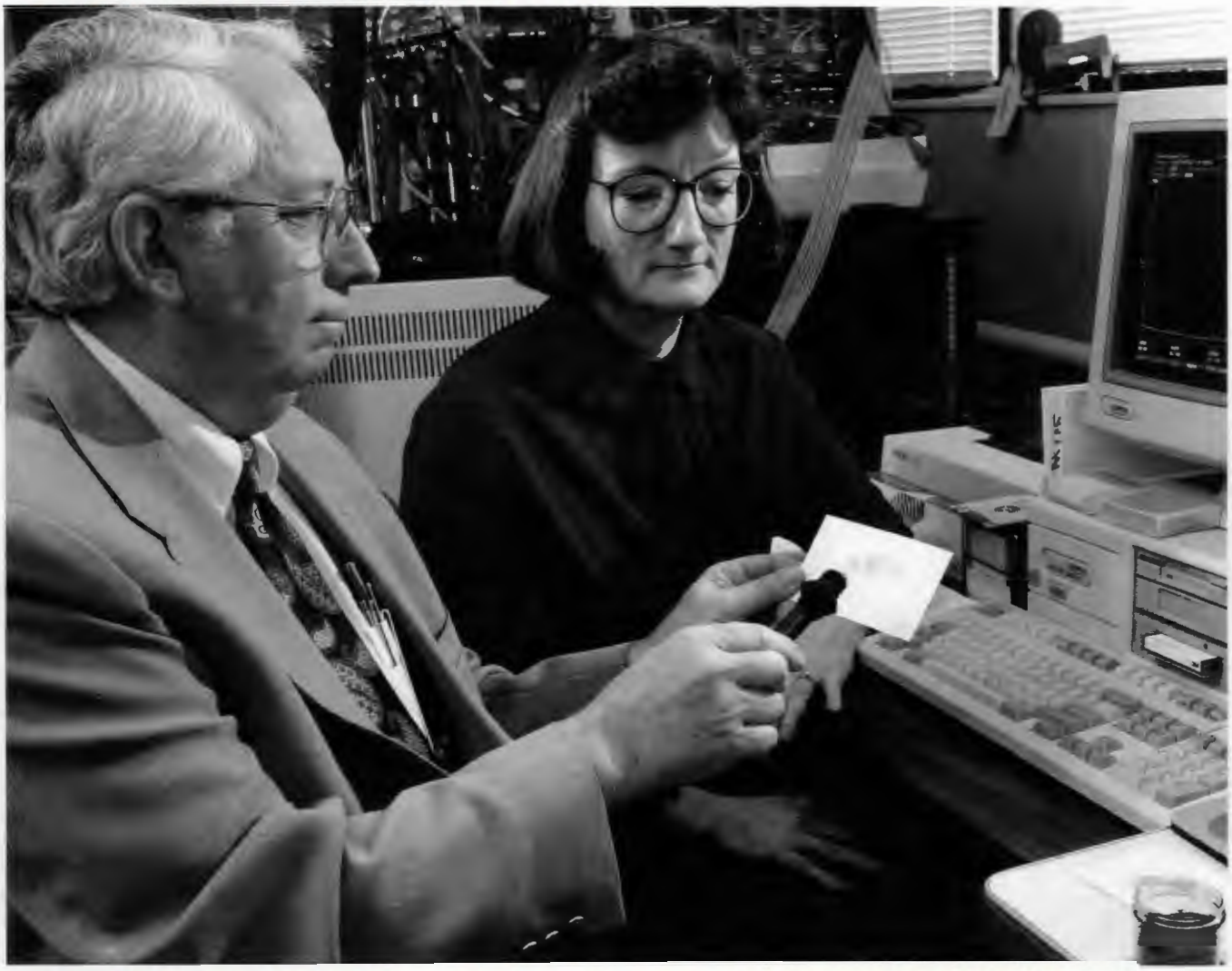
Knoxville Police Detective Art Bohanan lifts a child's fingerprints off a car as his granddaughters watch. He sought help from ORNL in explaining why childrens' fingerprints vanish faster than adults'.

Unfortunately, more and more of them seemed to be turning up as crime victims. The question, Bohanan decided, cried out for an answer.

Though not a scientist by training, Bohanan devised an experiment. He had children and adults handle two cases of Coke bottles. One case of the bottles he placed in his cool basement as the control group; the other he put in the back seat of his police car to simulate realistic field conditions. Each day for the next month, Bohanan removed a bottle from both cases and dusted them for fingerprints. He found what he had suspected all along: while the adults' prints remained, the children's prints began disappearing almost immediately; soon they were gone altogether. He repeated the experiment for an entire year, and although the children's prints lasted longer, they still vanished before those of the adults. Now that he had proof of what was happening, he turned to science—he turned to ORNL—for help understanding why.

To tackle the problem from multiple angles, ORNL Director Alvin Trivelpiece assembled a group of scientists from a variety of disciplines. As they discussed the case, Michelle Buchanan, an analytical chemist in ORNL's Chemical and Analytical Sciences Division, had a hunch. "It occurred to me that it must be a

To tackle the problem from multiple angles, ORNL Director Alvin Trivelpiece assembled a group of scientists from a variety of disciplines.



Knoxville Police Detective Art Bohanan and ORNL's Michelle Buchanan examine fingerprints. Buchanan's research suggests that children's fingerprints don't last as long as adult fingerprints because of a difference in chemical composition.

difference in the chemical composition of the prints," Buchanan recalls. "We decided to use gas chromatography–mass spectrometry—GCMS—to analyze the chemical composition of children's fingerprints."

In that instant, the investigation into the girl's murder changed dimensions. It moved out of the typical police crime lab, with limited scientific equipment, and into the national laboratory, where researchers work on the cutting edge of science.

Though beyond the reach of a typical police lab, this experiment, too, began simply enough. "We took small vials and put a couple of milliliters of rubbing alcohol from a drug store in each one," Buchanan explains. "We had a group of adults and the children shake the vials between their fingers. The alcohol extracted a small amount of the chemicals off the surface of their skin."

Buchanan and her colleague Keiji Asano now had the samples they needed for GCMS analysis. Working with the ORNL chemists was a group of undergraduate students, who participated in the project as part of the Science and Engineering Research Semester program.

Over the past few decades, gas chromatography–mass spectrometry has become the workhorse of the analytical chemist's laboratory, examining unknown compounds to extract precise information about their makeup. The students injected samples of the dissolved chemical compounds into the GCMS. After the chemicals vaporized there, they were separated on a heated capillary column by clinging to the viscous coating on the narrow column. Lighter, more volatile elements came through first; heavier elements held on longer.

By combining gas chromatography with mass spectrometry, the chemists learned which compounds were present. By hammering the molecules of each substance in the sample with electrons, a positive charge was given to each molecule. During this ionization process, most of the ions fell apart to form a number of fragment ions. The ions were then sorted in the mass analyzer, producing a spectrum that identified each compound, much like a fingerprint identifies an individual.

ORNL researchers are developing new chemical markers that make invisible prints fluoresce under hand-held lights.

When the researchers looked at the printouts, they were amazed. The data from the experiment could be laid down in two neat piles: children in one, adults in the other. The children's prints had far more of the compounds known as fatty acids. The adult prints also contained fatty acids but at much lower levels. The adult prints, however, were observed to contain larger quantities of fatty acid esters, which are less volatile than the fatty acids that are predominant in children's fingerprints. The difference in the fingerprints was like the difference between footprints of gasoline and those left by motor oil being tracked across the floor at a service station: although chemically similar, one evaporates in moments, the other hardly at all.

Now ORNL researchers could explain Bohanan's observation. In a hot car, the lighter fatty acids in children's fingerprints were volatilizing—just going away. When police dusted for prints with powder, there was nothing left for it to stick to. From the perspective of pure science, they had answered the question. But from the perspective of applied science—the kind of science that saves lives—they had raised more questions than they'd answered.

"We think the kids' fingerprints are still there, but the current technologies used by police just don't detect them," says Buchanan. Based on the results from these preliminary studies, organic chemists at ORNL are now trying to develop new chemical "markers" that police can use to make invisible prints fluoresce under special hand-held lights.

The search for an identifying compound has opened a second door. The researchers have detected a wide variety of substances in prints, including cholesterol and nicotine. They are currently investigating the potential of identifying trace components in fingerprints that can distinguish among individuals. Says Buchanan, "This raises the possibility that components in fingerprints could yield a profile of the suspect like 'female, smoker, diabetic, cocaine user.' " Soon, these tools may help police and the FBI unlock vast amounts of evidence now hidden at the scene of a crime—and help Bohanan and his colleagues bring killers to justice.

Close to the Vest

Moving at 2600 feet per second—more than twice the speed of sound, a bullet hits its target with as much energy per unit area as a 50-ton truck traveling faster than 200 miles an hour. This is because the bullet's much lower energy is focused into an even smaller area. If the target is a human being, the consequences can be deadly.

Police officers run the risk of being such targets at any time. To lower their risk of death, many officers wear protective vests made of very strong, specialty materials such as Kevlar or Spectrashield synthetic fibers, which are stronger than steel. But the same vest that keeps out bullets keeps in heat: During warm weather, police find them almost unbearably hot. And a "bulletproof vest" stops nothing if it's locked in the trunk of the patrol car.

To make this soft body armor bearable—and wearable, Moshe

Siman-Tov of ORNL's Engineering Technology Division and a team of engineers are resorting to one of the oldest laws on the books: the second law of thermodynamics. To grasp one form of this law in action, stir a cup of tea with a silver spoon. Too hot to handle? That's because heat is drawn from the tea and is conducted up the cooler handle through the silver molecules, which vibrate against each other and, in turn, against your fingers. Energy moves from hot to cold. Always. It's the Law.

Siman-Tov's team is using The Law to help officers keep their cool. Call it scientific law meets criminal law.

The team brought impressive credentials to the task. Previously they had developed ways to cool super-hot orbiting lasers for the Defense Department's "Star Wars" program; they also had devised better strategies for cooling nuclear reactors that operate at temperatures above 1000°F. Cooling a human, which operates at a meager 98.6°F, should be easy enough, they figured.

Under a 1995 cooperative research and development agreement with Safariland, a leading U.S. and worldwide manufacturer of bulletproof vests for law enforcement, the engineers set to work. The theory was simple, but the rules—make that The Rules—were tough: must be used for hours without an external power source, must be light, must be comfortable, can't restrict movement, can't compromise protection.

Some currently available designs require a powered system to bleed off the heat; they work, but they bend The Rules to the breaking point (too complex). Other designs are passive but break The Rules for other reasons (e.g., too heavy).

That is where new creative ideas came in to help. First, to carry away heat from the body, the team selected special fibers that conduct heat better than any other material, including copper or silver. Woven into fabric that can be tailored to be worn under the vest, the fibers will remove trapped heat if engineers can offer it a cooler destination. Enter thermal energy storage material that can grab heat and store it as latent heat (turning a solid to liquid to keep the vest wearer cool) until the police officer's duties are done for the day. Then the device can be "recharged" in the patrol car while officers cruise to their next mission.

Now, even as work continues on various parts of the concept, Siman-Tov and his team contemplate new ideas that will take advantage of nature rather than fight it. Details, however, are not available for this article because ORNL engineers follow The Rules.

The new design Siman-Tov envisions would also satisfy The Rules. It would obey The Law. And it would surely save some lives. Cool.

In collaboration with Safariland, ORNL is developing a technique to cool personnel wearing body armor to increase their comfort and ability to perform efficiently in hot or humid climates.

Examples of video footage of crime scenes after video enhancement at ORNL. Above are unenhanced and enhanced images of a bank robbery in Knoxville.

This bank robber was captured on videotape for less than one second, but ORNL video enhancement enabled identification of a suspect. (Orange dots were added to protect the identities of the accused.)

This ORNL video enhancement helped police find a suspect in this robbery of a Knoxville convenience store.

America's Most Wanted

"You have evidently seen more in these rooms than was visible to me."

"No, but I fancy that I may have deduced a little more ..."

—Arthur Conan Doyle

The video from the Memphis convenience store security camera recorded the crime in all its horror. The robbery and murder resembled a TV dramatization, but the victim was real. Unfortunately for police, the security camera was cheap, the light bad, the movement fast. Investigators were unable to get a good look at the killer. The tape was sent to Memphis video specialists to see if they could improve the image. They could not.

That wasn't surprising, says Teresa Subich, a graphic artist in ORNL's Instrumentation and Controls (I&C) Division. The typical security camera is doomed to take low-quality video by its bad optics, age, narrow recording bandwidth, and poor light sensitivity. And it's unlikely that all the older, low-quality cameras now in use will be replaced anytime soon. So Subich and

This video footage enhanced at ORNL reveals evidence of a murder of a convenience store owner in Chattanooga. The muzzle flash associated with the homicide suspect appears between the two zeros, and his foot is shown under the bottom 7. This evidence has been used in court. Identification of the muzzle flash discredited the suspect's story to the police.

her colleagues are bringing science into the picture.

A video camera uses the same concepts Alexander Graham Bell and Thomas Edison pioneered a century ago, working with weak electrical current and magnets, needles, and wax: the vibrations and impulses of sound and light can be converted into electrical signals in a charge-coupled device. If the process is reversed, the signals are converted back into sound and light. The conversions can be done in real time, as in a telephone chat or TV broadcast, or the signals can be stored as magnetic squiggles on videotapes—the modern equivalent of scratches in wax. Now, as in the days of Edison and Bell, the quality of the recording depends on the equipment and the conditions at the time.

But sometimes recordings hold more information than standard playback equipment can reproduce. To get at this information, which is often masked by interference, ORNL specialists are enhancing videotapes using commercially available equipment (Adobe Photoshop and other software on Apple Power Macintosh computers and other hardware) and their natural abilities to get the most out of these tools.

By grabbing digital information from videotapes frame by frame, then using the computer to delete interference and clear up images, the ORNL team has quickly produced a string of successes: they've helped solve a series of armed robberies, an ATM burglary, a large marijuana-growing operation, a bank robbery, and a hate crime. They've also improved the quality of video evidence from numerous other burglaries, robberies, homicides, and other crimes.

To date CASTLE's video enhancement technology has had a better than 50% success rate in providing evidence leading to an arrest or conviction in the 30 cases in which it has been used. Evidence extracted from tapes includes the identity of a person or a vehicle, which can be used in building a case for arrest and prosecution. The Tennessee Bureau of Investigation, the FBI, and police departments in Oak Ridge, Knoxville, Chattanooga, and other towns in Tennessee and in Georgia and Florida have obtained help through the program.

"We've gotten tremendous results, and demand is growing," says McKenney. "In one case, an arrest was made in one day after we got a surveillance tape and analyzed it. In another case we were able to identify the muzzle blast from a handgun used in a homicide case. The photographic evidence contradicted the defendant's testimony. A detective involved in the case said he was certain the subsequent guilty plea was a direct result of the CASTLE support."

Now, to move the technology out of ORNL and into police or private labs, Ken Tobin and Tom Karnowski, both of the I&C Division, are developing a new generation of software specifically designed to tweak security-camera videos. Such camera systems have some common problems, such as streaking caused by worn-out recording heads, blurry pictures resulting from dirty or inferior lenses, and dark images resulting from inadequate lighting. By developing computer programs that look specifically for these problems and automatically correct for them, researchers hope to help police extract better evidence from security videos at a much lower cost.

And that means the picture will be brighter for police and prosecutors.

The Face of Crime

Reconstructing a human from skeletal remains is a somber task for even hardened investigators. Skillful hands can never reassemble a lost life, but there is the chance that identifying an unknown victim could bring a killer to light and to justice.

In cases where no other identifying evidence can be found, forensic anthropologists can recreate the victim's face by modeling clay over the skull. Using pencil-eraser-sized

rubber markers attached to the skull, an expert molds the clay into "average" cheeks, lips, and other features. With skill, some luck, and a victim who's close to "average," an identification can sometimes be made. Unfortunately, the odds are low and the cost is high: Only one in seven such reconstructions leads to a successful ID; on average, the work takes two months and costs $2500.

Murray Marks, associate director of the Forensic Anthropology Center at the University of Tennessee at Knoxville (UTK), figured advanced technology could improve the process. Professor Marks had good reason to trust technology: his predecessor at UTK, William Bass, spent years pioneering physical and chemical techniques for identifying skeletal remains. (In the process, Bass became something of a legend, eventually inspiring Patricia Cornwell's 1994 novel *The Body Farm*; in fact, two characters in the book are modeled after Bass and Bohanan, and the "body farm" in the book is UTK's Anthropological Research Facility.) The collaboration Marks proposed to ORNL was not physical or chemical, but computational.

"Over the years, anthropologists have identified the thickness of tissue on a limited number of places on the skull," explains Marks. "It was clear that if we had more measurements, we could do a better job of reconstructing a face. One of the things that a computer can do very well is take many measurements."

At ORNL Marks met up with biologist Richard Mural and computational biologists Reinhold Mann and Ed Uberbacher, who were

If we had more measurements, we could do a better job of reconstructing a victim's face. One of the things that a computer can do very well is take many measurements.

Dr. William Bass, Knoxville's well-known forensic pathologist, examines the skull of a murder victim. Bass has been with the University of Tennessee's Anthropology Department.

The dark and sinister business of crime will never be shut down. But by developing techniques and equipment to identify victims, protect police officers, and bear witness against criminals, ORNL is helping to make that business riskier and less attractive to criminals.

working on the problem using ORNL's supercomputers. From the outset, the researchers knew they needed better data to work with. "Using average tissue thickness is not very accurate because there's a lot of variation around 'average,' " explains Uberbacher. "If you put an 'average' nose on someone like me, for instance, I'd be unrecognizable," he says. The tissue-thickness data typically used for facial reconstruction come from a limited number of measurements taken from cadavers a half-century ago. By taking measurements from hundreds of recent magnetic resonance imaging scans of living volunteers, the ORNL researchers began to develop detailed predictions that consider age, gender, and ethnic origins.

Next, instead of basing the reconstruction on only a dozen or so points, they used the computer to plot thousands of points so the surfaces of the face would be mathematically based on the shape of the entire skull, not just a few landmark points directly below the skin.

Even the computer became more accurate over time, learning from its experience how to better predict a face. "We can program the computer to combine information to predict an outcome in much the way a child learns," Uberbacher explains. "It's like learning the difference between a cat and a dog. A one-year-old child often gets the two confused. That's understandable—four legs, tail, fur, ears. With experience, though, the child gathers more information—shape, meow—and draws better conclusions." Using case-based reasoning, ORNL's computers can do the same thing, combining information from the database into a composite—matching this forehead and that jaw, say—to reach more accurate conclusions about the shape of the face of an unknown victim.

Today, it takes supercomputers like ORNL's Intel Paragon XP/S 150 to sift through gigabytes of data and create a three-dimensional image. But as the system is refined, Uberbacher, Mann, Mural, and Marks expect the time and cost of computerized reconstruction to drop dramatically: from a couple of months and $2500 to a couple of hours and $25. That would allow facial reconstruction to be widely used on unsolved crimes. New virtual reality features that allow forensics experts to add or subtract 20 years or 20 pounds with a keystroke should soon make results even more realistic. And remote access, by which scans of a skull can be e-mailed for face reconstruction, will make the technique available even to smaller police departments.

The dark and sinister business of crime will never be shut down. But by developing techniques and equipment to identify victims, protect police officers, and bear witness against criminals, ORNL is helping to make that business riskier and less attractive to criminals.

As Holmes would say to Watson, the game is afoot; it always will be. But the odds for the good guys are getting better.

Pete Xiques, a division manager at the Oak Ridge office of the Science Applications International Corporation, is a freelance writer in his spare time. He can be reached at peter.j.xiques@cpmx.saic.com **ornl**

ORNL and the University of Tennessee are working together to apply advanced computing and artificial intelligence to rapidly and inexpensively reconstruct faces of murder victims from their skeletal remains. Starting with an unidentified skull, the new technology is expected to predict the most probable face for the victim; identify gender, race, and age; match police photo books; and factor in genetic markers or DNA sequences that could be used to predict the victim's appearance.

Life on

Why Biodiversity Varies

By Carolyn Krause

Editor's note: In the early 1990s biological diversity—the variety and distribution of life on the earth—became a hot political issue. The chief reason: concern about extinctions of animal and plant species as a result of human activities such as the felling of tropical rain forests to provide land for agricultural production. Because the number of different plant species is highest in rain forests, some experts fear that tropical deforestation will aggravate the problem of species extinction, add more plants and animals to the endangered species list, and destroy species that may have not-yet-discovered medicinal properties, such as the ability to cure cancer. In addition, environmentalists seek to preserve forests because they take up atmospheric carbon dioxide, curbing global warming.

In 1994 the Cambridge University Press Ecology Series published a book *Biological Diversity: The Coexistence of Species on Changing Landscapes* by Michael Huston, a biologist in ORNL's Environmental Sciences Division (ESD). It has been described by one reviewer as "a bold attempt to find a common link, a grand unifying theory, underpinning many of the major patterns in the way in which organisms assemble themselves into communities on the face of the planet." The book, which earned Huston the honor of Author of the Year and Publications Award at the 1996 Lockheed Martin Energy Systems Awards Night, has been well received by the scientific community—more than 4000 copies have been sold, and it is being translated into Spanish and Portuguese. The following article tells the story of how Huston came up with his theory and the response to his work.

Earth:

Michael Huston examines the core of a young tulip poplar on the ORNL reservation. The core shows evidence of slower tree growth during the 1990s than in previous decades, possibly because of drought.

I was trying to answer one of the major unanswered questions in ecology—why are there more species in some regions than in others?

In 1976, when Michael A. Huston was a graduate student in biological sciences at the University of Michigan, he wrote a research paper that almost got him kicked out of graduate school. The paper proposed a hypothesis that challenged the widely accepted theory about coexistence of species of plants and animals in various environments, known as the principle of competitive exclusion.

"I was trying to answer one of the major unanswered questions in ecology—why are there more species in some regions than in others?" Huston says. "I proposed that species diversity was regulated by nonequilibrium processes rather than generally accepted equilibrium processes. Even more controversial was my suggestion that the productivity of tropical rain forests is low, since most ecologists think that tropical rain forests are the most productive ecosystems in the world because they have the highest number of species." The paper marked the beginning of Huston's scholarly attempt to refute two commonly held beliefs: that plants in tropical ecosystems grow at an unusually fast rate and that tropical rain forests can be converted to profitable agriculture and productive forestry.

Ignoring the recommendations of his graduate adviser, who told him not to waste his time working on species diversity because all of the top ecologists in the country were already concentrating on it, Huston developed his ideas and submitted his paper to one of the major journals in ecological and evolutionary theory. He also submitted the paper to the faculty evaluation committee as part of the preliminary examination process for his doctoral degree. The faculty committee found the paper totally unacceptable, and in early 1977 Huston was on the verge of being ushered out of the graduate program with a "terminal" master's degree when news arrived that the unacceptable paper had been accepted by the journal.

A Gulf Fritillary, a type of butterfly found only in the tropics, visits a common roadside weed in Everglades National Park. Huston's most recent studies in the tropics have been conducted in this park.

However, even before his paper was published, Huston's theory was attacked in a March 1978 *Science* magazine article by a prominent ecologist, who concluded (somewhat prematurely, Huston adds) that "among neither tropical rain forest trees nor corals is there a consistent correlation of diversity and growth rates, as predicted by the (Huston) hypothesis." When the paper, "A General Hypothesis of Species Diversity," finally appeared in January 1979 (*The American Naturalist*, Vol. 113, pp. 81–101), it attracted the attention of ecologists all over the world. "Because more than 1000 reprint requests came in the first two years," Huston says, "the university Biology Departmental took over the task of making copies and mailing them out." Needless to say, Huston was allowed to continue his graduate studies at the University of Michigan.

The writing of that paper was not the only time Huston would encounter resistance to his ideas. The publication of the paper, however, marked one of several times that he gained the attention of ecologists and exerted a potentially significant influence on the field of ecology.

Coexistence of Species

Where most ecologists see stability in nature, Huston sees instability.

In 1859 Charles Darwin explained how species arose in his book *The Origin of Species by Means of Natural Selection.* In recent decades, a question of intense interest to ecologists has been, how do existing species survive and coexist in spite of the many processes that cause extinction?

"The basic premise of most ecologists," Huston says, "is that the coexistence of species is based on the balance of nature. The idea is that no two species can live on the same resource, so if species coexist, they must be using different resources. For example, if you had two kinds of woodpecker eating the same types of insect inhabiting the same type of tree, one species would outcompete the other species, which would vanish from this forest. But you can have two different species of woodpeckers in a forest if the two species use different trees or eat different insect species."

The composition of a forest is largely determined by competition. Trees compete with each other for energy from sunlight, soil nutrients, and water. The leaves take in light and the roots take in water and soil nutrients. The tallest trees soak up most of the sunlight. Only the smaller trees that can tolerate shade, such as sugar maples, will survive in such a forest. Eventually, the forest will reach a state of equilibrium in which only a particular combination of species of trees, ferns, other plants, insects, birds, and mammals coexists. This picture of nature is called the competition equilibrium model.

Where most ecologists see stability in nature, Huston sees instability. As a graduate student, Huston found that models based on the assumption of competitive equilibrium were not particularly useful. "An unappreciated aspect of the principle of competitive exclusion," he says, "is that it may take a long time to reach the equilibrium state where weaker competitors become extinct." Period disruptions—death-causing disturbances such as drought, disease, insect attacks, asteroid impacts, fires, extreme cold, hurricanes, windstorms, lightning strikes, floods, bulldozers, and excessive predation—interrupt the process of competitive exclusion and prevent it from reaching its equilibrium end point. Even in the absence of disturbances, the rate at which the process of competitive exclusion approaches equilibrium can vary greatly in response to such environmental conditions as temperature, soil fertility, precipitation, and solar radiation. When the rate of competitive exclusion is slow, fluctuations in environmental conditions can shift the competitive

A strangler fig competes for light and will eventually kill this cypress tree in a South Florida swamp forest.

Species diversity is the result of a dynamic equilibrium between competitive displacement and disturbance.

An American egret stalks its prey in a flooded "prairie" surrounded by "tree islands" in Big Cypress National Preserve in Florida.

balance between species, allowing formerly inferior competitors to become dominant.

According to Huston, the species diversity found at any location is the result of a dynamic equilibrium between competitive displacement and disturbance. Consider the forest at Walker Branch Watershed, an ORNL research area for which Huston was project leader for five years. There, tulip poplars are a potentially dominant tree species under moist conditions. But in the past eight years, based on measurements of tree growth rings, their rate of growth has slowed dramatically. The probable reason is the series of unusually dry years, particularly 1988, 1993, and 1995. In contrast, the white oaks in the watershed are growing at nearly the same rate as before the droughts, because they are more drought tolerant than tulip poplars. A little drought has changed the forest dynamic, reversing the relative growth rates of two abundant species and slowing the process of competitive exclusion.

Diversity vs Productivity

So, how did Huston come up with the dynamic equilibrium model? And, what does the dynamic equilibrium model have to do with biological diversity in the tropics? His diverse life experiences seem to have influenced his views on species diversity.

"I grew up in Iowa, where the soil is unbelievably rich and fertile," he says. "I saw field after field of lush crops of corn, soybeans, and hay used for animal feed. I learned that the land had once been prairie and grassland, but human exploitation of the landscape had driven away wildlife such as elk, bison, wolves, and cougars, and some species such as the passenger pigeon have become extinct. Before I graduated from Grinnell College, I attended Deep Springs College near Death Valley, where I experienced a desert landscape that is unaffected by humans and sparsely populated with remarkably adapted plants and animals.

"In my first year as a graduate student at the University of Michigan, I traveled to Costa Rica to study tropical ecosystems. The tropics have played such a critical role in the

development of evolutionary and ecological theory that every student there hopes to make some new discovery, such as a new species of beetle or fungus. I went to Costa Rica full of questions about species diversity. During the wettest July ever recorded at the La Selva field station in the lowland rain forest, I wandered through treefall gaps, traced the roots of lianas across the forest floor, and watched the river flood the forest. I couldn't avoid noticing how different the tropical soils were from the soils of Iowa, in the red color, high clay content, lack of any organic layer, and apparent infertility. Yet there were some impressively large trees, and an overwhelming diversity of plants of all sizes. I didn't know anything about soil science, but I felt that the differences between the vegetation of Iowa and Costa Rica had something to do with the soils.

"Unable to fit what I was seeing with what I had learned, I was struck with an idea that, at the time, contradicted the foundations of ecological theory. Rather than an equilibrium balance of finely coevolved competitors reaching maximum diversity at the highest levels of productivity, I hypothesized that the high diversity I saw around me resulted from the opposite situation. Equilibrium had been disrupted by various types of disturbances, such as windstorms that blew over large trees. Low fertility of the soils seemed to ensure such a slow return to competitive equilibrium that many species were able to coexist in a state of nonequilibrium. I saw high diversity but low productivity."

In other words, plants in the tropics—numerous species of trees, vines, orchids, cacti, ferns, begonias, and epiphytes—compete for light, water, and soil nutrients, just like plants everywhere. However, because the soils are poor and high temperatures increase energy losses through respiration, the plants don't grow very fast from day to day, although they often grow year-round. As a result of this slow growth, superior competitors are not able to dominate very quickly, periodic dry years may alter competitive hierarchies, and many species can coexist in a nonequilibrium state. So the number of different species is highest in the tropical forests in spite of, or in Huston's view, because of the infertile soils.

In contrast, during the much shorter growing season in the temperate zone, plant growth on a day-by-day basis is actually much higher than in most of the tropics because of higher soil fertility and more favorable temperature conditions. However, the short growing season results in a lower annual total plant production than in the tropics, contributing to the conventional wisdom of ecologists that plant productivity is highest in the tropics. It is this "common wisdom" that Huston has tried to refute, but not without a lot of resistance.

Coral Reef Diversity

The second time Huston ran into a brick wall was in 1978 when he sought to describe patterns of diversity in coral reefs using data he had gathered while scuba diving.

"I have been repeatedly surprised by the resistance to ideas and data that contradict the common wisdom," he says. "I had some difficulty publishing data on coral species diversity that I collected as part of a field course in Jamaica during my second year in graduate school. Based on my hypothesis about species diversity, I predicted that the diversity of corals growing together on the reef surface should be higher in deeper water, where there was less light, than near the surface where coral should grow rapidly. During six weeks of daily diving on the reefs at Discovery Bay, I collected enough data to demonstrate that coral diversity did indeed increase from the surface to 20 meters in depth, after which it began to decrease.

"Reviewers of the paper I submitted on coral diversity patterns rejected the paper with the criticism that the data were obviously in error because it was well known that coral diversity *decreased* continuously with depth. A few years later, another paper came out demonstrating that the same pattern I had found also occurred in the Indian Ocean. So in 1985, seven years after I had completed my field work, I compiled and published a review paper on coral diversity documenting that diversity increased with depth on coral reefs around the world."

For his doctoral thesis, Huston sought to identify specific biological mechanisms that produced the patterns of diversity he had observed. At the La Selva field station in Costa Rica, he set up experimental tree plantations in which he monitored the growth and mortality of more than 1000 individual plants of four forest species—some in plots for mixed species and others in plots of just one species. The experimental treatments consisted of two levels of light (full sunlight and 30% of full sunlight, created under a giant tent of shade cloth) and two levels of soil fertility (fertilized and unfertilized).

"My goal was to understand forest succession in terms of the interaction of individual tree physiology with the environmental conditions under which each individual grew," Huston says. "The trees grew rapidly, and I based my thesis on the first two years of data, although I continued to monitor the plots periodically for over 10 years. I saw clearly that both the rate of succession and species diversity are strongly affected by soil fertility." Both rain forest trees and reef corals show the same pattern of diversity in relation to growth rates. The slower the growth is, the higher the diversity.

Individual-Based Population Models

Computer models of forest succession can predict changes in upcoming generations of forests that result from competitive exclusion and disturbances. Since the 1960s, ORNL scientists had been studying forests using systems ecology models. This approach ignored individual trees and treated the forest as a mass of plant tissue. Then, in the mid-1970s, ORNL's Hank Shugart and his students began working with computer models that simulated forest succession using the interactions of individual trees with each other and their environment. Huston was interested in working with Shugart on these models when he came to ORNL.

"In physics, the fundamental units are subatomic particles," Huston says. "In ecology, the fundamental units are individual organisms. The survival or extinction of individuals in each species is increasingly seen as important to ecological as well as evolutionary processes."

In 1986, after Shugart had departed the Laboratory, Huston worked with ESD's Mac Post and Don DeAngelis on individual-based models that incorporate ideas of nonequilibrium. DeAngelis was studying size bimodality in fish—why some fish populations have only large and small individuals and no individuals of an in-between size. Because Huston was interested in size bimodality in plant populations, he began interacting with DeAngelis.

Huston and Post used individual-based models to predict forest succession. They looked at oaks and maples as individual trees that respond in specific ways to the availability or lack of sunlight, water, and soil nutrients. They didn't tie a yellow ribbon around a young oak tree and watch it grow in a forest; instead they represented individuals of each species as equations in a mathematical model. They were seeing the whole forest through the individual trees; they were simulating the interactions of individual trees with each other and the environment to better understand how the forest would look. They were identifying ecological processes that affected the evolution of forests.

"Competition in forests even influences biochemical processes," Huston says. "Suppose you have a forest of mostly oaks and pines. The pine trees decline in growth and number because of age, drought, and perhaps an attack of pine beetles. The oak trees continue to thrive. As a result, the forest litter will consist of more decomposing oak leaves and fewer pine needles. The chemical composition of the soil will change, causing a shift in nutrients and the types of species that will be found in the future forest."

We introduced a major new approach to ecological modeling, which has the potential to integrate ecological processes across organizational levels and spatial scales.

In 1988 Huston, Post, and DeAngelis wrote an article published in *BioScience* that linked individual and population processes with ecological and evolutionary patterns. The paper described ORNL's models of forest succession and fish population structure, which simulated the growth and mortality of individual organisms and ultimately added them together to predict the composition of a forest community or a fish population. The paper made a big splash in the field of ecology and received the 1990 award of distinction (first place) in the category of Scholarly/Professional Articles in the International Technical Publications Competition of the Society for Technical Communication.

"Our paper articulated the rationale for and potential applications of what we called 'individual-based models,' " Huston says. "We introduced a major new approach to ecological modeling, which has the potential to integrate ecological processes across organizational levels and spatial scales. It was quickly embraced by researchers who could see that the models related directly to the individual organisms they were studying. Perhaps the most significant contribution of our paper was the demonstration that phenomena at all levels of organization, from the individual organism to the entire ecosystem, could be understood within the single conceptual framework of organisms interacting with each other and their environment."

The individual-based modeling approach was illustrated by a variety of specific examples in a book from a symposium that the ORNL ecologists organized with their University of Tennessee (UT) collaborators Lou Gross and Tom Hallam. The approach is now widely used in a variety of theoretical and practical applications. Tropical rain forest management; accumulation of environmental contaminants in fish and daphnia; power plant impacts on fisheries; and the survival of the deer, panthers, and wading birds of the Everglades are among the many current issues being addressed by individual-based models. (See the sidebar "Saving the Florida Everglades" beginning on p. 50.)

In collaboration with Tom Smith, an ORNL postdoctoral researcher and a graduate of the UT Ecology Program, Huston developed a model that describes the interactions of physiological adaptations of different plant species with variations in light and water availability. This approach produced a unified theory of plant community dynamics that predicts how shade tolerant different species would

be and how fast they would grow under different conditions of water availability.

Book on Biodiversity

In 1986, Huston received a request from Cambridge University Press to write a book on species diversity. "The request," he says, "provided me the opportunity to pull all of my work together and integrate it in a way that was simply not possible in a series of publications. While reorganizing my work to reflect my current understanding, I was pleasantly surprised to come up with a few new insights."

While writing *Biological Diversity: The Coexistence of Species on Changing Landscapes*, Huston served as leader of ORNL's Walker Branch Watershed Project, which was started in 1967. During his tenure, the Walker Branch Watershed Project supported a wide range of research in hydrology, geomorphology, soil biogeochemistry, stream nutrient cycling, and forest ecophysiology, and it continued long-term monitoring of precipitation (which could be affected by climate change), stream flow and chemistry, and forest dynamics. The goal of the research was and still is to determine the distribution of soil and water resources across the landscape and interactions between them and living organisms. The project also provided the opportunity for Huston to apply many biodiversity concepts developed in his book.

The book was published in 1994. It received many positive reviews and a few negative ones. Huston says that younger scientists tend to be supportive of his work and older scientists tend to criticize it. "The main criticism of my theory has been that it has not been adequately tested," he says. "The challenge for ecologists is to provide quantitative evidence to convincingly reject my ideas, or they will continue to gain emphasis."

The goal of the research was and still is to determine the distribution of soil and water resources across the landscape and interactions between them and living organisms.

An alligator lily in Everglades National Park.

In response to Huston's argument that high plant diversity is found on soils too poor for high agricultural productivity, one critic wrote that it is possible to have high productivity and high diversity on the same land. "Yes, it is possible with frequent disturbance to have high plant diversity and high plant productivity," Huston says. "In my book, I noted that prairie grass and herb communities in the highly fertile midwestern United States have high diversity. Why? Because of frequent fires that eliminated woody vegetation. Also, I pointed out that diversity of animals can be high in productive areas like savannas, where plant diversity is low but the growth rate of grasses is high."

Huston said that he has seen no significant criticisms of his book that would refute his theory. "Most of the new studies that I have seen since my book came out," he notes, "actually support my hypotheses more strongly than I would have expected, given the high variability of natural processes."

Biodiversity and Land Use

How can the world make the best use of its natural resources? How should land be used to ensure that (1) the world's population will be adequately fed and clothed and (2) biological diversity will be maintained, avoiding additional extinction and endangerment of plant and animal species and conserving living organisms that may be the source of tomorrow's life-saving medicines? Huston's research in biological diversity suggests rational answers to these questions. These answers are summarized in the final chapter of Huston's book and in his article "Biological Diversity, Soils, and Economics" in the December 10, 1993, issue of *Science* magazine (for which he received ESD's Distinguished Scientific Achievement Award in 1994). In the *Science* article he wrote that plant species diversity "should be higher on unproductive, poor soils than on fertile, productive soils where

plants are taller and total plant mass is higher. This pattern of highest plant diversity on poor soils and low plant diversity on the best soils is found throughout the world under a wide variety of conditions."

So, what are the implications of this phenomenon for land use and economic development? Is it possible to feed the world and preserve natural resources without causing major conflicts in land use?

"The only defensible reason to destroy natural habitat," Huston says, "is to improve the human condition. Land is justifiably needed for agriculture, forestry, housing, new factories, and expanding cities. But, in some cases, converting natural habitat to agriculture can destroy biological diversity without producing any real agricultural gains.

"Taking the rational view, we should not farm all over," he continues. "We should confine our farming to soils that are fertile and highly productive and use the most efficient farming techniques. Land that has a high diversity of plant species tends to have poor soil and often is not suitable for agricultural production. Some of our federally protected lands—national parks, national forests, and wildlife refuges—have been set aside because they are not useful for farming; but they have high diversity, so we are inadvertently protecting high diversity. Some parts of the Great Smoky Mountains National Park, for example, have a high diversity of plant species but little value for agriculture."

Huston encountered more resistance when his ideas on biodiversity and economics were first published in *Science* magazine. "I was surprised by the strong negative reaction from some parts of the conservation community," he says. "There are some who feel that human needs must be sacrificed to preserve nature. Aside from the moral or philosophical issues of human rights versus the rights of other organisms, I see little prospect that any individual will sacrifice his own or his family's well-being to save an endangered species or even an entire ecosystem. I believe biodiversity and natural resources can be preserved and the basic needs of current and future human populations can be fulfilled at the same time. I am optimistic that a better understanding of the functioning of ecosystems in relation to the maintenance of biodiversity and harvestable productivity will provide the key to a sustainable future for all life on the earth."

Dirt Is Destiny

Global mapping shows that the number of plant and animal species increases from either pole toward the equator, peaking in wet lowland tropical rain forests. Along this same latitudinal gradient, per capita gross national product (GNP, a standard indicator of economic condition) shows the opposite pattern, being lowest near the equator and increasing toward the higher latitudes. Huston believes it may be more than just coincidence that both patterns are consistent with his ideas about soils and species diversity.

"The same inverse relationship between species diversity and plant productivity that is seen at the local scale of a hillside also appears at the global scale," Huston points out. "The wealth of nations seems to follow the opposite pattern from plant diversity, being highest in many of the countries with the best soils, such as Japan, the Netherlands, the United States, and western Europe.

Huston notes that throughout human history, the highest levels of economic and cultural development have tended to occur in areas with rich soils, such as the "Fertile Crescent" of the Tigris and Euphrates Rivers; the Nile River Valley; Greece and Italy (before deforestation and erosion destroyed the soils); the Ganges, Yellow, and Yangtze river valleys; central Mexico and the Andes of South America; and, in North America, the Mississippi Valley, and the Pacific Northwest.

This is yet another issue where Huston meets resistance, this time from outside the field of ecology. "These observations make geographers and anthropologists very uncomfortable," Huston says, "because they are a form of 'environmental determinism,' which was misused in support of racist political agendas in the first part of this century. Nonetheless, the constraints imposed by the environment on human activities must not be ignored." Leaving room for the force of human will and ingenuity, Huston observes that even if two farmers work equally hard, the one whose farm happens to be located on fertile soil will make more money and have more time for cultural activities and will probably be able to send his children to a better college than the farmer who has the bad luck of settling on or inheriting less fertile land.

This same "luck of the draw" also applies to the nations of the world, Huston believes. Many less developed countries are located in tropical zones, where the soil is poor. Huston suggests that these countries cannot afford to take the approach of developed nations in temperate zones and arid regions: invest heavily in fertilization and irrigation to achieve high agricultural productivity. Because of low soil fertility in many of the less developed countries, Huston argues that they will never be able to develop a strong agrarian economy but rather must build their economies on mineral exploration, industrial production, tourism, or other activities.

So, who will feed the folk in the tropics? "Of all continents, North America has the highest proportion of fertile soils," Huston says. "Major changes are needed in our agriculture to achieve the highest yields efficiently and sustainably so we can supply food to the populations of less developed tropical nations. Large-scale organic gardening is not the solution because it

is less productive than industrial farming. We should farm in a way to minimize erosion and improve the soil."

In the past, Huston points out, many civilizations have destroyed their soil by allowing pastures to be overgrazed or by cultivating hilly land. Erosion occurred, leaving the productivity of the land permanently reduced. He says that two modern methods of agriculture should be used widely to reduce erosion. One method is no-till agriculture, in which little plowing is used and unharvested plant material is returned to the soil. The other is precision farming, in which (1) the field is divided into measured and precisely located parts using Global Positioning System satellites; (2) computerized tractors inject the precise amounts of fertilizer, pesticides, and seeds of the right hybrid species in each part of the field to maximize its productivity; and (3) a computerized harvester takes inventory of the crops it harvests at each field location to help the farm manager determine the changes needed to achieve the highest productivity.

In short, Huston believes that the rational use of land can conserve natural resources and biological diversity while still meeting the human need to be fed and clothed. "Preservation of areas of high plant biodiversity does not require the sacrifice of productive agricultural lands," he says. "There is no inherent conflict between the preservation of biological diversity and the economic improvement of the human condition."

Like an oak trying to grow in a forest dominated by tulip poplars, Huston's ideas will not die from competitive exclusion. His ideas are still alive today, and a growing body of evidence suggests his views on biological diversity may be valid. His theory may still be in the shadow of the current paradigms in ecology, but new evidence obtained by a new generation of ecologists may provide the truth, which though disturbing to some, will certainly change the balance of ecological thought. ornl

How To Order *Biological Diversity*

Biological Diversity: The Coexistence of Species on Changing Landscapes, **Cambridge University Press (1994).**

Telephone number: 1-800-872-7423. E-mail address: marketing@cup.org. WWW site: http://www.cup.org

The book has 701 pages, 193 line diagrams, and 24 tables. Its catalog number is 369304 (paperback) and 360935 (hardback).

A New Award

Michael Huston (along with ORNL's Betty Mansfield and Tuan Vo-Dinh) recently received the Department of Energy's BER 50 Exceptional Services Award. Huston was cited for "developing innovative concepts of the general patterns of biodiversity and how environmental change and human influences affect biodiversity."

Huston stands among the plastic troughs used to investigate the effects on forests of both increased and decreased precipitation that might result from climate change.

Saving the Florida Everglades

Michael Huston is now involved in a high-stakes project whose ultimate success may depend on whether his ideas about species diversity, ecological modeling, and land-use tradeoffs are proven right or wrong. The Clinton administration has made the restoration of Florida Bay, Everglades National Park, and other threatened South Florida ecosystems a national priority. One of the highest scientific priorities in the restoration effort is the generation of information using a computer modeling system based on ideas developed at ORNL and the University of Tennessee at Knoxville (UTK). Use of this individual-based modeling approach pioneered at ORNL has been identified as essential by an interagency task force that includes the Army Corps of Engineers, the U.S. Geological Service, the Environmental Protection Agency, the National Park Service, and the National Biological Service, along with such state and local agencies as the South Florida Water Management District. This multi-institutional collaboration is known as the Across Trophic Level System Simulation (ATLSS).

For the ATLSS project, Huston, Don DeAngelis (now with the U.S. Geological Survey), and Lou Gross (UTK) are linking multiple individual-based models. However, rather than fish and trees, the individuals in these models represent some of the major endangered species of South Florida, including the Florida panther, the Everglades kite, and the wood stork, along with their prey—deer, snails, and fish. In the ATLSS modeling system, virtual panthers stalk their simulated prey on a computerized landscape derived from satellite images. If the virtual water is too deep, the movement of the panthers is restricted, but that of their primary prey, the white-tailed deer, is restricted even more. The depth and distribution of water define the unique properties of the Everglades and Big Cypress Swamp, and restoration of the natural pattern of water availability is the primary method for restoring the ecosystem. The objective of the ATLSS models is to predict the biological effects of different patterns of water availability. Such information will assist the Army Corps of Engineers in formulating the restoration plan.

One of Huston's responsibilities is to use information available from hydrologic models to predict how the ecosystem's vegetation will respond in wet and dry seasons and in wet and dry years. The answers will reveal how much food will be available for the deer and how many deer will be available for panthers to feed on under different scenarios of water availability. The virtually flat landscape of South Florida presents an entirely different challenge to Huston than did the Walker Branch Watershed project for which he performed hydrologic and landscape modeling. The topographic relief on Walker Branch Watershed near ORNL exceeds that of the entire state of Florida, and the slope gradient of the Everglades is only about one inch per mile. "Water still runs downhill in Florida," he says, "but just not very fast."

The deterioriation of the ecosystems of the Everglades and Florida Bay has resulted from competing demands for land and water from the rapidly growing urban and agricultural areas around Miami. Resolution of this conflict between man and nature is where Huston's ideas about land use and biodiversity may come into play. The primary agricultural activity is located on the deepest and most fertile soils at the northern end of the Everglades, just downstream from Lake Okeechobee.

"This was a rational land use decision," Huston argues, "and need not lead to a serious loss in biodiversity. Plant diversity in this region was naturally low, and the vast stands of sawgrass have simply been replaced by sugar cane and other crops. This highly productive region is ideal for supporting animal diversity, rather than plant diversity. It may now actually support a higher density and diversity of threatened and endangered predators than it did prior to the coming of agriculture. We saw bald eagles nesting next to sugar cane fields, thriving on rats and rabbits. Other rare predators, such as bobcats, otters, foxes, barn owls, and a variety of hawks—and of course, 'Florida gators'—are also common in the agricultural area, surviving in and around the cane fields."

Although many conservationists see agriculture as the primary evil threatening the Everglades, Huston sees things differently. "The fertile soils of

Although many conservationists see agriculture as the primary evil threatening the Everglades, Huston sees things differently.

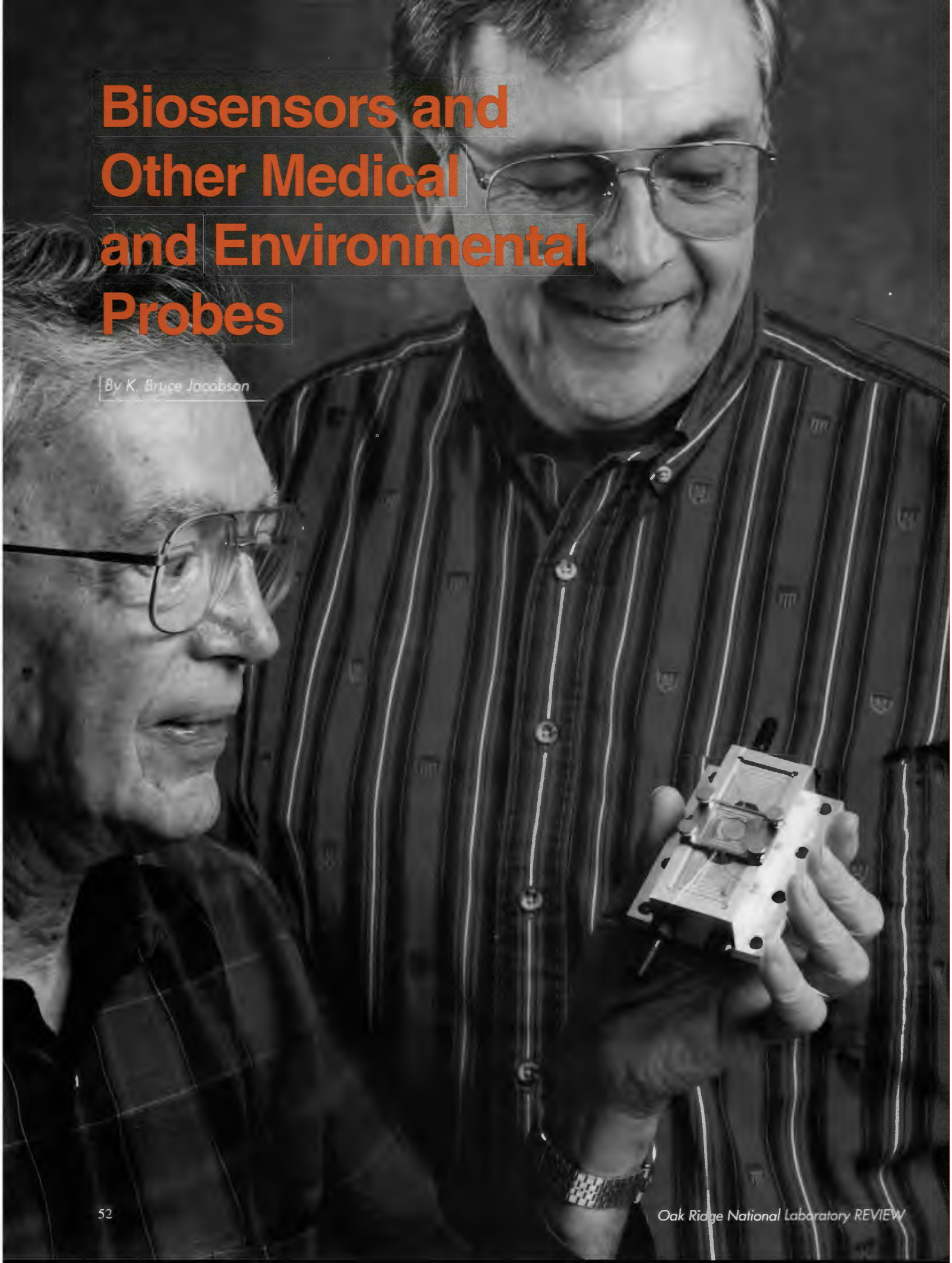
the Everglades agricultural area give it a contrasting and very important role in comparison with the rest of the system." Huston has seen, just as he expected, that the highest plant diversity is found in unproductive "wet prairies" with stunted pines and cypress. "These unproductive wetlands are great for protecting plant diversity, but lousy for most animals, especially the large predators," he says. "Different parts of the system make different contributions to the health of both the environment and the economy of South Florida."

Huston's task now is to convince decision makers who will determine the fate of the Everglades that man and nature can coexist sustainably, to their mutual benefit.

Cypress trees in Big Cypress National Preserve.

Biosensors and Other Medical and Environmental Probes

By K. Bryce Jacobson



Bacteria. Our invisible friends, our invisible enemies. Some aid our digestion, others destroy our poisons. Still other "bugs" make us sick. Living inside and outside our bodies, natural bacteria are a fact of life. We have learned to live with them and they with us. ■ Soldiers and sailors in action worry that even more dangerous bacteria are lurking in the environment. These are "killer" bacteria—the kind used as weapons. Such biological warfare agents are viewed by many to be as threatening to human life as nuclear weapons. In 1993, R. J. Wooley, director of the U.S. Central Intelligence Agency, proclaimed, "Proliferation (of nuclear, biological, and chemical weapons) poses one of the most complex challenges the intelligence community will face for the remainder of the century." General Colin Powell has stated that biological weapons worry him more than anything else. He has good reason to worry. A recent U.S. Arms Control and Disarmament Agency report on worldwide arms control compliance states that both Syria and Egypt have offensive biological warfare programs. ■ The key to protecting a military unit or community from dangerous bacteria is to detect them before they reach their intended victims. People can then be warned to leave an area or at least wear protective gear. ■ Bacteria can be detected using "biosensors." A biosensor is a device that detects, records, and transmits information regarding a physiological change or the presence of various chemical or biological materials in the environment. More technically, a biosensor is a probe that integrates a biological component, such as a whole bacterium or a biological product (e.g., an enzyme or antibody) with an electronic component to yield a measurable signal. Biosensors, which come in a large variety of sizes and shapes, are used to monitor changes in environmental conditions. They can detect and measure concentrations of specific bacteria or hazardous chemicals; they can measure acidity levels (pH). In short, biosensors can use bacteria and detect them, too.

Bruce Jacobson (left) and Carl Gehrs, manager of ORNL's Center for Biotechnology, examine a newly fabricated temperature control block for a genosensor chip designed by Mitch Doktycz. The genosensor chip can detect specific DNA sequences.

Genetically engineered bacteria can also be useful because of their ability to "tattle" on the environment. Such commonly used bacteria have been designed in Oak Ridge and Knoxville to give off a detectable signal, such as light, in the presence of a specific pollutant they like to eat. They may glow in the presence of toluene, a hazardous compound found in gasoline and other petroleum products. They can indicate whether an underground fuel tank is leaking or whether the site of an oil spill has been cleaned up effectively. These informer bacteria are called bioreporters. In 1990, when a bioreporter of naphthalene was developed and tested at the University of Tennessee at Knoxville (UTK), the ability of these bacteria to glow was demonstrated for President George Bush during his visit to UTK.

Oak Ridge National Laboratory has been developing biosensors and bioreporters for almost a decade. Carl Gehrs, director of ORNL's Center for Biotechnology, says that ORNL's program in biosensors is "a leader among DOE national labs, which is a best-kept secret." He added that ORNL is proposing to develop biosensors that can detect the presence of biological and chemical warfare agents for military use and for determining the effectiveness of cleaning up waste sites.

It is clear that Oak Ridge can make some impressive, even revolutionary, contributions to military applications of biosensors. One of the rewards of developing biosensors for military use is that the resulting devices may eventually have applications in everyday life. As President Clinton recently told a group of military officials, "What you have done here is what I wish to do nationally: take some of the most talented people in the world who produce some of the most sophisticated military technology and put that to work in the civilian economy."

ORNL's First Biosensor

The first biosensor developed at ORNL was intended for environmental monitoring. It used an antibody—a protein substance produced in the blood or tissues in response to a specific antigen, such as a bacterium or toxin normally foreign to the body. Antibodies destroy or weaken invading bacteria and neutralize organic poisons, forming the basis of immunity. Thus, ORNL's first biosensor was called an immunosensor.

In the mid-1980s, Tuan Vo-Dinh, Guy Griffin, and others in ORNL's Life Sciences Division were looking for a way to use light to detect cancer-causing agents in groundwater. So they attached to the end of an optical fiber an antibody that reacts specifically with the carcinogen benzo(*a*)pyrene (B*a*P). The anti-B*a*P antibody on the end of the fiber was immersed in a sample of groundwater. The antibody was allowed to bind the B*a*P in the groundwater sample. The antibody-B*a*P reaction product gives off light if illuminated by light of the right wavelength. So the right light was aimed through the fiber into the groundwater sample. After 5 to 10 minutes, the reaction product fluoresced, and the fluorescence was transmitted back up the fiber and measured. These successful results, reported in 1987 by Vo-Dinh and colleagues, brought the group a 1987 R&D 100 Award from *R&D* magazine and initiated the group's development of a series of fiber-optic-based biosensors.

Antibodies can be produced against bacteria, against complex carbohydrates, and even against smaller organic molecules that may cause cancer. To Vo-Dinh's group, the possibilities for applications of immunosensors seemed almost limitless. Indeed the possible uses for biosensors are limited only by our imagination. After all, there are many different ways to combine chemistry, physics, and biology with an electronic detector.

One type of biosensor has only five components: a biological sensing element, a transducer, a signal conditioner, a data processor, and a signal generator. The essential component must produce a signal that is related to the concentration of a specific chemical or biological substance in complex systems. This component takes advantage of the ability of a biomolecule, such as an antibody or enzyme, to specifically recognize the target substance.

In another approach to the use of immunosensors, microspheres of different sizes are labeled with antibodies that bind to different bacteria; thus, microspheres of one size have one particular antibody and microspheres of another size have a different antibody. The sizes of the microspheres are identified by their "morphological resonances" (shape-based light emissions when excited by a laser), and the bacteria that become bound are detected by the color of fluorescent dye with which they are stained. In a 1995 paper, Bill Whitten of ORNL's Chemical and Analytical Sciences Division suggests that up to 100 different types of bacteria can be identified simultaneously because the stained bacteria all would fluoresce at one wavelength of light and the diameters of the spheres could be illuminated at another wavelength. Although all the spheres fluoresce when excited by one wavelength, the morphological resonances, which look like saw teeth superimposed on a fluorescence emission spectrum, can distinguish among diameters of many different-sized spheres. This approach satisfies one of today's challenges in biotechnology: multiplex biosensors to obtain more information from one sample analysis. (See color photo on the inside back cover.)

Medical Telesensors

A chip on your fingertip may someday measure and transmit data on your body temperature. An array of chips attached to your body may provide additional information on blood pressure, oxygen level, and pulse rate. This type of medical telesensor, which is being developed at ORNL for military troops in combat zones, will report measurements of vital functions to remote recorders. The goal is to develop an array of chips to collectively monitor bodily functions. These chips may be attached at various points on a soldier using a nonirritating adhesive like that used in waterproof band-aids. These medical telesensors would send physiological data by wireless transmission to an intelligent monitor on another soldier's helmet. The monitor could alert medics if the data showed that the soldier's condition fit one of five levels of trauma. The monitor also would receive and transmit global satellite positioning data to help medics locate the wounded soldier.

Development of medical telesensors at ORNL is supported by the Defense Sciences Office of the Advanced Research Projects Agency, but the development is expected to have civilian applications. Wireless monitors attached to the skin could provide valuable information on the physiological condition of intensive-care patients in hospitals, high-risk outpatients, babies at risk of suffering sudden infant death syndrome, and police and firefighting personnel in hazardous situations.

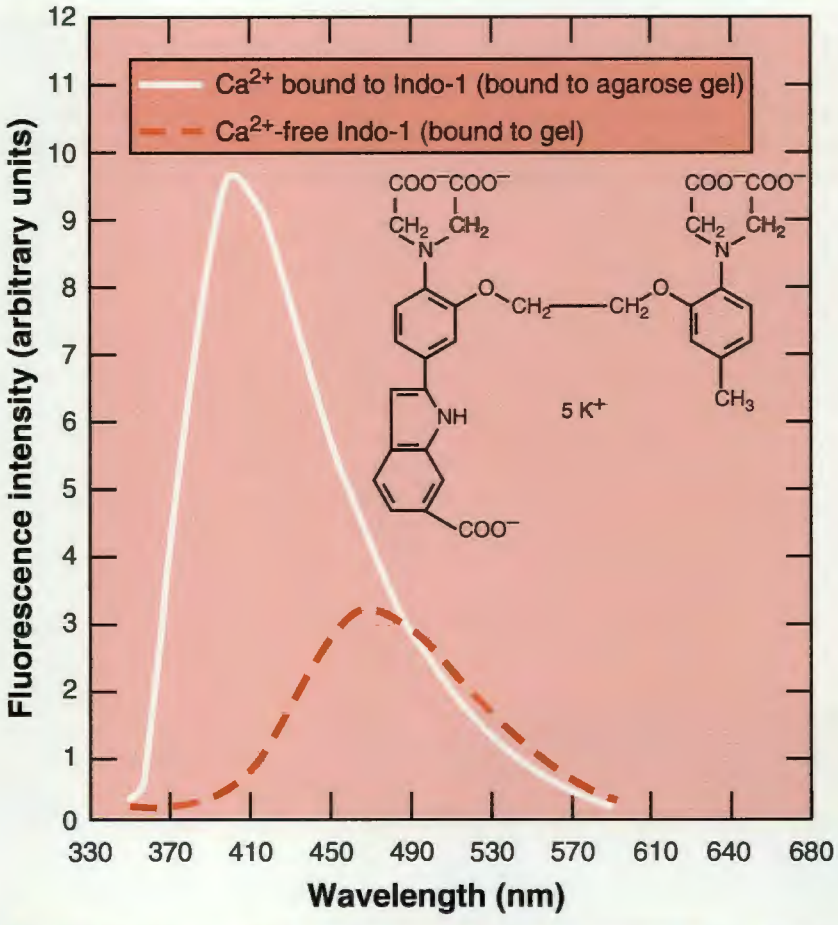
The goal is to develop an array of chips to collectively monitor bodily functions.

This "medical telesensor" chip on a fingertip can measure and transmit body temperature.

In ORNL's Life Sciences Division, Tom Ferrell has shown that a 2 × 2-millimeter (mm) silicon chip attached to the skin can measure body temperature. The chip contains a temperature sensor in an integrated circuit, a lithium thin-film battery that supplies the very low level of power required by the circuit and signal processing and transmission electronics, and an antenna that sends the data by radio signals (radio-frequency transmission) to a monitor when the chip is queried. Ferrell calls this biosensor a "medical telesensor ASIC" because it uses an application-specific integrated circuit for telemetry—automatic measurement and transmission of data from remote sources to receivers for recording and analysis.

Ferrell also expects that a chip can be developed to measure blood oxygen level. As the blood oxygen level changes, the color of hemoglobin in blood is altered. Such a chip would have a light source and light detector that could measure changes in the color of hemoglobin transmitted when it is illuminated by light. The results are reported by wireless telemetry.

Blood pressure and pulse rate may be measured by chips designed to detect pressure changes. Indeed, Jeff Muhs and Steve Allison, both of ORNL's Engineering Technology Division, are working with optical fibers made of silicone to take advantage of the unique properties of this substance. Unlike a glass fiber, a silicone fiber is flexible—it can be squeezed or stretched, and the amount of compression or expansion can be measured by changes in light



ORNL has developed a sensitive detector for monitoring changes in the body's concentrations of calcium ions. It may be useful in diagnosing disease or exposure to chemical warfare agents. This biosensor consists of an optical fiber to which is attached a synthesized hybrid molecule. One half of the hybrid molecule binds calcium ions and the other half fluoresces when calcium ions are bound to the molecule.

transmission through the fiber. Thus, silicone fibers embedded in roads can be used to weigh trucks. If a silicone fiber on a chip can sense pressure at various positions in the body, it may be used for monitoring blood pressure, pulse rate, breathing (chest expansion), knee bending during physical rehabilitation, and foot pressure distribution.

Aging, diseases such as diabetes and Alzheimer's, and chemical warfare agents cause changes in metal ion concentrations in the body. If these changes could be detected and measured, the information could provide clues about changes in disease states and exposure to toxins. Tuan Vo-Dinh and his coworkers have developed a biosensor using a glass optical fiber and a hybrid molecule he synthesized. One half of the hybrid molecule binds calcium ions and the other half fluoresces when calcium ions are bound to the molecule. By attaching this molecule to the end of a very small diameter optical fiber, Vo-Dinh measured the concentration of calcium ions in a solution. He plans to make a similar measurement within a single living cell!

Microcantilevers

An interesting alternative to the optical fiber is the microcantilever, which measures the presence of substances by nonoptical methods. It can act as a physical, chemical, or biological sensor by detecting changes in cantilever bending or vibrational frequency. Think of a diving board that wiggles up and down at a regular interval. This wiggling changes when someone steps on the board. Microcantilevers are a million times smaller but molecules adsorbed on a microcantilever cause vibrational frequency changes. Viscosity, density, and flow rate can also be measured by detecting the changes in vibrational frequency. Another way of detecting molecular adsorption is by measuring curling of the cantilever due to adsorption stress on just one side of the cantilever. Depending on the nature of chemical bonding of the molecule, the curling can be up or down. For example, if the microcantilever is bimetallic, just like the thermostat at home but a million times smaller, a temperature change as small as a millionth of a degree can be measured. There is much to learn about the basic mechanisms involved.

The microcantilever is ordinarily constructed of a silicon plank 100 micrometers (μm) long, 30 μm wide, and 3 to 4 μm thick (these dimensions are only approximate, and other geometries are sometimes used). When molecules are added to its surface, the extent to which the plank bends can be measured accurately by bouncing a light beam off the surface and measuring the extent to which the light beam is deflected. The vibrational frequency can be induced by piezoelectric transducers and measured with the same laser beam that measured the deflection because it generates an alternating current in the detector.

Temperature is measured by coating the silicon surface with gold or aluminum, which expands at a different rate than silicon. Because the difference

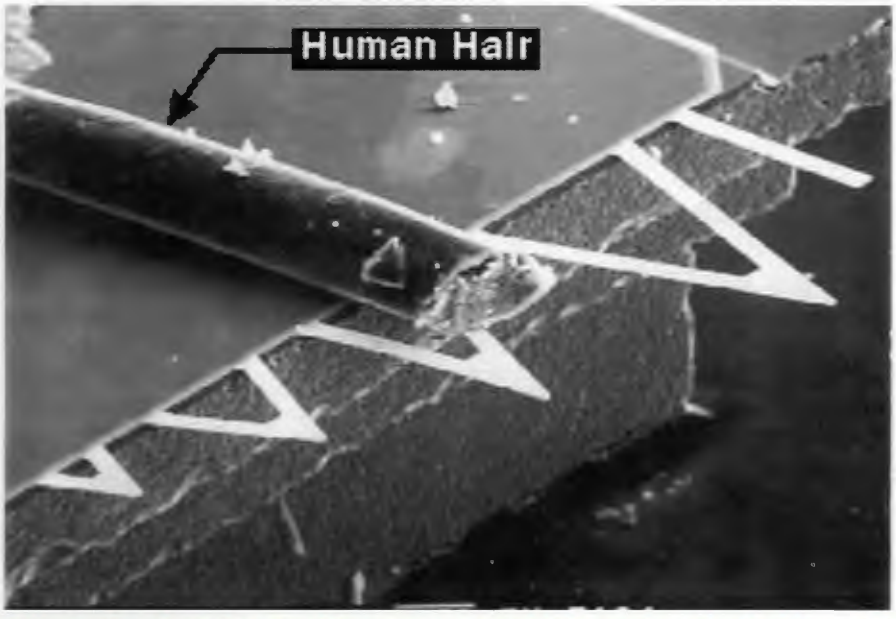
in heat expansion between silicon and gold affects bending of the microcantilever, temperature changes of a millionth of a degree can be measured. Chemical reactions generate heat, so this device can be used as a microcalorimeter to measure the heat of an enzyme-catalyzed reaction or a chemical reaction in a reaction volume of one microliter (1 μl).

Yet another mechanism of response was employed to measure proteins in solution. Antibodies were covalently attached to the silicon surface of a cantilever in such a way that the stresses induced in the antibody when it reacted with its antigen were detected. Detection of biological warfare agents or bacteria and viruses in the hospital laboratory should be expedited with this stressed antibody technique. Additional experiments are under way to demonstrate the usefulness of the microcantilever as a biosensor. Because of the small size and versatility of the microcantilever, arrays of sensors can be fabricated on a single chip to conceptually mimic the five sensory facilities: sight, hearing, smell, taste, and touch. ORNL researchers Thomas Thundat, Bruce Warmack, Eric Wachter, Patrick Oden, and Panos Datskos received a 1996 R&D 100 Award for development of the microcantilever.

Detecting Cancer and Health Abnormalities

Another type of biosensor uses sophisticated technology to detect a specific trait or abnormality in a living organism. ORNL researchers have invented several biosensors of this type.

Of these biosensors, the most publicized is the optical biopsy sensor developed by Tuan Vo-Dinh in collaboration with medical researchers at Thompson Cancer Survival Center in Knoxville. This sensor can tell whether a tumor in the esophagus is cancerous or benign. In the past, determining accurately whether a patient has cancer of the esophagus has required surgical biopsy. However, our laser-based fluorescence method has eliminated the need for biopsy, reducing pain and recovery time for patients.



Schematic of a microcantilever sensor, which can be adapted to detect physical, chemical, or biological activity.

Here's how it works. Laser light of the appropriate wavelength is directed to the inner surface of the esophagus by means of a fiber-optic device that is swallowed by the patient. The epithelial cells and tissue inside the esophagus fluoresce when excited by the laser light. When the esophagus interior is illuminated with blue light [410 nanometers (nm)], the normal tissue emits light at wavelengths different from those emitted by the cancer cells. Thanks to software developed by Vo-Dinh and colleagues, the spectral properties of the light at wavelengths ranging from 400 to 700 nm can be analyzed at various positions in the esophagus. Emissions from normal cells and cancer cells can be distinguished quite accurately; the difference is expressed as the differential normalized fluorescence index. Tests on more than 200 patients show that, compared with the results of surgical biopsies, laser fluorescence diagnosis is accurate in over 98% of the cases.

Another biosensor from Vo-Dinh's laboratory provides a way to monitor the status of diabetes without using blood samples. In this case, light is used to illuminate the eyeball and stimulate certain substances, including proteins, to emit fluorescent light. This fluorescence changes in intensity and wavelength when the distribution and status of proteins in the eye change. This truly noninvasive method depends on a relatively new development for selecting the wavelength of light for illumination. Instead of prisms or gratings to refract the light into different wavelengths, a device called the acousto-optic tunable filter (AOTF) is used. One AOTF selects the wavelength of light to shine on the eyeball and another selects the wavelength of fluorescent light emitted from the eyeball. Both AOTF wavelengths are scanned simultaneously using the synchronous luminescence technique developed previously for environmental screening. The AOTFs, which are manipulated

with a radio-frequency signal, can scan the entire visible spectrum and portions of the ultraviolet and infrared spectra in milliseconds to select the appropriate wavelengths to use to illuminate the eyeball. They can also select the correct wavelength to use to read the fluorescence signal from the patient's eye instantaneously. In this way many spectral scans can be taken and averaged in a computer to obtain the accuracy required to measure the status and changes in the eye proteins of diabetics. Vo-Dinh's group is also studying ways to apply optical techniques to detect skin, cervical, and colon cancers.

Bioreporters

Yet another example of a biosensor is based on detection of light emitted by a specially engineered microorganism that is involved in bioremediation. However, in this case the light originates from a particular protein that has been installed in certain bacteria by modern molecular genetic methods. In one case, the gene for luciferase is placed in the operon (a sequence of genes that specify enzymes that carry out a related series of metabolic steps) that is responsible for degrading unwanted chemicals such as toluene, an organic solvent. When the bacteria are metabolizing the toluene, the genetic control mechanism also turns on the synthesis of the enzyme luciferase, which produces light in the presence of oxygen. A variation on this capability was invented at ORNL to deal with situations in which bacteria degrade an organic solvent under conditions of very limited oxygen. In this case, a "green fluorescent protein," which emits green light (with a wavelength of 509 nm) when excited by blue light (395 nm), is installed in the operon. No oxygen is required for the light emission. Again, as the toluene is metabolized by the enzymes synthesized for that activity, the green fluorescent protein is also produced. Because it is active, it can be monitored by remote light activation and spectral emission analysis.

Bob Burlage of the Environmental Science Division has been installing these proteins and working with Vo-Dinh to create an optical biosensor to analyze the emitted light. Also, Michael Simpson of the Instrumentation and Controls Division Division is collaborating with Gary Sayler of UTK to produce a "critters on a chip" technology in which light sensors pick up and transmit information from chip bacteria that glow in the presence of trace levels of poisons, explosives, or pollutants. These types of biosensors are useful for monitoring efforts to clean up industrial spills because these light-emitting bacteria can "report" continuously the progress of biodegradation. Such bioreporters have proven successful using trichloroethylene, toluene, and various petroleum products in laboratory tests. They are now being tested on a much larger scale using a lysimeter.

In the late 1980s, a group at the Oak Ridge Y-12 Plant designed and built a set of 18 lysimeters. Each

Laser fluorescence diagnosis is accurate in over 98% of the cases.

Tuan Vo-Dinh of ORNL (left) and Bergein Overholt and Masoud Panjehpour, both of Thompson Cancer Survival Center of Knoxville, have developed a new laser technique for nonsurgically determining whether tumors in the esophagus are cancerous or benign.

lysimeter is a cylinder 2.4 meters (8 feet) in diameter and 3 to 3.6 meters (10 to 12 feet) deep that is filled with soil and monitored for the presence of a variety of substances. The current experiment in which Sayler is collaborating with Burlage employs several of these cylinders so that they can observe the effectiveness of genetically engineered bacteria in degrading naphthalene.

John Hiller of the Oak Ridge Centers for Manufacturing Technology proposes to adapt a luminescence spectrometer, which was devised to measure uranium concentrations in groundwater, to detect bacteria and other organisms that may contaminate drinking water. Such organisms release small amounts of ATP (adensosine triphosphate, the universal bio-energy chemical), which, in the presence of oxygen, is converted into light energy by luciferase, which will be added to the assay system to detect the ATP. The luminescence spectrometer would detect and measure the intensity of light emitted by luciferase to determine the concentration of contaminants in water.

Miniaturized Devices

Another class of biosensors uses various techniques to turn a biological system into a tiny electronic device, to analyze biological or physiological processes, or to detect and identify bacteria. Some of these techniques produce or are carried out in miniaturized devices.

The site for photosynthesis in a green leaf contains a complex set of enzymes and proteins that capture light energy and convert carbon dioxide into compounds that help the plant grow. If a platinum salt in a certain oxidation state is supplied to one of two photosynthetic systems in plant chloroplasts, one photosynthetic reaction system will use light energy to provide electrons that will reduce platinum to the metal form. The metal is deposited on the photosystem complex to form a tiny platinum center that can be employed in sophisticated diode-based microelectronics for measurements at extremely high sensitivity, resolution, and speed. Such a biomolecular optoelectronic sensor has been demonstrated by Eli Greenbaum, James Lee, Ida Lee, and Steve Blankinship, all of ORNL's Chemical Technology Division.

ORNL researchers have made dramatic progress in miniaturizating clinical and chemical laboratories—another aspect of our biosensor work. One useful miniature device is an infrared microspectrometer the size of a sugar cube, constructed by Slo Rajic and Chuck Egert, both of ORNL's Engineering Technology Division. Carved out of a solid block of plastic, the device measures 1.5 centimeters on a side and has no moving parts. It can be used for blood chemistry analysis, gasoline octane analysis, environmental monitoring, industrial process control, aircraft corrosion monitoring, and detection of chemical warfare agents. The plastic device uses a light source to excite certain types of

Mike Simpson shows the newly developed "critters on a chip" in which bioluminescent bacteria signal the presence of pollutants.

compounds in gases, liquids, and solids. These excited compounds give off infrared light of various wavelengths. Because the microspectrometer is precisely manufactured using single-point diamond turning, it can gather up the emitted light and channel it into an optical fiber for analysis. The measured emissions wavelengths are fed into a microchip, which identifies and determines the concentrations of chemicals in a sample. The device is inexpensive and performs well in different customized uses.

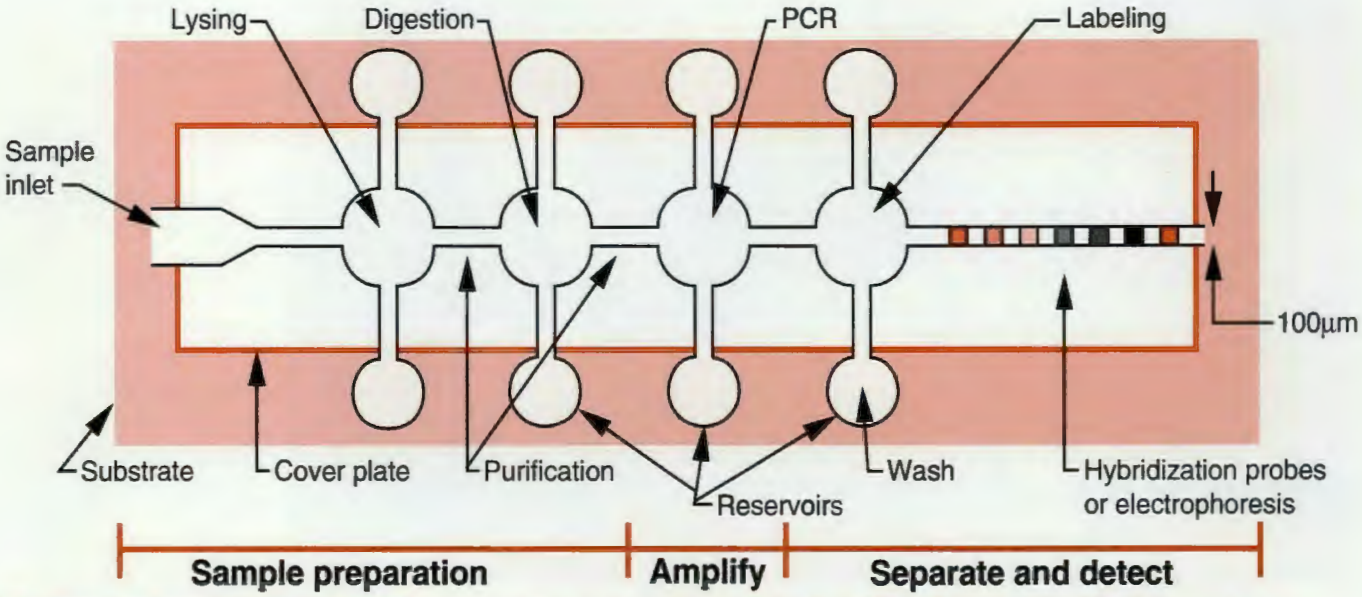
ORNL's best known miniaturization feat is the "lab on a chip." In 1996 this miniaturized chemical laboratory received a *Discover* magazine innovation award and an R&D 100 Award from *R&D* magazine. The chip consists of 50- to 100-mm channels that are etched into the surface of a microscope slide. When reagents are mixed together and forced to migrate down these channels by differences in electrical potential, reaction rates can be measured and chemicals can be separated. Laser-induced fluorescence monitors the reaction's progress along the channel and measures concentrations of the separated products.

Mike Ramsey, Steve Jacobson, and colleagues in ORNL's Chemical and Analytical Sciences Division have demonstrated that these miniaturized devices are often more accurate than standard laboratory procedures. They have separated mixtures by performing chromatography in these channels, demonstrated the separation of products of digestion of DNA with restriction enzymes, and demonstrated enzyme-catalyzed reactions. They are adapting such miniaturized devices for many clinical and military applications.

Biosensors and DNA Analysis

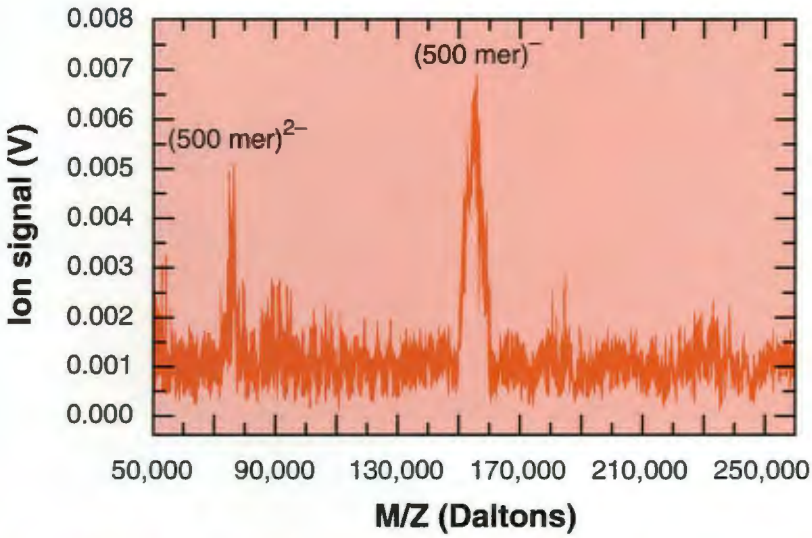
DNA can be used to identify organisms ranging from humans to bacteria and viruses. The identification consists of reading the sequence of the DNA letters (A, G, C, and T) that compose the alphabet used to describe the bases attached to the deoxyribose phosphate polymer that forms the backbone of the DNA helix. The bases join two strands of this polymer to

The infrared microspectrometer developed at ORNL can be used for blood chemistry analysis, gasoline octane analysis, environmental monitoring, industrial process control, aircraft corrosion monitoring, and detection of chemical warfare agents. *Photo by Tom Cerniglio.*



Conceptional design of DNA processing and analysis chip that Mike Ramsey and Bob Foote are developing.

DNA can be used to identify organisms ranging from humans to bacteria and viruses.



Laser desorption mass spectrometry has been used at ORNL to detect double-stranded and single-stranded DNA and to determine the sequence of bases in single-stranded DNA.

form a spiral staircase, where the bases and the hydrogen bonds that join them are the steps on the stairs. Just as in the English alphabet, the letters are combined in various groupings and sequences to form words, sentences and paragraphs that organize information in a manner that can be read and utilized. Therefore, much effort has gone into ways to read the sequence of the four letters of the DNA alphabet, and rather rudimentary methods have been developed that are reliable and useful. Using methods to form short sequences from the DNA of interest, DNA fragments are produced that have one of the letters at their end and that differ according to their sizes. As a result, DNAs containing 400 to 600 letters can be sequenced accurately. However, many hours are required to prepare the fragments and separate them by size (using gel electrophoresis). Using this method, the sequences of millions of DNA letters have been determined, enabling the identification of the site of a genetic mutation that causes such diseases as sickle cell anemia, Huntington's disease, fragile X syndrome (a serious type of mental retardation), and several hundred other inherited diseases or traits. Furthermore, by combining sequences obtained ~400 at a time, the entire genome of a yeast was determined in 1996, a major accomplishment that led to the identification of an entire new group of genes that had not been recognized before. Many labs that were involved in the sequencing effort have now switched their attention to studying these new genes to learn of their function and significance. The Human Genome Project, which is sponsored by DOE and the National Institutes of Health, plans to go well beyond yeast and determine the sequence of all DNA letters in the human genome. Undoubtedly, this information will lead to the discovery of many new human genes and a more sophisticated understanding of our health and disease states. More details may be found in the Primer for Molecular Genetics on the DOE World Wide Web site http://www.ornl.gov/TechResources/Human_Genome/publicat/primer/intro.html.

Because the methods used to sequence the yeast DNA required dozens of labs in Europe and the United States to work together for several years to determine the total sequence, new and faster methods to read the DNA sequence would clearly be advantageous. If the methods were faster and less expensive, DNA sequence information would be as common as your blood type and would be much more informative. You could determine whether you are a carrier of a disease gene known to exist in your family, whether blood at a crime scene was that of the arrested suspect, or whether a biowarfare bacterium was descending on a battlefield. In some of these uses, the need to know the DNA sequence may be urgent. Because the current methods are not fast enough to satisfy such needs, many laboratories, including ORNL, are developing faster methods. In addition to sequence information, methods are also being developed to identify the site where a DNA sequence has been modified.

When a chemical reacts with DNA in the cell nucleus, possibly causing damage, a chemical compound called an adduct forms from the addition of the two species. ORNL researchers led by Bob Hettich and Michelle Buchanan in ORNL's Chemical and Analytical Sciences Division have used mass spectrometry to identify chemicals that form adducts with DNA. They have determined both the chemical identity of the adduct and the specific DNA site at which it occurs.

Simply speaking, DNA is like two strings of beads. One string contains beads of four different colors—red, blue, green and yellow—arranged in a particular order. The order of beads in the other string is governed by this rule: red must be paired with blue, and yellow must be paired with green. Thus, if the order of the first four beads in the first string is red, green, blue and yellow, the order of the

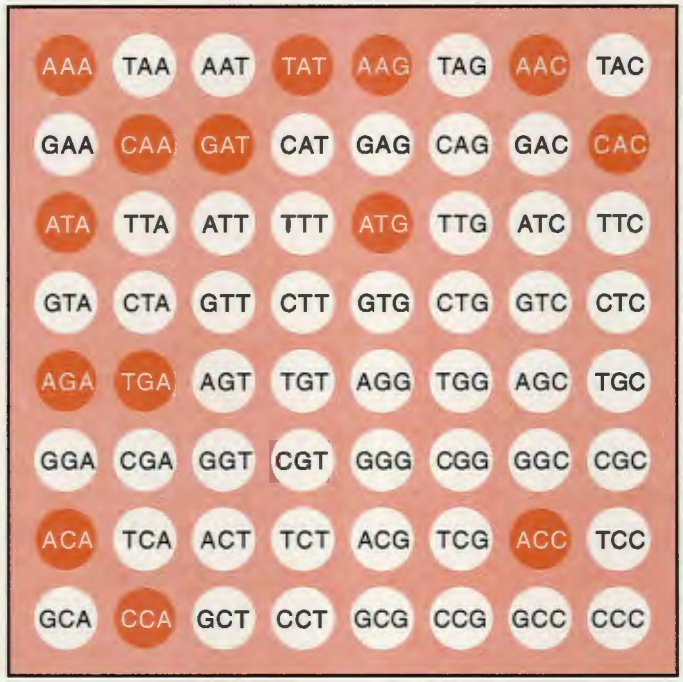
matching four in the second string is blue, yellow, red, and green. The DNA sequence consists of a string of chemical bases, known as A, T, C, and G, and the DNA molecule is folded, looped and coiled in various ways. For double-stranded DNA, the rule is that A on one strand must pair with T on the other, and C must pair with G.

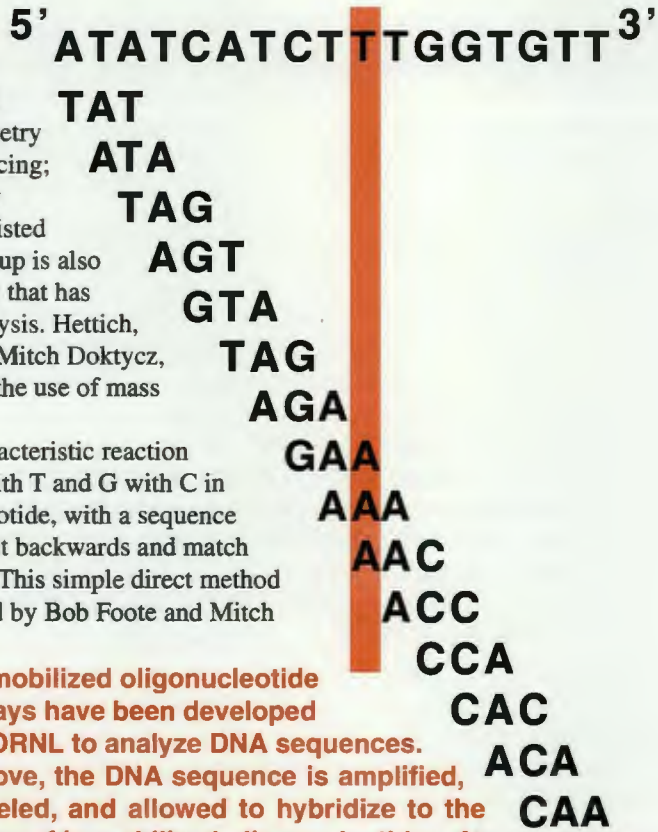
Over the past four years ORNL's mass spectrometry groups have shown that DNA fragments of about 50 to 75 nucleotides (bases) can be sequenced to obtain the order of the A, G, C, and T letters. Because mass spectrometry accomplishes the sequence determination in less than a second, this speed supersedes that of gel electrophoresis by orders of magnitude. However, the gel method can do 400 to 600 letters on 50 samples at a time and is not in danger of being replaced yet. Other ways of characterizing DNA consist of determining the sizes of fragments produced by restriction endonucleases, enzymes that cut DNA when they find a specific sequence of letters. A physicist friend of mine calls these enzymes magic scissors because they not only cut the DNA but do so reliably at a sequence site that is specific to each of the restriction enzymes, of which there are over 400. The pattern of sizes of the DNA fragments produced by these magic scissors can be unique to the DNA from a biological species or even an individual.

Gel electrophoresis is the usual method of classifying the size pattern but mass spectrometry can do that very well, and again in much shorter time. This application of mas spectrometry to DNA characterization will come much sooner than sequencing; indeed, one of the ORNL labs held the size record in 1996 by characterizing a 500-base fragment of DNA using matrix-assisted laser desorption ionization mass spectrometry. An ORNL group is also pursuing use of an electrospray method of mass spectrometry that has advantages such as simplicity of sample preparation and analysis. Hettich, Buchanan, Winston Chen, Scott McLuckey, Greg Hurst, and Mitch Doktycz, along with Rick Woychik, have made major contributions to the use of mass spectrometry for DNA analysis.

Besides mass spectrometry, other methods exploit the characteristic reaction between two strands of DNA. Again, recalling that A pairs with T and G with C in opposite strands, a short strand of DNA, called an oligonucleotide, with a sequence of 5'-AGCTTTAACC will bind to 5'-GGTTAAAGCT (read it backwards and match it to the previous letter series) but not to 5'-GGTTAGGACT. This simple direct method of selecting DNA of complementary sequences has been used by Bob Foote and Mitch Doktycz, both of the Life Sciences Division.

They synthesized a number of different DNA sequences directly on a glass surface and showed that the complementary sequence of the free DNA could be obtained by determining to which of the sequences it would bind. The free DNA was labeled with phosphorus-32 so that the pattern could be observed by autoradiography; in other words the glass was placed against a photographic film for a time, after which it was developed to determine the locations of the radioactive spots. In this case the





Immobilized oligonucleotide arrays have been developed at ORNL to analyze DNA sequences. Above, the DNA sequence is amplified, labeled, and allowed to hybridize to the array of immobilized oligonucleotides. At right, the DNA sequence is deciphered by overlapping the hybridizing probes of similar sequence. The technique has applications in medicine, forensics, agriculture, and environmental bioremediation.

immobile DNAs contained only eight bases and thus could determine the sequence of only eight bases in the free DNA. Longer immobile DNAs would give longer reads in the free DNA. This technique is often called sequencing by hybridization (SBH).

Interestingly, Doktycz and his colleagues have shown that the rules "A binds to T" and "G binds to C" are not completely reliable; mismatches can and do occur in hybridization experiments. If the mismatch is at or near the end of the DNA strand, the rules are more likely to be broken than if the mismatch is at an interior position. The ORNL researchers developed a number of rules that predict when a mismatch is likely to occur. If these rules are ignored in an interpretation of binding patterns, the reader could be misled as to the true sequence of the DNAs of interest. ORNL is collaborating with three other organizations that are developing this method of sequencing by hybridization. Because hybridization methods are so much faster than gel electrophoresis for sequence determination, it is likely that hybridization may become the method of choice for many applications for DNA fingerprinting. Ken Beattie, who recently joined the Life Sciences Division, brings his international experience with SBH to ORNL. He has proposed use of a flow-through SBH chip for multiple applications—genome sequencing, assessing the effectiveness of bioremediation, and evaluating the quality of agricultural microorganisms, plants, and animals, for examples.

The work of Foote and Doktycz used phosphorus-32 to label the DNA fragments. Other ways of labeling DNA are also employed. Currently, the most used are fluorescent labels, but Bruce Jacobson and Heinrich Arlinghaus of Atom Sciences, Inc. have been exploring the use of enriched stable isotopes of tin and rare earth elements to label DNA fragments for sequencing by hybridization.

When a tin-labeled DNA segment hybridizes to its complementary DNA sequence in an array of short DNAs on a glass or nylon surface, the segment's location is determined by a laser-induced resonance ionization microprobe, which uses a laser beam to dissociate all atoms within several hundred monolayers of the sample surface. Those atoms that appear as ions are discarded; however, the neutral atoms of a selected element (in this case, tin) are converted to ions by illuminating them with a resonance laser that is tuned to the quantum energy of that element's electrons, causing only that element's atoms to be ionized. The ions produced in this way are introduced into a mass spectrometer, which separates them into isotopes according to differences in mass and measures the concentration of each tin isotope.

By working in a clean room, researchers using this highly selective and extremely sensitive technique have located DNAs that were hybridized to the complementary sequence with little background from either environmental tin or tin from noncomplementary tin-labeled DNAs, detectable on noncomplementary sequences. Because 10 stable isotopes of tin exist, it is possible to use all 10 labels at one time to "multiplex" the process. Ways of labeling specific DNA strands or fragments 8 to 20 bases long with tin enriched in a specific isotope have been devised by Rick Sachleben, Gil Brown, and Fred Sloop, all of ORNL's Chemical and Analytical Sciences Division. They have also developed a way to label specific DNAs with individual enriched stable isotopes of several rare earths, enabling the use of 20 or more labels at one time. Use of mass spectrometric detection of the stable isotopes increases the multiplexing possibilities greatly, allowing much more information to be obtained than is possible using only four fluorescent labels at a time. It is also an improvement because it overcomes the problem of the general fluorescent background when using nylon. Because phosphorus-32 decays with a half-life of about 14 days, the tin labeling approach also looks attractive. Stable isotope labels may someday play a significant role in future DNA analyses. Imagine the SBH chip being interrogated by 10 or 20 stable isotope-labeled DNAs at one time. The laser atomization and mass spectrometry would identify each label in one pass, making the process much more efficient in time and materials. In addition, the laser atomization method would be accomplished in a few minutes, again much faster than present gel electrophoresis.

Another hybridization method being developed at Oak Ridge uses a process called surface-enhanced Raman spectroscopy (SERS). Hybridized DNA is transferred from the nylon membrane to a glass strip coated with tiny silver spheres. The dye labels attached to the DNA bases have unique Raman infrared spectra, but the normally weak Raman lines are greatly enhanced by the presence of the silver spheres. This enhancement allows DNA bases to be detected at sufficient sensitivity to be useful for DNA sequencing studies. Earlier, Vo-Dinh, Mayo Uziel, and Alan Morrison, using SERS, detected a fluorescent carcinogen on DNA. Then, Dan Jacobson and Tom Ferrell demonstrated the power of SERS for DNA sequence analysis. Recently, Vo-Dinh, Kelly Houck, and David Stokes have developed it into a highly sensitive method that received an R&D 100 Award in 1996.

Yet another approach to DNA analysis taken by Vo-Dinh, in collaboration with members of the I&C Division, is to design an array of charge-coupled device (CCD) detectors and attach to their surface specific sequences of DNA. Free DNA strands are labeled with fluorescent molecules and hybridized to the bound DNA.

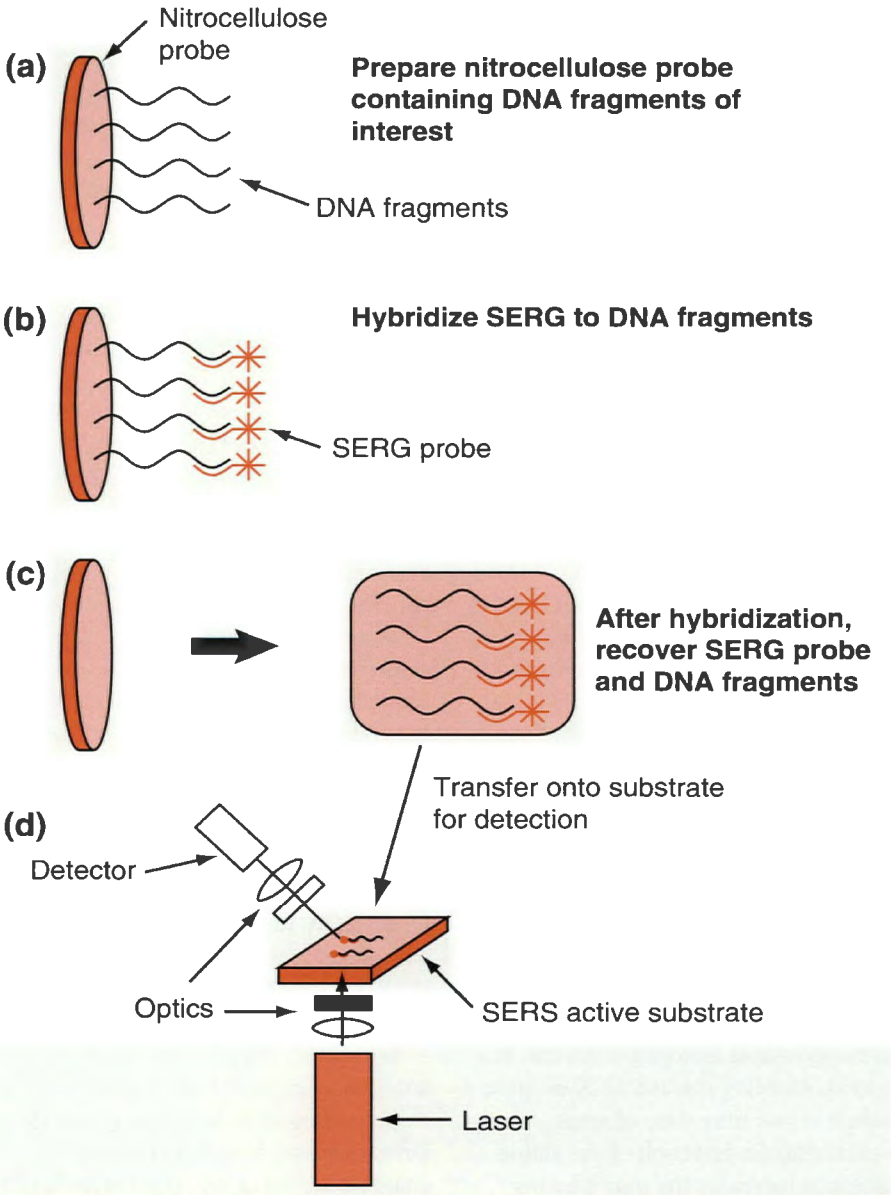
When illuminated with laser light of the correct wavelength, the fluorescent tags of the hybridized DNA emit light signals that are detected by the individual CCD detectors behind each DNA site.

Because each of the CCD pixels has a different but known short DNA sequence bound to it, the sequence of the piece of the longer DNA strand that hybridizes with the short strand can be identified. By assembling all the information from the pixels, a larger portion of the DNA sequence is obtained. Because bacteria have unique DNA sequences, these hybridization methods hold great promise as the basis for new techniques to rapidly analyze DNA, characterize its source, and identify bacteria.

DNA analysis of a different type depends on magic scissor enzymes, as described previously. For example, the enzyme EcoRI cuts DNA when 5'-GAATTC is on one strand of the DNA and its complement 5'-CTTAAG is on the other; the cut separates the G from the A in both strands. This sequence occurs rather frequently in DNA, so the enzyme produces a large number of fragments. The enzyme Not I requires eight nucleotides in the sequence 5'-GCGGCCGC and its complement 5'GCGGCCGC; such a sequence occurs infrequently, so fewer DNA fragments are produced, and they are generally much longer than those fragments cut by EcoRI. Because of the availability of more than 400 restriction enzymes that have unique and well-known sequence requirements, the DNA fragment patterns produced by the various enzymes can be used to characterize an individual's DNA. This is the basis for DNA fingerprints obtained through separation by size of DNA fragments by gel electrophoresis. Such fingerprints are used widely for evidence in research and in judicial courts.

To determine which DNA fragments make up a fingerprint, they must be separated and identified. The "lab on a chip" developed by Mike Ramsey and colleagues has been adapted to perform such separations within a few minutes—much faster than standard gel procedures. Like microcircuits and computers operating in parallel, these chemical separations chips can be used in parallel for DNA analysis. In one application, liquids containing DNA and a restriction enzyme are injected into different chambers etched into the chip. Electric fields pump the liquids through a microscopic channel into a reaction chamber, where the enzyme cuts the DNA into pieces of different lengths. The DNA snippets are then electrically pumped to the separation channel, where they are tagged with fluorescent dyes for detection.

The DNA fragments of various sizes are sorted in a liquid containing fibrous



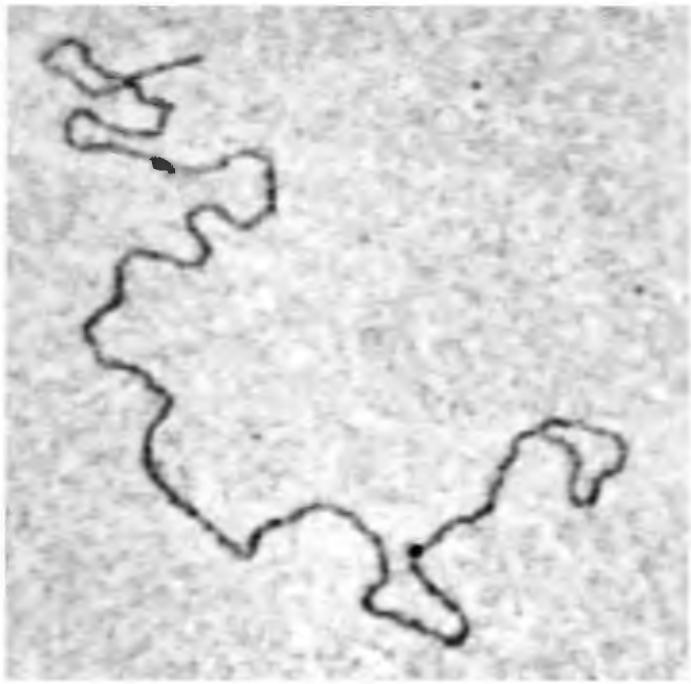
ORNL's surface-enhanced Raman gene (SERG) probes can locate free DNA molecules that have hybridized to other DNAs fixed on a surface. The technique has use in medicine, forensics, agriculture, and environmental bioremediation.

strands of a polymer. The DNA fragments get tangled with the polymer strands, which slow them down as they pass through. Small chunks of DNA find their way through the tangled web faster than the larger ones, so separation results. As the fragments are separated, they are illuminated with a laser light, causing them to fluoresce. The detected light intensities are fed to a computer, which sorts through signals from separated fragments to provide a sample analysis.

Automation and miniaturization are the two by-words in Ramsey's lab. To eliminate manual manipulation of DNA, Ramsey and his colleagues propose to build a more comprehensive chip that can prepare the DNA from a biological sample by lysing the cells, extracting the DNA, digesting it with restriction enzymes, amplifying it with the polymerase chain reaction, attaching fluorescent labels, and then obtaining the electrophoretic fingerprint. All steps would occur in a series of tiny chambers on the chip, and the results would be obtained in minutes rather than hours or days, as is the case now (see figure on p. 60).

ORNL has developed a DNA mapping and sequencing technique using atomic force microscopy (AFM) to measure the length and width of double-stranded DNA molecules. The AFM is a sensitive device that traces the surface of a material, producing a three-dimensional map. Certain viruses have circular DNA of known sizes, as characterized by various methods. Dave Allison, Doktycz, and Warmack, all in the Life Sciences Division, showed that the AFM can measure sizes of viral DNA circles.

The magic scissors enzyme, or restriction endonuclease, cuts a DNA sequence each time it occurs in the strand. But the mutant form of this enzyme simply binds to, rather than cleaves, the DNA strand. The AFM can image the resulting knot, or protein bump, formed on the DNA thread. ORNL researchers can identify where the enzyme binds to the DNA within 100 base pairs, which is a very high resolution. They've shown that the distance from one bump to the next, as imaged by the AFM, was exactly as predicted from enzyme cutting experiments analyzed by gel electrophoresis.



This atomic force microscopy image shows two knots, or "protein bumps," formed on the DNA thread. Each knot results when a mutant enzyme binds to, rather than cleaves, the DNA strand.

Through genetic engineering, other enzymes and proteins could be developed that bind to, rather than cut, particular DNA sequences. By using the AFM to view a DNA strand treated with different engineered enzymes, it may be possible to determine a certain sequence of its chemical bases, a certain map position, or a spacing of genes and other biochemical landmarks on chromosomes. Using this biosensor, ORNL researchers have shown that the AFM can characterize a DNA strand according to distances between particular restriction binding sites, eliminating the need to enzymatically cut the DNA into fragments for separation by gel electrophoresis. Because the AFM method is faster than gel electrophoresis, the genome sequencing community is already starting to employ this technique for DNA characterization and mapping.

Lipids in Bacteria and Human Fingerprints

Some bacteria can be identified by analyzing lipids and fatty acids with mass spectrometry, according to ORNL research. A lipid is a hydrocarbon compound in which the hydrogen and carbon atoms are linked in a long chain; a fatty acid is derived from a lipid. Bacteria are made of either polar or nonpolar lipids—that is, the lipids are soluble or not soluble in water depending on the ionic groups present. Using different solvents, ORNL researchers led by David White of the Environmental Sciences Division have extracted nonpolar and then polar lipids from a few dozen different types of bacteria. To identify each component of the mixture, they used gas chromatography and mass spectrometry. White has shown that each type of bacteria has an identifiable signature based on the unique chemical pattern in specific lipids. This technique could be used to identify rapidly many bacteria in the

environment or those used during biological warfare.

Another bacteria detection method being developed by Bill Whitten does not require prior extraction. He has shown that, by illuminating airborne bacteria with laser light to obtain a mass spectrum, different bacteria can be distinguished by their individual spectra. U.S. military organizations are seeking methods for identifying bacteria within five minutes to provide soldiers with enough warning about the hazard to employ effective countermeasures.

Our experience in analyzing lipids with mass spectrometry may have forensic applications. Lipids are the main components of human fingerprints. Recently, the Knoxville Police Department sought ORNL's assistance in determining why, under the same conditions, fingerprints of young children disappear readily but adult fingerprints persist for weeks. Mass spectrometry of gas chromatographic analysis of lipids collected from fingers of children under the age of 10 shows that the spectra of children's lipids differ significantly from those of adult lipids. Lipids from children contain unesterified fatty acids, which disappear into the air from fingerprints exposed to the hot Tennessee sun. However, fatty acids in adult lipids are esterified with long-chain alcohols, making them much less volatile. Michelle Buchanan worked with Art Bohanan, a crime specialist in the Knoxville Police Department, to bring this finding at ORNL to the attention of the forensic community and to help stimulate support for forensics research at ORNL (see Pete Xiques' "ORNL's War on Crime, Technically Speaking" on p. 30). Tuan Vo-Dinh and colleagues have developed computer software that can analyze the spectra of standard fingerprints very rapidly and enhance spectra of fingerprint images too weak to be read visually, making possible identification of children's fingerprints.

Anthropometry

Perhaps the most unusual of ORNL's biosensors is a new technique to measure human body surfaces. Such measurements, called anthropometry, are used by tailors, artists, and scientists. One of the finest minds in science to take a strong interest in anthropometry was Leonardo da Vinci, who drew the famous *Proportions of the Human Figure* some 500 years ago. An ORNL scientist who has moved the field forward is Judson Jones of the Computer Science and Mathematics Division. He has developed a technique using laser beams and mirrors to determine the shape of human body parts. He measures the topology of a solid surface, using amplitude-modulated laser radar, which measures arc lengths along complex and often inaccessible body contours. Because laser radar measures the phase and amplitude of a reflected, modulated laser beam, only one optical path is required between the sensor and the subject. Multiple images are combined by integrating information from different virtual viewpoints, any number of which can be created with strategically positioned mirrors. Arc lengths along arbitrary contours, surface areas, and volume estimates all become possible. The accuracy of the measurements is within 1 mm. Because creating "clothes that fit" may be accomplished using a single camera with several mirrors, a blue jeans manufacturer has shown interest in this methodology.

Oak Ridge scientists have been developing biosensors and bioreporters steadily for almost ten years. Now that the medical, military, and industrial communities are expressing more interest and providing more support, we can expect an accelerated pace in new developments to use or evaluate living organisms, including bacteria, to gain valuable information about our bodies and the environment. ornl

An ORNL technique using laser beams and mirrors can determine the shapes of human body parts. Its accuracy could facilitate the creation of clothes that fit.

BIOGRAPHICAL Sketch

K. Bruce Jacobson is deputy director of ORNL's Center for Biotechnology. He received his B.S. degree in chemistry from St. Bonaventure College. After serving two years in the U.S. Army, he earned his Ph.D. degree from Johns Hopkins University. Following a postdoctoral appointment at the California Institute of Technology, he became a staff member of the Biology Division at ORNL in 1958. He holds an additional appointment as adjunct professor in the University of Tennessee–Oak Ridge Graduate School of Biomedical Sciences. His research interests include the development of new technologies for DNA sequencing, the mechanism of enzyme action, the structure-function relationships for transfer RNA, pteridine metabolism, and biochemical genetics. Currently, he is a staff researcher in ORNL's Life Sciences Division.

BaP detector using antibodies ..... Tuan Vo-Dinh

Biological threat detector using optical spectra ..... Bill Whitten

Medical telesensor ASIC ..... Tom Ferrell

Pressure sensor using silicone fiber ..... Jeff Muhs,
..... Steve Allison

Calcium ion detector ..... Tuan Vo-Dinh

Microcantilevers using mass and vibrational frequency ..... Thomas Thundat,
..... Bruce Warmack,
..... Eric Wachter

Optical biopsy sensor for cancer detection ..... Tuan Vo-Dinh

Diabetes monitor using protein fluorescence ..... Tuan Vo-Dinh

Bacteria with luciferase that eat toluene ..... Robert Burlage,
..... Larry Simpson,
..... Tuan Vo-Dinh

Biosensor/Probe	Principal Investigator(s)
Bacteria with green fluorescent protein that eat toluene	Robert Burlage, Larry Simpson, Tuan Vo-Dinh
Platinized chloroplasts	Eli Greenbaum
Microspectrometer	Slo Rajic, Chuck Egert
Lab on a chip	Mike Ramsey, Steve Jacobson
DNA analysis by mass spectrometry	Michelle Buchanan, Winston Chen, Mitch Doktycz, Greg Hurst, Scott McLuckey
DNA analysis: in situ synthesis	Bob Foote, Mitch Doktycz Ken Beattie
DNA analysis: labeling with tin isotopes	Bruce Jacobson
DNA analysis: surface-enhanced Raman labels	Tuan Vo-Dinh, Kelly Houck, David Stokes
DNA analysis: CCD pixels and fluorescence	Tuan Vo-Dinh
Genome mapping with atomic force microscopy	Dave Allison, Mitch Doktycz, Bruce Warmack
Lipid signatures of bacteria	David White
Mass spectral signatures of bacteria	Bill Whitten
Lipid fingerprints of children	Michelle Buchanan
Anthropometry	Judson Jones

Hybrid Lighting: Illuminating Our Future

By Michael R. Cates

In "scriptori" of the Middle Ages, monks sat beneath open windows in the monastery and meticulously copied manuscripts all day long, dipping their quills for the last time when the sun sank beneath the horizon. The natural light of day made it possible to reproduce the intricate details of their work—and allowed their eyes to survive the nearly timeless daily ordeal. So it has been throughout all of human history: to see clearly, daylight was needed. Torches, bonfires, candles, oil lamps, and the like have enabled people to see well enough to perform routine tasks; but those forms of artificial light were a burden to visual acuity and long-term eye use. Only the introduction of electric lighting, barely a century ago, posed a serious challenge to the primacy of the traditional pattern of daylight and darkness. Today, on the verge of entering a new millennium, we now live almost every waking hour in a world of artificial light. ❦ The modern world is flooded with extra light. In all developed and developing countries, the vast majority of the population performs its daily work in enclosed structures equipped with lighting systems. Many people sit at desks, spending hour after hour reading, writing, filing, and studying. We have come to expect an abundance of light because the tasks of our technological age require greater perception of detail and longer times for high-resolution viewing. As a result, it is common to see rooms in homes and businesses lit so well and so uniformly that small print can be read in any corner. Many offices today have both bright ceiling fixtures and high-intensity lamps on the desks.

In the United States alone our electric lighting bill is about $100 million a day. Lighting uses 25% of all our electricity. Because of the demand for extra illumination, our nation's use of artificial lighting, paradoxically, peaks near 40% at the time of day when the sun is highest and natural light is the most abundant, as shown in the graphs on this page.

Lighting costs money—more than most people realize. The costs are not just simply the prices of fixtures, replacement lighting elements, and the electricity to operate them. We must also pay the price for artificial lighting's inefficiency—namely, its production of heat. About 10% of our cooling and ventilation costs result from clearing away the heat generated from lighting. As the use of artificial illumination has grown more extensive and necessary, numerous efforts have been made to reduce cost, increase efficiency, and improve quality. Significant improvements that have resulted over the years include extensive use of fluorescent fixtures; halogen, sodium, and mercury vapor elements; and automatic turn-on and turn-off systems. Compared with standard incandescent bulbs, these improvements have been major; nevertheless, the world's light bill will continue to rise considering that the amount of office floor space is expected to double worldwide by 2020.

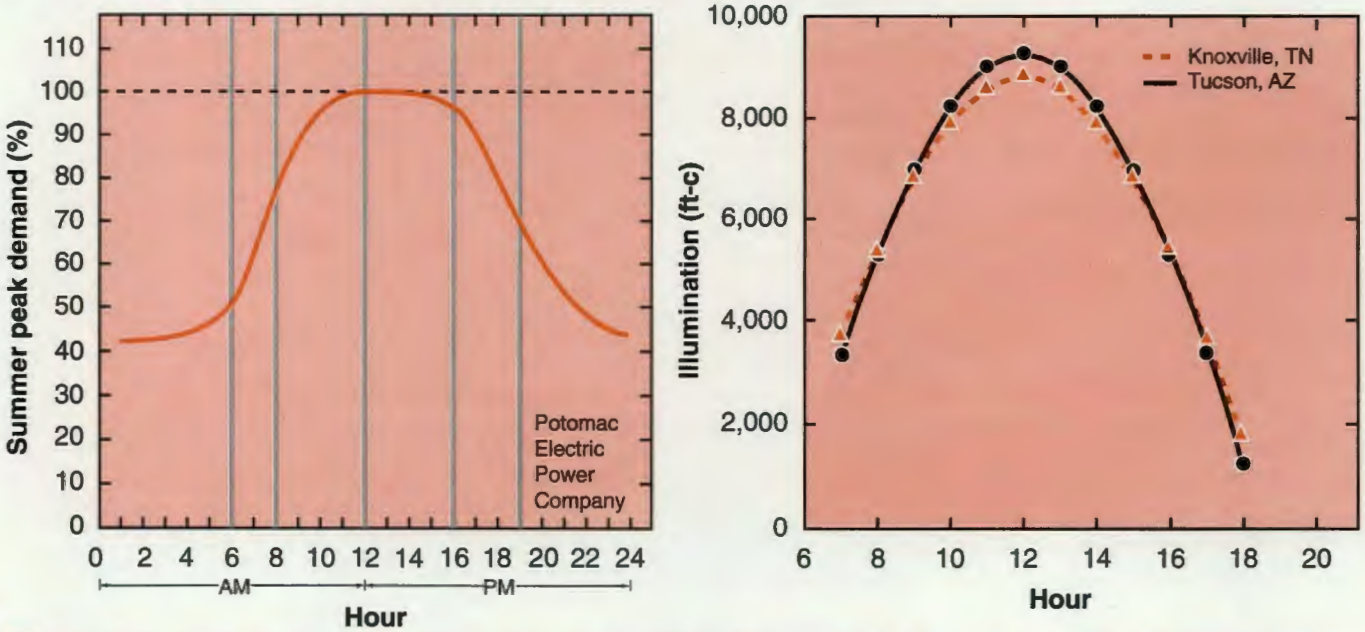
For many years the DOE has been aware of the national energy problems associated with lighting. So DOE has sponsored programs to develop and evaluate improved systems. One obvious way to reduce energy use for lighting rooms is to supplement artificial light with natural light. In these programs, based on available technology and practical cost consideration, emphasis has been placed on windows and associated devices to optimize use of light passing through windows. The idea of supplementing artificial light with natural light clearly is a useful step; however, the proper course would be perhaps a reversal of emphasis: to supplement natural light with artificial. Use of artificial light to add to daylight is the fundamental idea behind a system we call hybrid lighting.

What is Hybrid Lighting?

Picture a room with windows. Let the sun shine in. Sensors determine where light levels are too low, where the dark spots are. Special lamps turn on to illuminate those areas so that the room has a uniform light level. As the light levels begin to change, sensors provide feedback to the lamps, which adjust levels of artificial light to maintain constant lighting in the room.

Hybrid lighting is a combination of natural and artificial illumination to be used indoors for all lighting needs. Ideally, hybrid lighting is effectively indistinguishable from standard artificial lighting except in quality and

Hybrid lighting is a combination of natural and artificial illumination.



Relative solar illuminance vs time of day in the United States. Note that use of artificial lighting peaks at the time of day when the sun is highest and natural light is the most abundant. In hybrid lighting systems, sunlight is redirected rather than wasted or converted into heat and is also conveniently available in midday, when the need for energy conservation is the most critical.

We must also pay the price for artificial lighting's inefficiency—namely, its production of heat. Some of our cooling costs result from clearing away this heat.

Mike Cates examines the flow of light through a large "light pipe."

cost, where it will likely be an improvement. Hybrid light fixtures will allow use of all available natural light and supplement it with the amount of artificial light required to bring the total level of illumination to the rated value. As shown in the graph here, the level of natural light available is quite high during working hours in most places on most days. For many hours during a typical work week, essentially all illumination could be provided by natural light. In fact, fully hybridized lighting in industrial and commercial working environments could cut artificial light requirements in half. By combining natural light and improved artificial sources available today—centralized, high-efficiency light sources— energy costs for lighting could be reduced by one-third.

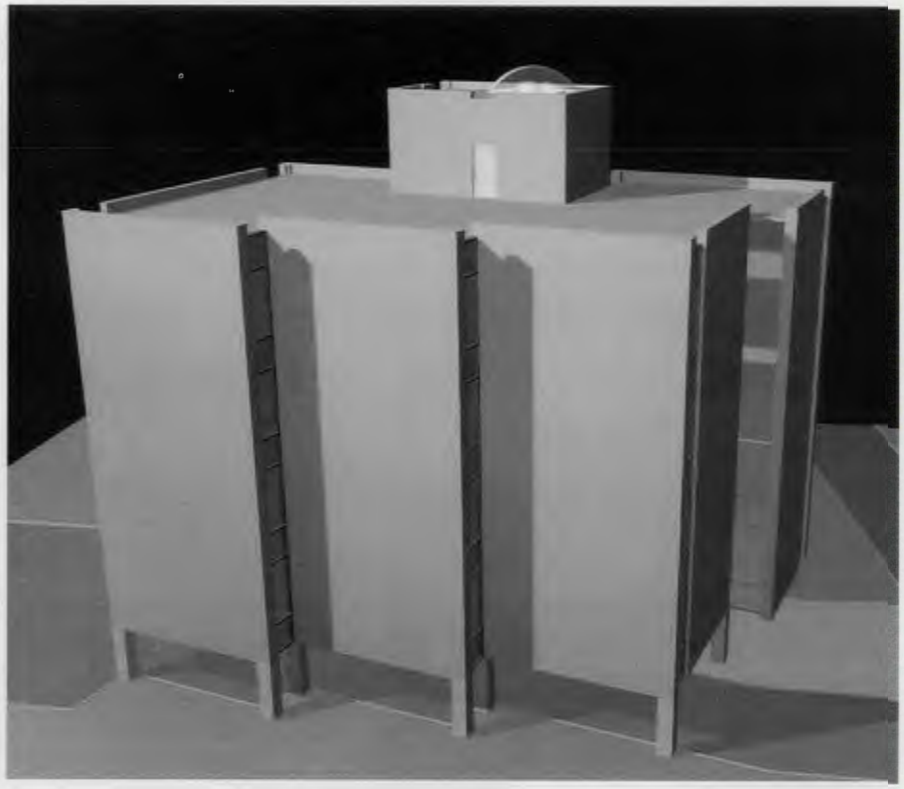
Why Is Hybrid Lighting Needed?

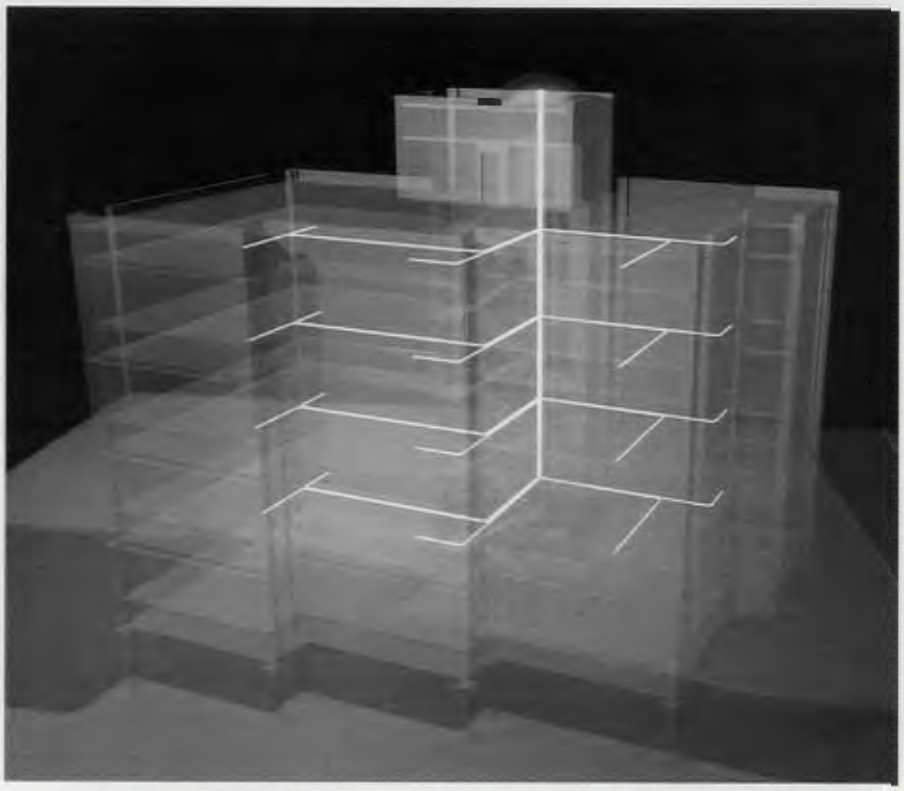
Considering the light bill for the industrialized world today, there is a financial incentive to use higher-efficiency lighting. The real problem boils down to two factors: cost and degree of user friendliness. If you entered a hardware store tomorrow and heard that new, twice-as-efficient lighting fixtures were available free of charge with free installation, you would probably ask for them. If, at the other extreme, you were told that the price of the fixture and its installation would be prohibitively high, you would not be interested in them. The goal of hybrid lighting development is to find the practical middle ground: costs that are manageable and future savings that are significant.

Lighting costs are an issue because they include not only fixture prices but also installation, retrofitting, and maintenance. When new construction is planned, modern lighting costs that are higher than those for standard, low-efficiency lighting can be justified (unless they are exceptionally high), because of long-term efficiency. For retrofitting, the same argument holds, again, as long as the cost is not extraordinary. For maintenance it is important that hybrid systems cost little if any more than today's standard systems. Long-term efficiency improvements can pay for only so much. Despite the massive benefit to the whole society that accrues when large amounts of electric power are saved, individual investors will not cooperate unless their individual "bottom line" is in the black.

As for user friendliness, we must not underrate its importance. Consider fast food in the United States today. Is it a multibillion dollar industry because the food is cheaper or even tastier than similar food you could prepare at home? No, the enormous success of the industry arises mostly because of the user-friendliness factor. We don't have to pay too much, don't have to cook, don't have to clean up, don't have far to go, and can buy a meal that has the quality we expect. We aren't involved in the details; we simply go get (or call for, or fax for!) fast food whenever and wherever we want it. Similarly, when we throw the switch to light a room, we normally expect to have no further involvement with the process. Without the user friendliness factor, cost arguments are usually abandoned because our time and effort often mean more to us than cost. Of course, we can attach a kind of virtual cost to our time and effort: with such a cost added in, the pure monetary savings of some innovation could be washed away in a flood of the red ink of inconvenience.

Related to user friendliness, and a factor of extreme importance, is





The solar collector on the roof gathers sunlight to illuminate the building; inside the building are light pipes to transport the light to each room.

aesthetic appeal. Lighting engineers all over the industrialized world spend considerable effort in designing lighting systems that are attractive, interesting, unobtrusive, and highly decorative; they are often major points of focus or part of an overall theme. Any successful hybrid system must be able to meet most of the criteria for aesthetic appeal. Ideally, hybrid systems should be able to take virtually any form, especially since standard light bulbs, fluorescent tubes, and the like may not be needed. Despite the convenience, low cost, and all the other more tangible factors, attractiveness will often be the final decision maker in the selection of a lighting system, even in some commercial enterprises.

Schematic of light-coupling components in a typical hybrid lighting arrangement.

Given these caveats, the idea of passively redirecting as much natural light as possible, combined with artificial light as needed, has obvious appeal. Hybrid lighting would already be a fact of everyday life if the realization were as obvious as the concept. The importance of energy conservation and illumination quality have been understood for a long time, but little changed in business and home lighting systems from the end of World War II until a few years ago. Recently, however, political and financial incentives have arisen that urge improvements in these areas. Heightened concerns about environmental quality and waste disposal within developed countries have led to more interest in efficiency and quality. Increased information-based economic activity has brought more and more workers indoors, requiring them to have improved illumination. After hours, too, average citizens spend longer times indoors, both at home and in businesses that stay open later and later. The opening up of previously closed Third World societies has revealed numerous environmental problems related to energy use as well as untapped resources and economic opportunities. In response to the perceived need to reduce growth in energy consumption, major producers of lighting equipment have begun widespread marketing of higher-efficiency bulbs and fluorescent tubes, improved ballasts, and new designs for various replacement components. Many of the technical capabilities have been available a long time but have only recently been commercialized. With these improvements in artificial lighting, however, little has been done to emphasize natural light. In homes, taking advantage of the sun and sky has been limited mostly to skylights and picture windows. For commercial buildings large windows are often used, but primarily for the view afforded rather than the extra light provided. Stores like Wal Mart, however, are making greater use of natural light to attract customers.

In recent innovations of the lighting industry, no extensive emphasis has been placed on combining natural and artificial lighting in any quantitative, integrated way. Hybrid lighting has recently begun to make sense economically because it has begun to make sense technically. With the former energizing the latter, we have entered a period in which hybrid lighting is finally practicable. So, how do we make it happen? What are the remaining technical hurdles? What stands in the way of our taking advantage of a clearly beneficial concept?

Components of Hybrid Lighting

Hybrid lighting systems are produced by a combination of four technologies: collecting natural light, generating artificial light, transporting and distributing light to where it is needed, and controlling the amounts of both natural and artificial light continuously during usage. For an example of a typical configuration, see the pictures at far left. Here, sunlight is collected on the roof of a commercial building, transported by optical fibers, monitored for intensity and spectrum, combined with artificial light, and released in preset amounts at specific locations. A description of these four technologies follows, along with an evaluation that weighs factors of cost and user friendliness. You will see that each technology has its own challenges.

Light collection and concentration. All natural light comes, of course, from the sun. On a cloudless day, with the sun high in the sky, the amount of sunlight falling on the surface of the earth is more than 1000 watts per square meter,

Enough light strikes the roof on a sunny day to light every room in the building … The problem is collecting the light, then getting it where you want it to go.

so we do have a lot of light to work with. We are instinctively aware of the abundance of light when we step outside and squint briefly as our eyes make the transition to the difference from the adequate but much less intense light in our home or office. Keep in mind that 1000 watts of light per square meter is the value in the visible wavelengths. As compared with incandescent or fluorescent light bulbs, it is pure light. A 100-watt light bulb, for example, uses 100 watts of electricity but produces only about 17 or 18 watts of light. The rest is heat. One square meter of bright sunlight, then, is equivalent to turning on about 55 100-watt light bulbs. Most offices or small rooms can be very well lit by two or three light bulbs; consequently, a square meter of sunlight could theorectically light about 20 rooms or offices. If the roof area of a building is taken to be approximately the floor area of any one of its floors, enough light strikes the roof on a sunny day to light every room in the building even if it's more than a hundred stories high! The problem is collecting the light, then getting it where you want it to go.

Yes, the sun is a wonderful giant light source, but we on the earth are constantly moving with respect to it. Depending on the time of year and time of day, the sun's light arrives from different angles. The most efficient way to gather the light is to constantly track the sun's position and focus the maximum amount of available light all the time. This sort of thing is done in some experimental solar energy plants and solar furnaces. For lighting, however, this technique is probably too cumbersome and expensive. Trackers are electromechanical devices that have moving parts. Moving parts wear out much more often than static systems. They require energy and some sort of microprocessor to keep them going. They can fail or get out of alignment. They can be blown over or away in a storm; be damaged by hail; or get their mechanisms clogged with leaves, dirt, twigs, pine needles, or whatever. Fortunately, as we have seen, for a large part of a sunny day, considerably more sunlight hits the roof of a building than is needed inside to light it; consequently, it makes sense to develop and place on roofs fixed, passive collectors and concentrators that look good and require little or no maintenance. A number of designs have been worked on, often, however, with the goal of optimizing collection efficiency. The goal should be rather to optimize cost, maintainability, attractiveness, and efficiency, probably in that order.

A representative illustration of this kind of optimization is the use of skylights. In many cases they add a useful amount of light that is both attractive and essentially free of maintenance. Though skylights can and will play an important role in hybrid systems, in themselves they are not efficient enough, nor do they distribute light to remote locations. Collectors, which are required for distributing light, though necessarily more complex than a passive skylight, can be designed with optimization in mind. For example, a collector could have three fixed parts, one looking straight up to catch the sun in the middle of the day, and two angled parts, to catch the sun in the morning and afternoon. Such a collector might be very inefficient compared with an active tracker and relatively inefficient compared with a multicomponent passive system; however, it could easily be much cheaper and require less maintenance, even if its collection area had to be scaled up by comparison.

Concentrators can be lenses or mirrors. Modern plastic materials can probably be used, cast, molded, or extruded rather than finished with any kind of precision. It is not necessary to have image-quality optics. Plastic materials may also be able to filter out naturally occurring ultraviolet light or to allow the transport of infrared wavelengths into different optical circuits for nonlighting purposes.

Generating artificial light. Incandescent and fluorescent lamps are designed to produce a spectrum of illumination that serves a particular purpose. If exactly duplicating sunlight were our purpose, artificial lights would have to look like a 5750 K blackbody shining through several miles of atmosphere, made up mostly of nitrogen, oxygen, and water vapor. Clearly, the challenge is formidable. Few incandescent lamps can operate either efficiently or for any length of time at extremely high temperature, so a compromise has been worked out. Standard 100-watt bulbs, for example, operate at about 2850 K. Of course, this kind of light makes things look a little yellowish compared with the vivid clarity and whiteness of sunlight. Fluorescent fixtures, which were designed partly to deal with that spectral problem, have the added benefit of being more electrically efficient. Fluorescent lamps operate by producing a high-voltage discharge through a gas volume that, in turn, emits light well up into the ultraviolet portion of the spectrum. The ultraviolet light stimulates fluorescence from a powder layer deposited on the inside walls of the glass envelope or tube. The particular phosphor on the tube walls determines the visible spectrum it emits. The most common fluorescent lamps, in use in virtually all commercial buildings, emit a white spectrum that is reasonably close to that of natural light. Other phosphors are used to make yellower light or to approximate the optimum distribution

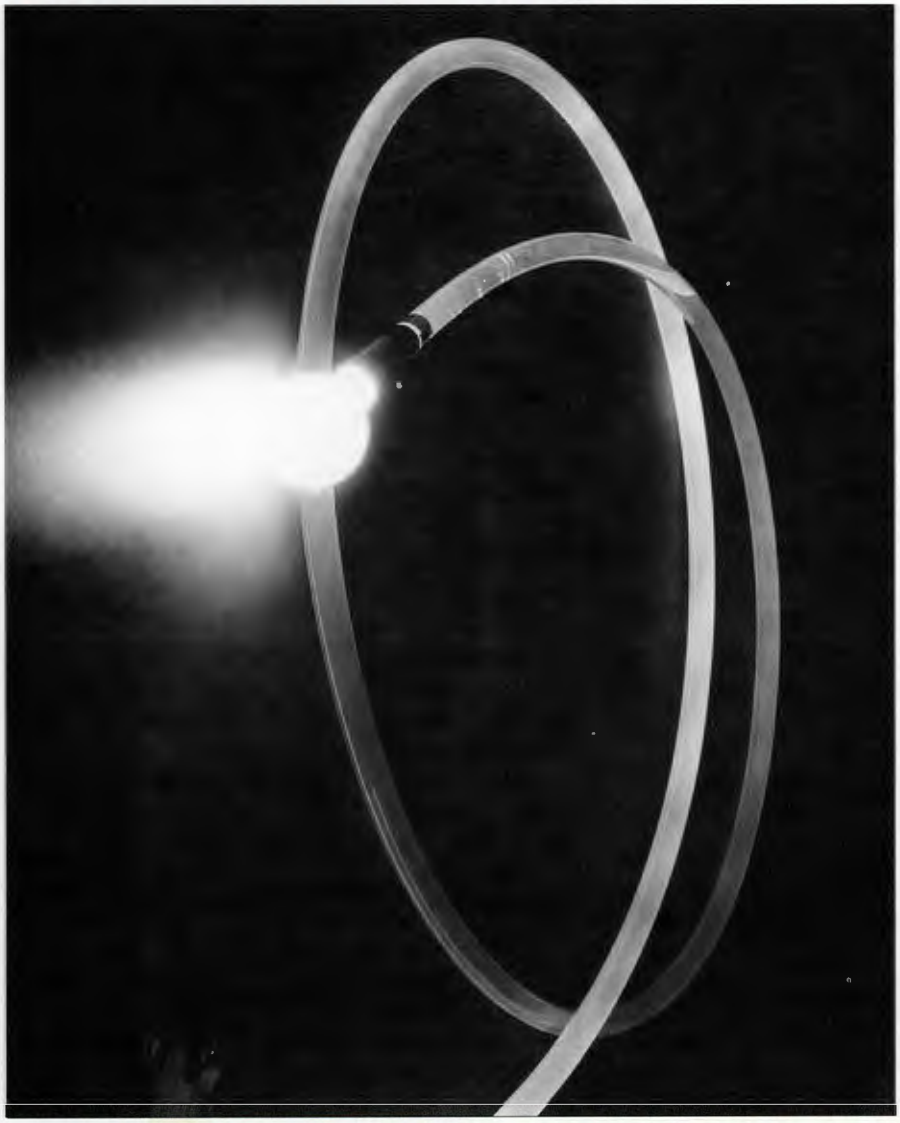
of wavelengths for growing plants (as in grow-lamps).

Halogen lamps and bulbs containing metal vapors produce well-defined spectra that are effective sources of illumination. But like the incandescent and fluorescent sources, they also are no real match for sunlight. Because no artificial source is just right, practicality takes over. We have gotten used to artificial lights that are not just like sunlight. Besides, sunlight itself varies enormously. Sunset and noon are equally valid times of the day, after all. And human beings, struggling to survive and thrive over the millennia, learned to use red light as well as blue. We have also learned to open our eyes wide to the dim illumination at sunset and at night and peer carefully through shaded eyes in the squintingly bright middle of the day. Because we don't need precisely tailored spectra in artificial illumination, cost and convenience become the overriding factors. Nevertheless, the more closely lighting approximates the solar spectrum of a clear day, the better our visual acuity.

There are also psychological factors relating to illumination spectra. Lighting that is lower in intensity and redder in color "feels" quite different to the human psyche than brighter and bluer light.

Hybrid lighting can, in principle, generate any of a variety of spectra and intensity levels, but most people would probably be satisfied if indoor lighting approximated that experienced outside. In theory, if cost is no major consideration, the user could dial a spectrum, very much like dialing the frequency equalizer of a stereo. Microprocessors would activate various filtering and monitoring instrumentation and, voila, out would come the dialed-in spectrum. But, let's save that for the next decade of hybrid lighting. Let's assume that people will be content with sunlight of the given day mixed with a good standard artificial spectrum, perhaps with some blue enhancement in the early morning and later as the afternoon wears on.

Most people would probably be satisfied if indoor lighting approximated that experienced outside.



Large-core optical fiber conducting sunlight into a diffusing bulb.

Perhaps the most important new consideration in the production of artificial light is the use of a centralized source. Gone would be the need for separate light bulbs and the maintenance associated with them. Gone would be the heating in each lit room that comes from the wasted energy of operation. Centralized sources, taking advantage of the most efficient processes available having staggering luminous efficiencies that dwarf those of existing fluorescent lights, can be locally cooled and ventilated. They can be isolated but accessible, like a water heater or washing machine. It is also possible to design centralized systems where one or more spare sources are wired into the system, coming on automatically when the active one fails. Fortunately, this idea is more than just a dream. Companies like GE Lighting and Fusion Lighting, Inc., are making

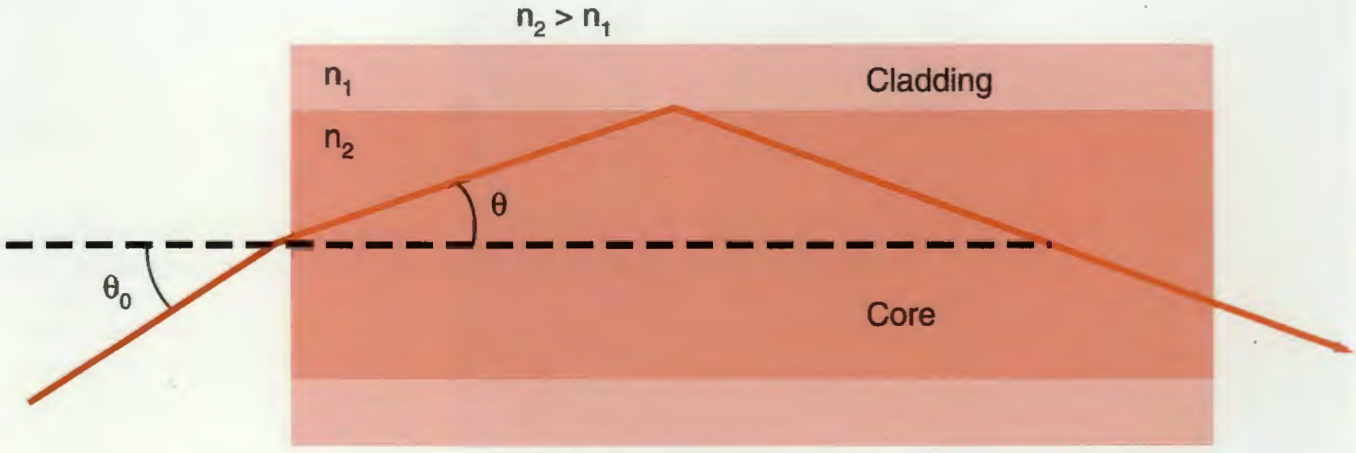
legitimate headway on a variety of new concentrated light sources.

Light distribution. Imagine street lights without light bulbs; the illumination from the top of the lamp posts is piped from light sources at the sidewalk level—making it easier to change burned-out light sources (see drawing below). Imagine a tunnel subway having only 5% the present number of light bulbs interconnected with passive systems bringing in outside light.

The secret to light distribution is fiber optics. Optical fibers have already brought about a revolution in the technology of data transport and communication. Their entry into our homes is imminent—to carry television, computer, and telephone signals. Yet, these little bundles of single-mode high-purity silica strands are unlikely to be used for lighting. That will become the job of their flabby, less sophisticated cousins—fibers of plastic, perhaps filled with a clear gel—that are approximately the size and weight of the electric wiring now ubiquitous in modern construction. The photograph on p. 77 shows a gel-filled fiber with a frosted bulb attached to the end. The bulb glows from the sunlight piped through the fiber. In new construction and in many types of retrofitting, plastic "wires" for light can be handled and routed like electric wiring. Large optical fibers like this, often called optical light guides, are capable of transporting large amounts of light. For example, bright sunlight passing through a square-meter area—enough to light several rooms—can be focused into and transported by a guide one square centimeter in cross section or less. This guide can lead into a number of small guides, in much the same way electric current is distributed into different outlets of a particular circuit.

Optical fibers of any cross section are more efficient when they are fabricated with a highly transparent central core surrounded by a transparent cladding of material with a lower index of refraction than the core, as illustrated in drawing below. At the interface of core and cladding, light impinging at less than a certain angle (called the critical angle), is perfectly reflected off the optical interface with the cladding and continues down the core to its ultimate destination. Light guided in this way will have a very low leakage rate; consequently, little heating will occur along the guide. Light guides, then, can be handled without special equipment; they will not produce an electric shock of course, although looking at the bright concentration of sunlight could be hard on the eyes. Light coming out of an optical wave guide, however, is not generally as dangerous as that from a laser, because the waveguide light exits in an expanding cone (determined by the numerical aperture of the guide) as opposed to the more dangerous, narrow collimation of a laser beam.

Controlling illumination. Because sunlight is so variable, both in intensity and in location, hybrid lighting must have active control of light levels at all times. Fortunately, current technology has provided a number of inexpensive, compact sensors and electronic components that will help with the problem. A typical day for most of us goes something like this: the sun rises on a clear morning, clouds develop at midday leaving the early afternoon partly cloudy, giving way perhaps to late afternoon clearing before sunset. Of course, other days are cloudy from dawn to dusk and a few are continuously clear. Whatever the conditions, hybrid lighting sunlight collectors will be taking what is available and routing it to the various fixtures in various rooms. Most of the time artificial light must be added to what nature provides if we are to achieve a uniform level adequate for modern activity.



Schematic of an optical fiber having a highly transparent control core surrounded by a transparent cladding whose index of refraction is lower than that of the core.

Light sensors will almost surely be an integral part of every hybrid lighting fixture. It is possible to sample several wavelength bands in the visible spectrum by using filtering techniques or sensors with sensitivity peaked in certain wavelength bands. Thin-film photodiodes and similar devices can be located in unobtrusive, hidden, or decorative places. Circuit chips can be similarly configured. In mass production these controlling elements will not make up a large fraction of the lighting cost despite the fact that they will make the difference between a curiosity or decorative system and a full-time, hands-off lighting package.

To illustrate the idea, consider the light fixture pictured below. For clarity, we have attempted to simulate a typical fluorescent light fixture containing four 40-watt tubes. In this case, however, two of the tubes are replaced by diffusers into which sunlight is routed from an optical fiber system something like those previously mentioned. Built into the fixture's structure are a couple of illumination sensors that constantly monitor the room light level. Part of the electronic package taking the place of the usual ballast is an active controller, laid out in a rugged solid-state circuit design. The current and voltage to the second pair of tubes, true fluorescent lamps, are varied to produce a total level satisfactory to the constantly vigilant room sensors. If the fluorescent tube has sufficient brightness capacity to illuminate the room fully when no sunlight is available, such an arrangement can provide a room with a level of light that always seems about the same as far as the user is concerned.

Looking ahead

As the human population grows and the global economy expands, drawing in more and more of the previously excluded portions of society, demand for energy is certain to increase at a precipitous rate. Growth in the production of goods and services will naturally follow in a similarly skyrocketing fashion. Enormous increases in pollution, waste, and resource depletion will go hand in hand with all these increases in production. In the United States and in other industrial societies, we may continue to believe that the costs and availability of resources and energy will remain about the same. Realistically, however, most of us know this is a foolish assumption, especially because of its near-certain negative impact on our children and grandchildren. If for no other reason, population growth and demand for more energy justify development and deployment of hybrid lighting systems.

As technology develops in the coming decades, some of its

Hybrid lighting sunlight collectors will be taking what is available and routing it to the various fixtures in various rooms.

An example of a hybrid lighting fixture in which sunlight is routed through an optical fiber to two of the four 40-watt tubes. The fixture's sensors constantly monitor the room light level.

Population growth and demand for more energy justify development and deployment of hybrid lighting systems.

improvements can be important to hybrid lighting. There will probably be major gains in the quality of the components previously discussed, along with decreases in their costs. For example, more easily manageable optical fiber bundles with better optical transmission, improved collectors and control circuits, and better spectral selection are very likely to come about for fewer dollars. As solar conversion to electricity improves in efficiency and drops in cost, the same sunlight that is piped inside buildings and homes can be used to produce electricity to control illumination (as well as other numerous—and perhaps new—uses for electricity). Hybrid lighting systems will give us a head start in designing collectors and appropriate architectural configurations that make best use of our ever-present fusion energy source eight light-minutes away. With the development of light storage systems—perhaps batteries that store light chemically, like high-energy fireflies—sunlight can be saved during bright days and used at night and on dreary gray afternoons. In the home of the future, the latest hybrid system would, upon your departure for work in the morning, switch off the light distribution and put the system into a light "storage" mode. The stored solar energy would then be used at some time when you are at home. With reasonable technological luck and a few years time, our children's or grandchildren's homes will likely be self-contained energy systems, providing light and power for themselves, with perhaps some left over for the community grid.

No matter what the future holds, lighting will continue to demand a large fraction of our energy needs. And, as technology grows all over the world, the requirement for higher-quality lighting will grow with it. Now, in an era of relative plenty, it is wise to advance the technology of lighting so that the future will run no risk of going dark. ornl

In this concept for a street light, the source of light is at the bottom rather than the top of the pole, making it easy to replace the light bulb. The light is transported up the pole and out the lamp at top.

Suggested Reading

***Building Technologies Program 1993 Annual Report*, Lawrence Berkeley Laboratory, LBL-35244, June 1994.**

Joseph B. Murdoch, *Illumination Engineering*, McMillan, 1985.

"Plastic Optics Shine in High Volume Production," *Photonics Spectra*, March 1995.

BIOGRAPHICAL Sketches

Mike Cates is a physicist in ORNL's Engineering Technology Division. Previously he was in the Centrifuge Division at the former Oak Ridge Gaseous Diffusion Plant and in ORNL's Applied Technology Divisions, where he established the Photonics and Laser Applications Group. A pioneer in developing phosphor-based thermometry, he has extensive experience in fluorescence applications, imaging, fiber-optics sensors, and related areas of photonics. His first contact with Oak Ridge was as an Oak Ridge Associated Universities fellow during his doctoral program. After graduation he worked at the Los Alamos National Laboratory for 12 years before joining the ORNL staff. Collaborating with Cates on the hybrid lighting project is Jeff Muhs, also of the Engineering Technology Division (shown with Cates in the photograph). Two other researchers in the same division, Steve Allison and Bart Smith, are becoming more involved in this project.

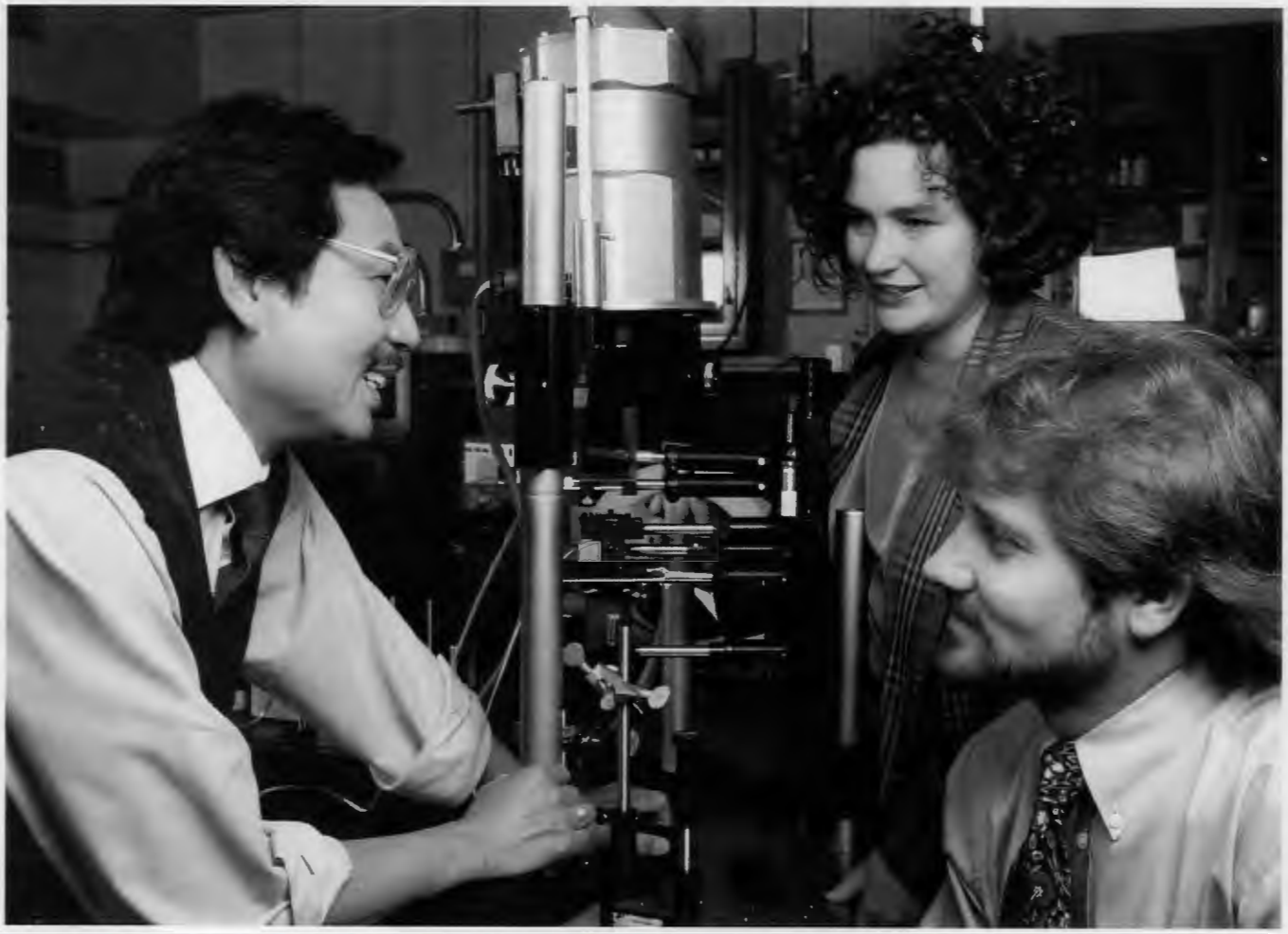
Mike Cates (left) and Jeff Muhs show components that should make possible hybrid lighting in which sunlight and artificial lighting are blended to save energy.

ORNL Wins Six R&D 100 Awards

In 1996 ORNL received six R&D 100 awards from *R&D* magazine, bringing ORNL's total for these coveted awards to 85. However, three former or present employees were named on three additional R&D 100 awards. Winning entries and researchers from the Laboratory are

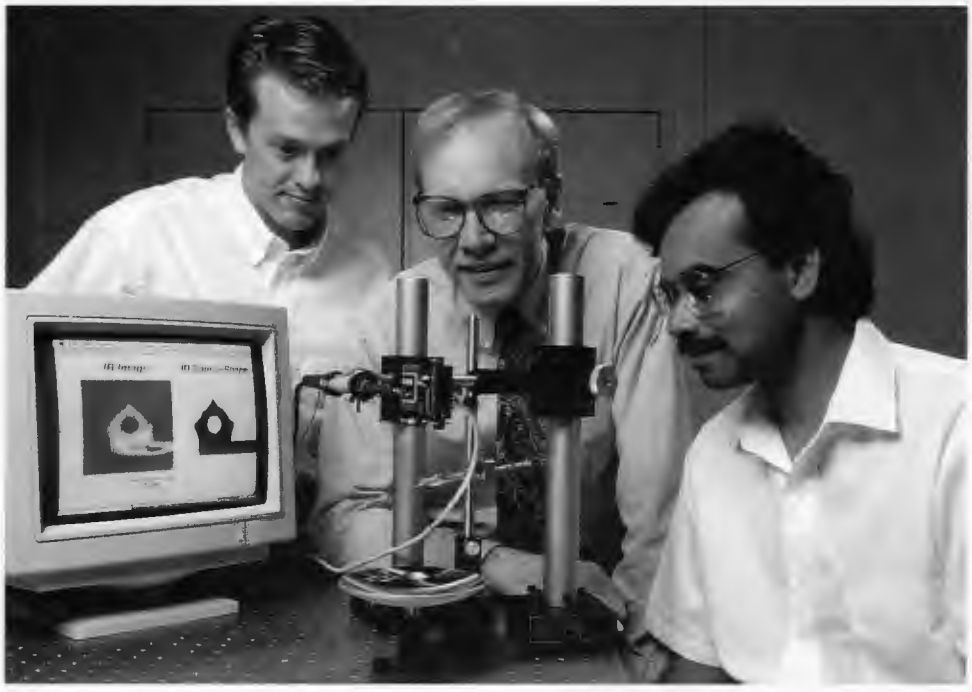
- *Surface-enhanced Raman gene (SERGen) probe* by **Tuan Vo-Dinh, Kelly Houck,** and **David L. Stokes** of the Life Sciences Division. This SERGen procedure simultaneously provides a simple, rapid, and inexpensive test for detecting specific DNA fragments in multiple sequences. It can be used to identify, sequence, and map genes. The probe quickly and quantitatively screens for multiple genetic diseases in a single measurement. It could be used for medical diagnoses at small medical clinics. (For details, see p. 64.

- *Noncontact micromechanical thermometer* and *microcantilever mercury vapor sensor*, two technologies grouped together, developed by **Thomas Thundat, Bruce Warmack, Eric Wachter, Patrick Oden,** and **Panos Datskos,** all of the Life Sciences Division. The noncontact micromechanical thermometer is a miniature, battery-operated temperature sensor based on a simple, revolutionary concept that can measure temperature differences with a sensitivity of 0.001°C. The microcantilever mercury vapor sensor is a miniature, battery-operated device based on a revolutionary concept that can detect mercury vapor in air with 100 times better sensitivity than any commercially available mercury sensor. (For



Tuan Vo-Dinh (left), Kelly Houck, and David Stokes are developers of the R&D 100 Award–winning surface-enhanced Raman gene probe, which is used to detect multiple DNA biotargets such as gene sequences, bacteria, and viral DNA fragments. *Photograph by Tom Cerniglio.*

Microcantilever sensors have very high sensitivities.



ORNL researchers (from left) Patrick Oden, Bruce Warmack, and Thomas Thundat received an R&D 100 Award for two technologies—the noncontact micromechanical thermometer and microcantilever mercury vapor sensor. *Photograph by Tom Cerniglio.*

details, see the highlight in the *Review*, Vol. 29, Nos. 1&2, 1996, pp. 47–48.)

- *Thin-film rechargeable lithium batteries* by **John Bates, Nancy Dudney,** and **Chris Luck** of the Solid State Division. The product is a group of solid-state rechargeable lithium batteries that are less than 10 micrometers thick, each based on different cathode materials. They have energy densities unequaled by any other battery technology, can be cycled thousands of times, and can be fabricated on a variety of substrates and devices in arbitrary shapes and to any required size to meet requirements of a specific application. (For details, see the *Review*, Vol. 25, No. 2, 1992, pp. 46–56.)

- *Potassium tantalate (niobate) substrate* by **Lynn Boatner** and **Ron Feenstra,** both of the Solid State Division, in collaboration with Michael Urbanik of Commercial Crystal Laboratories in

ORNL researchers John Bates and Nancy Dudney think the thin-film lithium battery they developed could be useful in a variety of applications, especially those with size constraints. The battery, which won an R&D 100 Award in 1996, is fabricated on one side of the ceramic substrate and provides power to the circuit on the opposite side. *Photograph by Tom Cerniglio.*

Naples, Florida. Potassium tantalate (niobate) represents a highly attractive substrate material for the growth of epitaxial oxide superconducting films and multilayer structures with other metallic, magnetic, ferroelectric, or electro-optic oxides. These substrates are noteworthy for their high mechanical and chemical stability and their relative ease of fabrication. (For details, see "Technology Transfer" on p. 10 in this issue of the *Review*.)

- *Laboratory-on-a-chip* by **J. Michael Ramsey** and **Stephen Jacobson** of the Chemical and Analytical Sciences Division. This microfabricated device containing tiny chambers and finely etched channels performs chemical and biochemical procedures under computer control using minuscule quantities of samples and reagents. (For details, see the *Review*, Vol. 27, No. 3, 1994, pp. 65–66; Vol. 29, Nos. 1&2, 1996, pp. 46–47.)

- *Gencell 101* by **Craig Dees,** a former ORNL scientist. Gencell 101 is an inexpensive alkaline cellulase enzyme produced by a species of bacteria belonging to a newly identified genus. The most immediate potential application of Gencell 101 is in textile finishing. For example, the bacterial enzyme could be used to "stone wash" jeans without stones, replacing the fungal enzyme, which ultimately may be more expensive. It also has potential for commercial application in areas where cellulase is being used, such as food processing, detergents, drain cleaners, and septic system treatments. In addition to being cultivated for the enzyme, the bacteria may be used for waste treatment. (For details, see the *Review*, Vol. 28, No. 4, 1995, pp. 103–104.)

ORNL researchers Ron Feenstra (left) and Lynn Boatner believe their new potassium tantalate substrate will be useful in making large wafers for the growth of oxide superconducting films. Their invention earned an R&D 100 Award. *Photograph by Tom Cerniglio.*

In addition to ORNL's six R&D 100 awards, this year three others have strong ORNL connections.

Fahmy Haggag, who worked in the Metals and Ceramics Division for nine years until he left ORNL a few months ago to concentrate on his company, Advanced Technology Corporation, received an R&D 100 award for his *portable/in-situ stress-strain microprobe system*. The nondestructive testing device evaluates welds by making small dents. A nonportable version of the device is being used at ORNL to evaluate nuclear reactor pressure vessels. Haggag entered his invention privately.

Tommy Phelps of the Environmental Sciences Division was a player in a Westinghouse Savannah River Technology Center winning entry. The PHOSter method for

phosphate-accelerated bioremediation system uses triethyl phosphate to clean up sites polluted with chlorinated hydrocarbons or petroleum. Also listed on the award were Oak Ridge Institute for Science and Education postdoctoral researcher Susan Pfiffner (who is also Phelps' spouse) and Savannah River's Brian Looney, Terry Hazen, and Ken Lombard.

Finally, **Buddy Bland** of ORNL's Center for Computational Sciences was named as a liaison on a winning entry by Sandia National Laboratories and Giganet Corporation for their OC-12C communications board. According to Bland, ORNL helped test the board for real-life applications.

ORNL has won a total of 85 R&D 100 awards.

Craig Dees received an R&D 100 Award for Gencell 101, an inexpensive alkaline cellulase produced by a species of bacteria from a newly identified genus. Gencell 101 may be used for textile finishing, food processing, and producing detergents. ***Photograph by Tom Cerniglio.***

The Right Stuff Back at the Reservation

The nose of the airplane points down a hundred yards of gravel road; the road curves down a sloping field walled in by pines and poplars. With the plane's engine screaming at full throttle, pilot Dave Farmer starts his takeoff roll.

The plane jounces forward 50 feet or so, then bounds into the air and climbs steeply. Just as it clears the treeline, the plane catches a gust of wind, flips onto its back, and plummets earthward. But with a flick of his wrist, Farmer coolly rights the plane and spirals it upward a thousand feet.

Farmer, clearly, is an expert pilot. As a matter of fact, Farmer is outstanding in the field—er, make that standing out in the field: He's flying the plane—a model aircraft with an eight-foot wingspan—by radio control. A few steps away, ORNL geophysicist Jon Nyquist huddles over a video monitor and helps Farmer navigate to their target, a waste facility they're photographing from the air to document new construction.

"You're over the bridge now," Nyquist calls. "Okay, you're approaching the facility. Get ready; shoot. Again. Again." Farmer presses a button on his radio console; a half-mile away, in the belly of the plane, a 35-mm camera blinks three times.

From takeoff to turnaround, the mission will last about 15 minutes—and cost a small fraction of what a conventional aerial photograph would cost. "Three years ago," says Nyquist, "we spent a couple million dollars to get an aerial survey of the entire Oak Ridge Reservation." Those photos, taken from a full-size aircraft at 4000 feet, showed features ranging from historic log cabins to reactor cooling-water pipes. Assembled into a huge photo mosaic, the survey functioned as

a detailed snapshot of the government reservation as of 1993.

But that was then; this is now. And now—as always—things are changing: trees come down, buildings go up, roads get rerouted. For planners, engineers, or environmental scientists, an aging snapshot, no matter how detailed, becomes progressively less useful.

Nyquist, a geophysicist in ORNL's Environmental Sciences Division, hit upon the idea of using smaller, cheaper model aircraft to update the aerial survey's myriad photos—called "tiles"—quickly and cheaply when the need arose. As luck would have it, Farmer—a technician in Nyquist's section—had years of experience building and flying radio-controlled airplanes as a hobby. Over the past two years, they've put together a small fleet of small aircraft—seven in all, including a helicopter that can hover just like the big ones. Now, tile by tile, they're updating the aerial photos to show new construction, land-use changes, and other differences as they arise.

But how do they match their shots, snapped from 500 feet, with the earlier survey's photos from nearly 10 times that altitude? The answer lies in computer trickery. "It's done by 'rubber-sheeting' the image," says Nyquist. "If you've got some control points that you know match up—buildings, groundwater monitoring wells, cooling towers—the computer can bend and stretch the rest of the image to fit. It's like putting a patch on a quilt." Or like morphing from face to face in a music video.

So far Nyquist and Farmer have flown about 50 missions, logging about 20 hours in the air. But updating aerial photos is just the beginning of Nyquist's plans for the radio-controlled air force. He's now equipping one of the planes with a magnetometer, an instrument that can be used to prospect for iron ore—or detect buried drums of nuclear or chemical waste. Soon he hopes to add a receiver that can pick up the very-low-frequency radio waves the U.S. Navy uses to communicate with submarines around the globe. By reading changes in those radio waves as they're warped by power lines, pipelines, and geologic faults, he'll get an additional layer of data on features above and below the ground.

And by digitizing all the electromagnetic data and merging it with the photos, Nyquist hopes to build a multilayered geophysical picture of the Oak Ridge Reservation and post it on the World Wide Web (for a sample,

But updating aerial photos is just the beginning of ORNL's plans for the radio-controlled air force. One plane will be looking for buried drums of waste.

ORNL's radio-controlled airplane shown flying.

check http://www.esd.ornl.gov/ern/airborne/airborne.html).

As Farmer works the controls, the plane makes a half-dozen passes over the cluster of buildings where low-level radioactive waste is packaged and disposed of. Satisfied they've got the shot, Nyquist calls, "Okay, that's good," and Farmer turns the plane back toward the field.

As it circles and banks into the wind for landing, the plane drops below the trees edging the field. Nyquist's video screen fills with branches and leaves, and he yelps. Farmer guns the throttle and yanks back the stick; the plane reappears through the crown of a tall poplar, which it clears by a leaf's breadth. Both men heave cheerful sighs of relief.

Facing the incoming plane, Farmer works the controls intently. The plane settles to the grass and stops at his feet, like some winged spaniel, some high-tech boomerang, some outsized carrier pigeon bearing vital information.

As Farmer carries it back to the truck, there is the barest hint of a swagger in his step.—*Jon Jefferson*

Cancer-Causing Gene Involved in Embryo Development

Here's the situation. A gene that causes leukemia in mice has been identified. You can turn the gene off.

ORNL's radio-controlled airplane, being held by Dave Farmer, is used to map the Oak Ridge Reservation.

No gene, no leukemia, no problem. Right? No.

Researchers at ORNL have done that very thing. One such gene, called Evi1, is involved in causing leukemia in mice. The human Evi1 gene is also involved in leukemia. In both instances, the Evi1 gene is functioning in cells where it is normally not found.

So what is the normal function of a gene that was initially identified because it caused cancer? Researchers in ORNL's Biology Division, which is home to the fabled Mouse House, used a technique in which mouse embryo cells were mutated in culture and reintroduced into the mouse to produce a strain of mice in which the Evi1 gene is no longer expressed. The mutant mice are "developmentally delayed" and die in the womb.

Principal investigator Michael Mucenski points to the experiment as evidence that a gene that may be so troublesome later in life plays a critical role in embryonic development. "Genes that are involved in cancer," he says, "have a normal biological function in the body. The generation of mutant mice allows us to determine what that function is."

ORNL's Mouse House, home to a myriad of mutant strains of mice, is a favorite repository for researchers who investigate genetic diseases or other conditions where genetic factors are suspected. Research like the Evi1 experiment, says Mucenski, "will help scientists eventually determine the biological function of genes and learn more about gene interactions that occur normally and in disease states." Medically speaking, that should be good news to all.

ORNL Technique Predicts Epileptic Seizures

A discovery by ORNL researchers could lead to early detection and perhaps control of seizures in victims

These results provide a basis for future work that may detect, and perhaps control, some uncontrollable seizures in epileptic patients.

ORNL researcher Lee Hively (left) is part of a team that worked with the St. Mary's Biomedical Research Center to devise a method to predict epileptic seizures 8 to 15 minutes before they occur. Neurologist Michael Eisenstadt (center) headed the St. Mary's team that collaborated with ORNL scientists to analyze the EEG data they used in making the discovery. ***Photograph by Bill Norris.***

of epilepsy, a condition that affects about 1% of the population, or nearly two million people in the United States.

Using advanced research techniques they developed, four staff members at ORNL evaluated electroencephalogram (EEG) data for changes in a patient before, during, and after a seizure. By analyzing the data, which show the electrical impulses that make up brain waves, they found they could detect a seizure 8 to 15 minutes before it occurred.

"These results provide a basis for future work that may detect, and perhaps control, some uncontrollable seizures in thousands of epileptic patients," says Lee Hively, one of the ORNL researchers. "One possible technology might be a portable beeper device that incorporates a brain wave monitor and the ORNL seizure prediction scheme. The device could alert the wearer when an epileptic episode is imminent, allowing the person to stop any dangerous task, such as driving, seek help, or take medication. A more advanced version might add a feature to direct small electronic impulses to stop the seizure before it occurs."

Such a device could build on previous research at other laboratories with living sections of a rat's brain. In their research, scientists used chemicals to induce what appeared to be an epileptic seizure and then applied electrical impulses to force the brain back to normal function.

Hively and ORNL colleagues Ned Clapp, Stuart Daw, and Bill Lawkins worked with Dr. Michael Eisenstadt, a neurologist at St. Mary's Biomedical Research Center in Knoxville. Eisenstadt provided the EEG data and medical interpretations. ORNL staff

members focused on devising methods to study the millions of measurements.

Complicating this task is the fact that EEG data contain not only signals associated with brain activity but also aberrations that accompany actions such as eye blinks, muscle twitches, and chewing. These aberrations obscure the brain wave signal, so researchers had to develop a method that could correct for them. The researchers' diverse backgrounds (mathematics, statistics, chemistry, physics, and nuclear engineering) helped them develop analysis tools to interpret the EEG data.

In explaining the team's success, Hively said, "We used real-world tools that can handle real-world data. Most other analytical techniques can handle only model data."

Normal brain activity includes seemingly random, or chaotic, features, with local brain regions behaving relatively independently. These features show up on an EEG as weak correlations between measurements at different locations of the brain. In a person experiencing an epileptic seizure, however, brain waves at different locations have a "large periodic component and a strong correlation between locations," Hively says. Furthermore, the analysis of chaotic features clearly shows a transition between the nonseizure and seizure states, lasting 8 to 15 minutes and ending with a seizure.

The research was sponsored by the Laboratory Directed Research and Development program at ORNL. ORNL has filed invention disclosures for seizure detection, seizure prediction, and removal of low-frequency artifacts from brain wave data. Low-frequency artifacts—"background noise" resulting from eye blinks, chewing, and muscle twitches—are inherently present in an EEG and can obscure brain wave information. Researchers believe the artifact removal technique could be used as a nonintrusive monitor of worker alertness during extreme stress, possible drug abuse, or fatigue.—*Ron Walli*

Flaw Detection System Helps U.S. Textile Industry

On-line sensors at three U.S. textile plants are providing information that will help keep textile industry jobs in the United States and improve the quality of domestically produced fabric. The sensors are used to inspect textiles as they are manufactured to locate flaws and stop the process so corrections can be made to ensure production of defect-free fabric.

The sensors are part of the American Textile Partnership's (AMTEX) Computer-Aided Fabric Evaluation (CAFE) project, developed by ORNL, the Oak Ridge Y-12 Plant, and other DOE laboratories. CAFE is one component of the $20-million AMTEX partnership between DOE labs and the textile industry. Other CAFE members have included Argonne National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratories. Funding for the project is provided by DOE's Defense Program.

Tests of the sensor system performed last year at the Y-12 Plant provided encouraging results, but controlled tests don't always predict what will happen under harsh, real-world conditions. Since July 1996, however, the inspection systems have been providing some valuable information at three textile plants in the Southeast. Although some modifications are needed, plant managers are encouraged by the results.

"We've been compiling data for the past few months and the systems are working as expected," says Glenn Allgood, manager of the CAFE project and a member of ORNL's Instrumentation and Controls Division. "Dust, lint, heat, and other real-world conditions aren't interfering with the sensors at all."

Industry representatives agree that the technology holds promise.

"The CAFE project is nearing the final stages of development for a series of on-line sensors that represent a tremendous opportunity for textile manufacturers to gain more control of their fabric forming processes," says Mark Kametches, industry project manager. "Upon commercialization, these sensors could have a major economic impact on the weaving, knitting, and printing segments."

Management at Glen Raven, which employs 2500 at its plant outside of Burlington, North Carolina., is also certain the project will help the textile industry.

"We're confident that the technology is worthy of the time and money we've spent," says Bill Martin, product engineer at Glen Raven. "We've found that the sensors do many times more than what we thought they would do. The system is going to help us improve quality and hold costs flat, which is what we need to be competitive in the world marketplace. This is going to change the way we do business."

On-line tests began in July and will run through early 1997, says Allgood, who notes that the system enables laboratory researchers to monitor the systems—and compile data—from remote locations. The inspection system also provides operators with the location of the defect, which saves time and money because they can stop the loom, make corrections, and tag the defective material for rejection.

Using visual inspection only, it is possible for defective material to work its way through the entire textile system, eventually reaching the marketplace, before retailers and consumers notice the flaws. Thanks to the new inspection system, textile mills and apparel manufacturers will

minimize production of reduced-price, second-grade merchandise.

By mid-1997, elements of the on-line inspection system should be available to the industry for routine plant use, according to Allgood, who expects the industry to provide cost-effective information.

"The textile industry is looking for return on investment," Allgood said. "They're going to be looking at the bottom line, and we're confident our on-line inspection system will meet their needs."

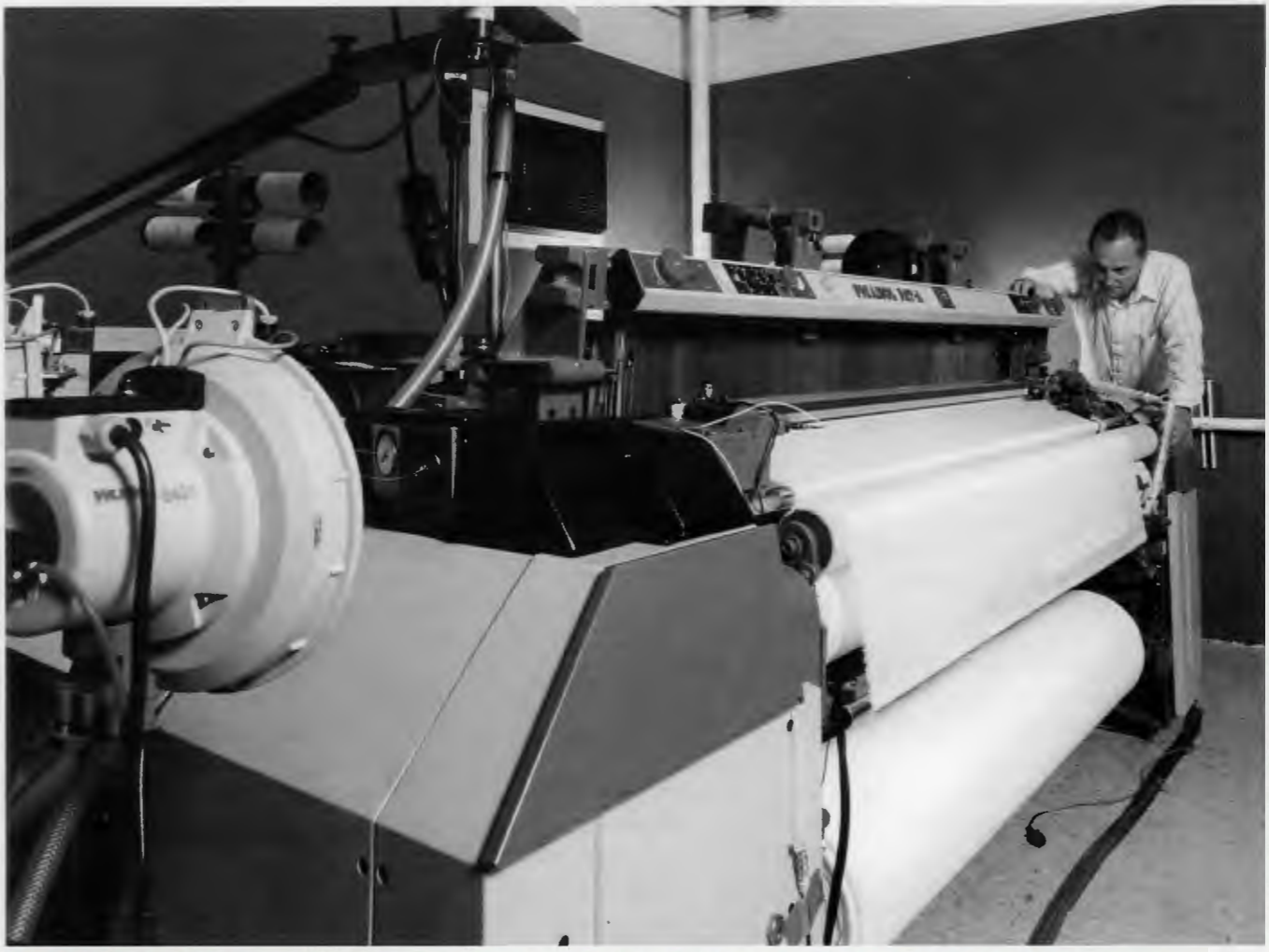
More than 1.6 million people in the United States work in the textile industry. In fact, textile production exceeds the automotive, petroleum, and primary metals industries in contributions to the Gross National Product, according to AMTEX. The partnership was formed because of the important role the textile industry plays in the nation's economy.

"The goal of AMTEX is to strengthen the competitiveness of the textile industry, which consists of the fiber, textile, apparel, and fabricated product sectors," Kametches said. "The partnership draws upon the resources of the textile industry, the Department of Energy, DOE labs, other federal agencies and universities."—*Ron Walli*

Radioactive Ion Beam Facility Dedicated

On December 12, 1996, ORNL's Holifield Radioactive Ion Beam Facility

An on-line sensor system has been developed to inspect fabric for flaws as it is woven.



ORNL's Jack LaForge is a member of a team that seeks to make the U.S. textile industry more competitive worldwide. ORNL and five other DOE laboratories contribute to the Computer-Aided Fabric Evaluation project, which incorporates on-line fabric inspection in weaving looms to dramatically increase the quality of U.S.-produced fabric. *Photograph by Bill Norris.*

Facility (HRIBF) was dedicated as an international user facility in a ceremony featuring dignitaries from the White House's Office of Science and Technology Policy, DOE headquarters, the state of Tennessee, Oak Ridge Associated Universities, Vanderbilt University, and the University of Tennessee. The dedication was followed the next day by a symposium on radioactive ion beam physics presented by speakers from England, Germany, Switzerland, ORNL, and various U.S. universities.

Dave Hendrie, director of DOE's Division of Nuclear Physics, congratulated the ORNL staff led by Jim Ball, Fred Bertrand, and the late Russell Robinson for designing and constructing the HRIBF. "You can count this effort as a success," he said, "and today is one of those glorious days for science in general."

Hendrie recounted the history of the project, which was conceived in 1991 as funding dwindled for ORNL's Holifield Heavy Ion Facility (HHIRF). "When HHIRF ran into funding troubles a few years ago," he said, "you had a good idea for a modest-size, cost-effective facility. You sold the idea to DOE. You put it together over the years. It turned out to be timely."

The timeliness of HRIBF was also underscored by Ernest J. Moniz, associate director for science in the White House's Office of Science and Technology Policy. He noted that interest is rising in the search for origins of life and matter, as underscored by Bill Moyers' 1996 PBS series on Genesis and a December 1996 White House symposium on the search for origins chaired by Vice President Al Gore.

About a third of the experiments using HRIBF radioactive ion beams will try to solve mysteries in nuclear astrophysics. These studies will focus on the formation and fate of stars. One goal is to better understand nova and supernova, the spectacular stellar explosions that produce all the heavy elements, including the carbon, nitrogen, and oxygen that make life on the earth possible.

On December 12, 1996, ORNL's Holifield Radioactive Ion Beam Facility was dedicated as an international user facility.

Chang Hong Yu inspects the recoil mass spectrometer in the nuclear structure experimental station for the new Holifield Radioactive Ion Beam Facility.

On August 30, 1996, researchers generated the first radioactive ion beam at ORNL—a final milestone before the facility can be used to study nuclei that cannot be produced naturally from elements that exist on the earth. The beam consisted of radioactive arsenic ions produced by bombarding a liquid germanium target with protons. In 1997, scientists from

HRIBF will serve a national and international community of about 300 scientists from 33 states and 20 foreign countries.

universities and laboratories around the world will be conducting experiments they hope will answer questions about nuclear physics and nuclear astrophysics. The first-of-its-kind facility provides a resource for unique challenges.

"The HRIBF is the only facility in the world dedicated to the acceleration of radioactive ion beams with sufficient intensity and energy to be useful for nuclear physics and nuclear astrophysics," says Jerry Garrett, scientific director of the Holifield facility. "It will serve a national and international community of about 300 scientists from 33 states and 20 foreign countries, providing a unique new tool for understanding nuclear matter, the main constituent of the visible universe."

Akito Arima, a nuclear physicist who is president of Institute for Physical and Chemical Research at RIKEN in Tokyo and former president of the University of Tokyo, said during the dedication that anticipated HRIBF discoveries could include extremely large deformed nuclei and new superheavy elements.

HRIBF's radioactive ion beams will provide a tool for creating nuclei beyond their limits of stability, helping to answer important questions about the nature of the nucleus. Two-thirds of the experiments at the facility will be devoted to studying the structure of exotic nuclei that exist for just a fraction of a second.

Typical experiments will run from a few days to a few weeks, according to Garrett, who said the beam will be available about 2500 hours a year. Usually, only one experiment can be done at a time, but sometimes two nuclear structure experiments can run concurrently.

Already, Garrett has received 16 proposals for experiments from 54 researchers at 22 institutions within the United States, Canada, France, India, Italy, Romania, and the United Kingdom. Annual beam time is limited because of maintenance activities involving the facility's components, which consist of two accelerators (the world's largest electrostatic accelerator and a cyclotron) and a high-voltage radioactive ion injector. Some of the experiments in 1997 are expected to examine the shape of radioactive arsenic nuclei and to study nuclei that decay by emitting protons.

About a third of the experiments using HRIBF radioactive ion beams ... will focus on the formation and fate of stars.

Workers completed physical construction of the facility in September 1995— on time and within budget. Researchers produced the first stable (nonradioactive) beam in late October 1995 and have been commissioning, or fine-tuning, the facility over the past several months.

Reconfiguration of ORNL's former HHIRF began in mid-1992 after DOE funded an ORNL Physics Division proposal outlining new physics opportunities that could be obtained at a low cost because no major civil construction was required. A total of $2.6 million was provided by DOE's Nuclear Physics Program Office over a four-year period ending last year.

Jim Ball, deputy associate director and former Physics Division director, acknowledged the contributions to the HRIBF project of Jerry Garrett, Dave Olsen, Jim Beene, Gerald Alton, the late Russell Robinson, the University of Tennessee's Lee Riedinger, Vanderbilt University's Joseph Hamilton, Cyrus Baktash, and Michael Smith, who heads the nuclear astrophysics initiative and spearheaded the effort to get the Daresbury Recoil Mass Separator to the Oak Ridge facility from England.

Other speakers at the dedication were Hamilton, head of Vanderbilt's Physics Department; Joseph E. Johnson, president of the University of Tennessee; Fred Bertrand, director of ORNL's Physics Division; Edward G. Cumesty, assistant manager for laboratories, DOE's Oak Ridge Operations Office; former ORNL division director Bill G. Eads, Tennessee Department of Economic and Community Development, presenting a letter from Governor Don Sundquist; nuclear physicist P. Gregers Hansen of Michigan State University; and Alvin W. Trivelpiece, ORNL director and president of Lockheed Martin Energy Research Corporation.

Hendrie concluded the dedication, saying "I see the future of physics as quite bright." ornl

Two-thirds of the experiments at the facility will be devoted to studying the structure of exotic nuclei that exist for just a fraction of a second.

Breast Cancer Treatment Method Devised

A new method capable of destroying breast tumors without surgery and side effects has been developed at ORNL. Three ORNL scientists have applied for a patent on this minimally invasive therapy for breast cancer which combines laser light and presently available drugs. The technique will be tested in animals and later human volunteers, possibly in six months to two years.

When fully developed, the technique will use a focused laser light beam that passes harmlessly through skin and delivers photons in a one-two punch to the target. The beam of light, two photons at a time, is absorbed by the targeted tumor tissue, activating an ingested pharmaceutical agent that is taken up by rapidly proliferating cells like those found in tumors. The activated agent disables the DNA of the cancer cells, halting their reproduction. Activation of the pharm-aceutical agent is limited to the focus of the beam as a result of the unique physics of the photoactivation process called simultaneous two-photon excitation.

The laser light can be focused deep within the tumor tissue, and the drug is activated only in the focus of the beam. Therefore, unlike the case with conventional radiation or chemotherapy, only tumor tissue is affected. Normal tissue is not damaged outside the focus of the beam even on its line of flight entering and exiting the body.

The ORNL scientists have already demonstrated that the technique can selectively kill *Salmonella* bacteria and human breast cancer cells. The scientists believe the technique could be used to treat skin, liver, and breast cancers as well as a variety of other cancers.

By adding specialized molecular biology reagents, the researchers believe that the laser-drug combination can function like a scalpel on genetic material without damaging the cells. Theoretically, the technique could be used to damage the AIDS virus incorporated into human genetic material without damaging the cells of the immune system where it has inserted itself. A variation of this technique can also be used to image breast tumors, thus eliminating the risks of using radiation for mammography.

The developers of this new approach for "photodynamic therapy" are Craig Dees, molecular biologist formerly with ORNL; Eric Wachter, ORNL physical chemist; Walt Fisher, ORNL physical chemist; Gil Brown, ORNL organic chemist; and Bill Partridge, ORNL mechanical engineer and

ORNL chemist Eric Wachter is part of a team that is testing the medical uses for this two-photon, near-infrared laser. The light from this laser can target and damage cancer cells by activating an ingested drug that concentrates in them. ORNL scientists in different disciplines believe their two-photon laser technique has great potential for curing breast cancer. *Photograph by Tom Cerniglio.*

postdoctoral researcher. The work was funded by ORNL's Laboratory Directed Research and Development Program.

The idea for the technique emerged one day when Fisher and Wachter saw Dees in the hall and asked him if a special laser technique could have therapeutic applications. Dees thought of the breast cancer application and went to Brown, in a room nearby, because of his ability to synthesize drugs that could be activated by laser light.

"The beauty of a national laboratory," says Dees, "is that it gives you the opportunity to bring together the right combination of specialists needed to solve complex problems. Our interdisciplinary team effort has proved to be very productive."

Dees says that many drug companies are trying to alter drugs in their search for a minimally invasive therapy for breast cancer that has no side effects. "What we have done," he adds, "is to change the fundamental activation method so that it more precisely stimulates a drug to destroy a tumor without affecting surrounding, healthy tissue."

A drug that could be safely used with this laser method is 8-MOP, a derivative of psoralen, which is approved by the Food and Drug Administration. Psoralen, a photoactive agent, is normally used with ultraviolet light to treat a variety of skin diseases and near-surface lesions, such as psoriasis and skin cancer. The Oak Ridge scientists believe that many other photoactive agents will work equally well with the new method, opening avenues to the treatment of many other diseases.

"The key to the success of our technique is effecting simultaneous absorption of two photons of low-energy, long-wavelength light within a small volume of tissue," Wachter says. "We can focus the light beam on the targeted area using a lens or mirror that can be adjusted under computer control. The laser light can penetrate the skin with the potential of striking a target at any depth."

In their experiments, the scientists use two lasers. The first is an argon-ion laser that produces visible light in the blue-green range. This light "pumps" the second laser, a mode-locked titanium:sapphire laser, so that it delivers a high-frequency pulsed beam of near-infrared light. This red beam is safe—it will illuminate but not harm the skin of your hand. But when focused at a targeted area under the skin, the light pulses have a peak power that can devastate cancerous cells.

"The mode-locked laser produces a beam that has a low average power, but with an exceedingly high peak power that is easily focused into a narrow zone," Wachter says. "As a result, we can target and destroy a cluster of cancer cells and leave normal cells intact. Two-photon laser excitation allows us to achieve pinpoint activation of therapeutic agents in a tightly controlled area. In contrast, commonly used one-photon laser excitation can cause undesirable activation at low intensities and can produce damage over far wider areas than is desired."

In experimental trials, an agarose gel tissue model has been used. A dye was dispersed throughout this thick, gelatinous material to simulate imaging agent in tissue. When the red beam from the mode-locked laser is focused in the center of the gel, an isolated point of blue light is visible at the focus. The blue dot marks the spot where the dye is fluorescing. It also indicates the point where cancer-cell-destroying chemistry would take place if a phototherapeutic agent were present in actual cancerous tissue. The same ability to focus deep in tissue has been demonstrated in a tumor that was removed from a mouse with breast cancer.—*Carolyn Krause*

Teaming Bacteria Degrade PCBs in Tainted Soils

Years ago, electric transformers did more than transfer electric energy from one circuit to another and change a circuit's electrical characteristics. They also transformed the characteristics of soils and the beds of rivers and creeks.

Before polychlorinated biphenyls (PCBs) were banned in 1977, they were used as insulating fluids for transformers and other electrical equipment. When the discarded devices deteriorated, PCBs leaked into nearby soil and water. Millions of pounds of PCBs from leaking electrical equipment and industrial discharges still remain in soil, sediments, and groundwater.

Because of their stability and lack of reactive properties, PCBs were good insulators. However, these same properties cause PCBs to persist in the environment and to resist removal. From water and soil, they enter the food chain and build up in the tissues of plants and animals. Eventually, people eating these tissues accumulate PCBs, which have been linked to birth defects, cancer, and other illnesses.

Recently, ORNL researchers have harnessed two types of bacteria to break PCBs' hold on the environment. Here's the story.

In the early 1990s, Terry Donaldson and Mark Reeves sought to remove PCBs from soil using naturally occurring bacteria. Then Reeves became the ORNL principal investigator for a cooperative research and development agreement (CRADA) involving General Electric Company. The goal of the CRADA was to find the most effective way to use bacteria from river sediments to remove toxic PCBs from the contaminated sediments of the Hudson River in New York.

When Reeves became head of the Laboratory Directed Research and

Development Program, K. Thomas Klasson became the ORNL principal investigator for the project. Klasson is leader of the Remediation Technology Group in ORNL's Chemical Technology Division. Klasson, Reeves, chemical engineer John Barton, and technician Betty Evans came up with an effective but inexpensive remediation system using two types of bacteria—anaerobic bacteria, which do not require oxygen, and aerobic bacteria, which do.

"This is an important advance," Klasson says of the results of his research. "Previously, researchers had to mix PCB-contaminated soil with river sediment to cause PCB degradation. Sediment is the only environment in which anaerobic PCB-degrading bacteria were known to thrive. We successfully transferred the anaerobic bacteria to PCB-contaminated soil and achieved PCB degradation without adding any sediment. We also developed and used our two-stage anaerobic-aerobic biodegradation method to enhance the removal of PCBs from the soil."

The toxicity and persistence of PCB compounds in the environment depend upon the number and location of their chlorine atoms. During anaerobic dechlorination, the first stage of treatment, the bacteria convert PCB compounds into less hazardous products.

When an anaerobic microbe metabolizes a PCB, it removes a chlorine atom from a PCB ring and replaces it with a hydrogen atom. As a result, the PCB is easier for an aerobic microbe to attack. The aerobic bacterium then replaces another chlorine atom with carboxylic acid (COOH), transforming the less hazardous product from the first stage into harmless carbon dioxide and water.

"The two-stage treatment degrades 70% of the PCBs in our soil samples to harmless substances," Klasson says. "Our preliminary studies show that chemical reactions between the remaining PCBs and a solution of special suspended solids to which the toxic compounds are attached eliminate the rest of the PCBs. That's encouraging because our goal is complete destruction of PCBs."

GE supplied the ORNL researchers with both anaerobic bacteria in river sediment and a strain of the aerobic bacterium *Pseudomonas*. Klasson's group separated out the anaerobic bacteria from the river sediment and successfully transferred them to soil samples from a Tennessee Valley Authority (TVA) site and ORNL. The TVA soil contained PCBs from transformers and capacitors at power substations. The ORNL soil came from White Wing Scrap Yard, which is contaminated with PCBs from electrical equipment. The work on the TVA site is

We successfully transferred the anaerobic bacteria to PCB-contaminated soil and achieved PCB degradation without adding any sediment.

Thomas Klasson and Betty Evans examine a gas chromatogram showing PCB removal by anaerobic and aerobic bacteria.

The ORNL process shows potential for complete PCB degradation.

being funded by the Electric Power Research Institute.

"Although we separated out anaerobic bacteria from the river sediment," Klasson says, "we could not isolate the strain to identify or name it."

In the ORNL study, flasks about the size of 10-oz. drinking glasses were filled with PCB-containing soil, bacteria, water, mineral salts, and an organic carbon source such as acetone. To promote mixing, many flasks were shaken in an orbital shaker. Every 3 or 4 weeks each flask was sampled to assess its PCB content. The anaerobic process takes 15 weeks to a year to reach completion.

The anaerobic process was developed for the CRADA with GE. ORNL researchers developed the aerobic process outside the CRADA. In 1997, after the Environmental Protection Agency issues a permit for field application of genetically engineered organisms, a demonstration of the anaerobic-aerobic process will be held in Chattanooga, Tennessee, by ORNL, TVA, and the University of Tennessee. The goal is to show that this approach to PCB bioremediation can be scaled up.

GE has already run two demonstrations using anaerobic bacteria at a New York site on the Hudson River and at Woods Pond, Massachusetts. "GE found that large-scale processes mimic lab experiments," Klasson says, adding that scaled-up processes will consist of large tanks in which the solution of soil and bacteria is mechanically agitated or of artificial ponds in which automated rakes do the mixing.

The work was funded by DOE's Mixed Waste Integrated Program and Buried Waste Integrated Program, both of which are part of its Office of Technology Development.

Today, Klasson says, small environmental companies are using aerobic bacterial processes to demonstrate partial PCB degradation at electrical utility sites. The ORNL process currently being developed, however, shows potential for complete PCB degradation. Someday, some version of the ORNL process may be used widely to undo electrical transformers' environmental damage by transforming PCB-contaminated soils into clean ones.—*Carolyn Krause*

Producing Hydrogen Enzymatically

Hydrogen is the fuel of dreams. If the world's most abundant element could be produced cheaply, Americans could use it instead of gasoline, reducing the U.S. appetite for imported oil and saving the country billions of dollars. This dream fuel is a clean fuel. Burn it in air and you get harmless water vapor and a few oxides of nitrogen. Unlike fossil fuels, the largest source of our energy, combustion of hydrogen does not produce carbon dioxide, a significant greenhouse gas.

To keep the dream alive, DOE's Hydrogen Program sponsored a hydrogen-powered bus during the 1996 Summer Olympic Games in Atlanta, Georgia. At one time, it was believed that hydrogen could be produced inexpensively from water by electrolysis using nuclear power, once envisioned to be a source of cheap electricity. Now, DOE is looking at other ways to produce hydrogen, including use of microorganisms.

In a dream world, where rags become riches, trash would be turned into fuel. Energy would be extracted from old newspapers, grass clippings, and cheese whey—waste products of renewable resources—to heat and light buildings and propel cars and planes. How? Use the fungal enzyme cellulase to convert cellulose, starch, and lactose—complex sugar molecules that make up these wastes—into the simple sugar glucose. Then use bacterial enzymes to convert glucose ($C_6H_{12}O_6$) into hydrogen.

In ORNL's Chemical Technology Division, Jonathan Woodward and colleagues from the University of Georgia and the University of Bath in England have demonstrated a new biological method for converting glucose into hydrogen. The process also produces gluconic acid, a metal-binding chemical widely used in the manufacture of foods and drugs and the treatment of metal.

The new process has also generated considerable excitement. Following publication of a paper by Woodward and colleagues on the method in the journal *Nature Biotechnology*, Woodward received considerable media attention from organizations such as Reuters, BBC, Voice of America, the *Washington Post*, *Washington Times*, *New Scientist*, and *Chemical and Engineering News*.

Not surprisingly, the media seemed particularly fascinated by what the Woodward paper said about newspapers. It stated that the 16 billion pounds of cellulose in a year's worth of U.S. newspapers could generate enough hydrogen to replace all the natural gas consumed by 37 cities the size of Oak Ridge (pop. 27,000).

The development of the process was supported by DOE's Office of Energy Efficiency and Renewable Resources, Hydrogen Program, Office of Utility Concepts. "Our biological process produces hydrogen at the same rates as other biological methods," Woodward says. "Right now we produce one atom of hydrogen for every molecule of gluconic acid. Under ideal conditions, we should produce 12 times as much hydrogen. We must find the best conditions to make current enzymes more efficient and experiment with other enzymes to extract more

The 16 billion pounds of cellulose in a year's worth of U.S. newspapers could generate enough hydrogen to replace all the natural gas consumed by 37 cities the size of Oak Ridge.

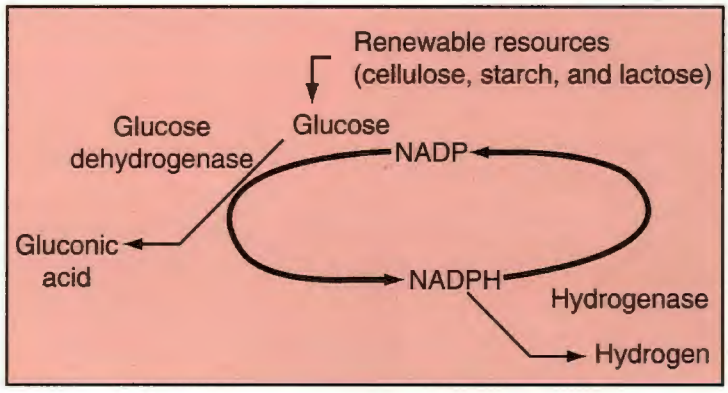
hydrogen from glucose and convert gluconic acid to hydrogen."

At the same time, Woodward's group is trying to tackle the more difficult first step of the two-step process of making hydrogen from cellulose and other complex sugar compounds that are abundant, inexpensive, and renewable. "The bottleneck in the cellulose-to-glucose process is the cellulase enzyme," says Woodward, who has long been experimenting with the fungal enzyme cellulase to increase its efficiency in breaking down cellulose into glucose. "We need a stable enzyme that works faster to catalyze production of glucose from cellulose. Right now it takes two days to produce glucose from cellulose. Our goal is to make cellulase ten times faster to get glucose in 30 minutes to an hour."

In the new process, glucose is combined with glucose dehydrogenase, a bacterial enzyme. In the presence of a compound called NADP, this enzyme converts a glucose molecule into gluconic acid and attaches a freed hydrogen atom to NADP, forming NADPH. Another enzyme, a hydrogenase isolated from bacteria found in a deep-sea hydrothermal vent, then releases the hydrogen from NADPH, generating hydrogen gas and enabling NADP to repeat the cycle. The process requires a temperature of 50°C (122°F).

The hydrogenase used is an expensive enzyme that Woodward obtained from Mike Adams of the University of Georgia. Woodward learned about it from his former section head, Chuck Scott, who bought the enzyme from Adams for his experiments in using bacteria to liquefy coal. "Hydrogenase," says Woodward, "is one of two enzymes that I know about that will accept electrons from NAPDH to evolve hydrogen."

Once the enzyme process for producing hydrogen from complex sugars is optimized, the next step will be to find ways to make inexpensive enzymes so that the process will be practical for industry. "Through genetic engineering," Woodward says, "scientists should come up with cheaper enzymes. They will isolate and clone microbial genes responsible for the desired enzymes. To churn out the enzymes in great quantities, the cloned genes could be inserted into rapidly reproducing *E. coli* bacteria."



This bacterial enzyme process converts glucose from renewable resources into hydrogen.

The enzymes would likely be placed in a bioreactor column, where they would convert cellulose into glucose, and glucose into hydrogen. It's the stuff of dreams now, but someday it may be reality.—*Carolyn Krause*

Miniature Night-vision Camera Devised

Night-vision cameras similar to those that helped make Desert Storm a success could become a safety feature in automobiles and commercial aircraft because of a discovery by ORNL researchers.

Infrared night-vision imaging systems typically installed in military vehicles and aircraft cost about $100,000, making them impractical for most civilian applications. Researchers at ORNL, however, have developed a revolutionary uncooled micro-cantilever infrared camera using microcantilevers, which are similar to miniature phonographic needles. The new technology could improve resolution and reduce the cost to less than $1,000 per unit if mass production can be achieved.

In automobiles, night-vision cameras could allow drivers to see past oncoming headlight glare and beyond what they can see with headlights. These cameras would most likely be used in much the same way drivers use rear-view mirrors, for occasional but vital monitoring of traffic. Aboard airplanes, infrared cameras could aid pilots when weather conditions reduce visibility.

While conventional infrared night-vision systems require cryogenic coolers, sophisticated optics, and costly sensor materials, ORNL's uncooled microcantilever infrared camera uses inexpensive, mass-produced silicon microcantilevers and a mirror.

"The heart of this novel camera consists of a mirror and a cantilever placed at the focus of the mirror," says

Thomas Thundat, principal researcher and a member of ORNL's Molecular Imaging Group, a part of the Life Sciences Division. "The mirror forms an infrared image of the object to be photographed. Brighter areas of the image formed at the focal plane have a higher number of photons and are, therefore, hotter compared to darker areas. The infrared photograph is taken by scanning the cantilever sensor over the image at the focal plane."

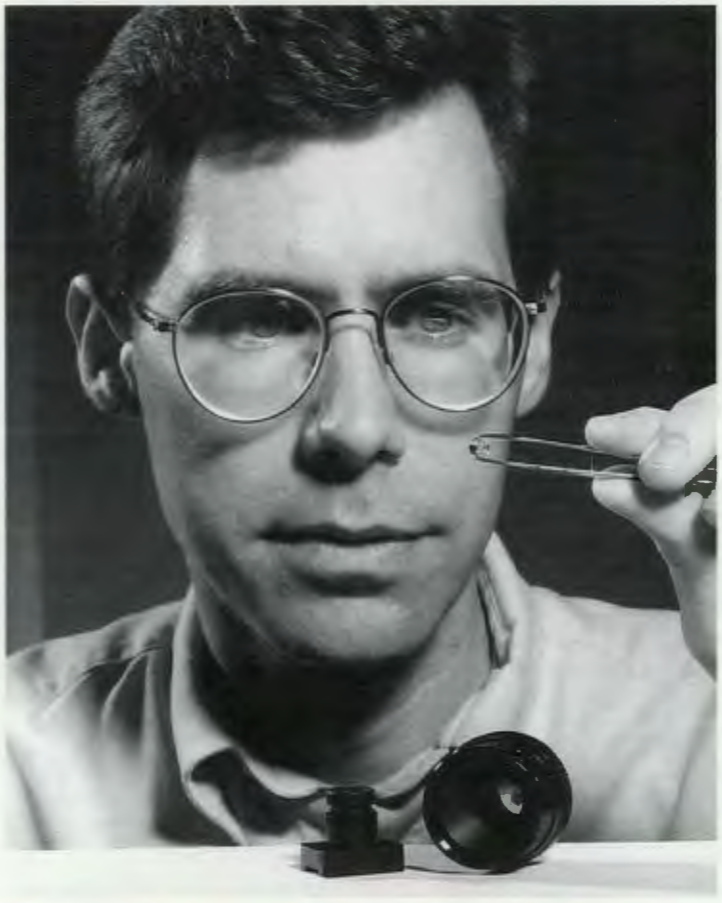
As the cantilever scans the focal plane, the amount of cantilever bending changes with brightness of the image because of heat absorption by the cantilever. This bending is monitored as electrical resistance changes in the cantilever and is displayed as a two-dimensional photograph of the object.

Instead of scanning using a single cantilever, ORNL's team is developing a device that can generate instantaneous photographs by using a two-dimensional array of microcantilevers closely packed on a support structure.

Research for the uncooled microcantilever infrared camera was funded in part by DOE's Environmental and Biological Sensor Development Program and by the National Science Foundation. Thundat and colleagues Bruce Warmack, Rick Oden, and Panos Datskos envision possible use of the camera in hundreds of industry process control systems, military operations, automobiles, airplanes, and security systems. It could also be adapted for use by firefighters and for energy conservation.

According to the researchers, the main advantages of the uncooled microcantilever infrared camera are its lower cost, reduced size, and ability to operate without liquid nitrogen cooling—thus, the use of "uncooled" in its name.—*Ron Walli*

The hidden lens makes the camera unobtrusive, and that's important to law enforcement personnel.



A special diffractive optical element is the key to ORNL's patented lens, which is about the size of a button. David Sitter (above), an inventor of the lens, says that ORNL overcame a technological barrier by shrinking the size and number of lenses in the optical system. The ORNL unit uses just two lenses. ***Photograph by Tom Cerniglio.***

Miniature Camera Increases Security

A miniature video camera small enough to fit in a badge has been developed at ORNL to help police officers and guards maintain security. Lockheed Martin Corporation has licensed the ORNL technology to Turtle Mountain Communications.

Researchers in ORNL's Instrumentation and Controls (I&C) Division have adapted a commercial video camera to make it easier for law enforcement personnel to use. The researchers reduced the size of the lens and equipped it with a transmitter that sends the picture to a site up to 30 meters (100 feet) away, such as a police car.

Preston Leingang, president of Turtle Mountain Communications in Maryville, says the camera should be able to transmit pictures to a remote location, such as a police station, after further development. Turtle Mountain Communications specializes in communications suites for command, control, communication, computer, and intelligence systems Another key feature of the camera is its disguised lens. The aperture, which admits light into the optical system, has been moved from the middle of the lens mechanism to the front, leaving only a pinhole size opening. "The hidden lens makes the

camera unobtrusive," says co-inventor David Sitter, "and that's important to law enforcement personnel."

The researchers have submitted a proposal to the National Institute of Justice to commercialize the camera in a joint venture with Turtle Mountain Communications. Their goal, says Richard Crutcher of the I&C Division, is to cost-efficiently enhance a commercial camera containing single-chip electronics with new lens developments.

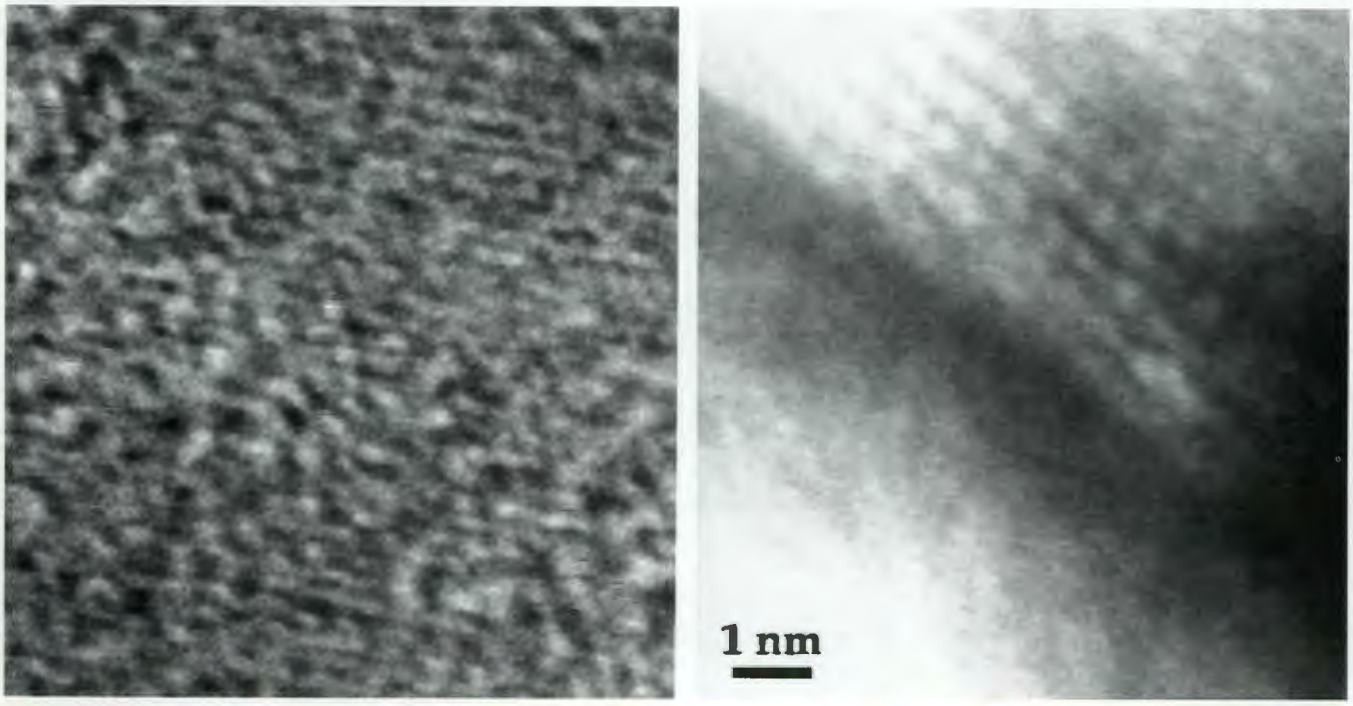
The researchers expect the camera to be a little larger than a microcassette case, making it possible to place it in a police or security badge or other small object.

"This technology has been looked at by a number of customers," says Scott McKenney of ORNL's Special Projects office. "Potential user agencies have overwhelmingly been impressed with the technology and consider it to be state of the art."

Leingang is enthusiastic about his company's involvement in this project. "Many people are not aware that the U.S. government can assist businesses with new technologies," he says. "A lot of companies just don't have the money to do the research necessary to make technological advancements. National laboratories are essential to the future of high-technology ventures."

Correction

Because of omissions in communication, a faulty version of the following images was printed on p. 60 of the Vol. 29, Nos. 1&2, 1996 "State of the Laboratory" issue of the *Review*. The correct images below are related to research on catalysts used to reduce pollutant emissions from automobiles.



Images of a rhodium catalyst supported on gamma alumina taken with the 300-kilovolt scanning transmission electron microscope. In the phase contrast high-resolution image (left), the type of image normally taken with conventional microscopes, the rhodium is invisible. However, the rhodium is seen clearly in the Z-contrast image (right), taken simultaneously from the same region. The arrangement of the rhodium atoms corresponds to no known form of metal or oxide, but does correspond to normally vacant atomic sites in the alumina. The rhodium is thought to have dissolved into these normally empty sites, where it will no longer be catalytically active. This image reveals clearly for the first time how a catalyst can lose its activity through aging, limiting its automotive applications.

Technology Transfer Award for Useful Crystal Substrates

They don't peer into a crystal ball to predict the successful materials of tomorrow, but ORNL researchers Lynn Boatner and Ron Feenstra study many crystals in the search for new technologically important materials. If they had been able to read a crystal ball, however, they might have foreseen that their pioneering research on single crystals for thin-film growth would eventually be recognized through a prestigious 1997 technology transfer award as well as a 1996 Research and Development (R&D) 100 Award.

Boatner and Feenstra, both physicists in ORNL's Solid State Division, received a Federal Laboratory Consortium (FLC) Award for Excellence in Technology Transfer on April 15, 1997, in East Brunswick, New Jersey. The award citation reads, "For the development and production of new single-crystal substrates for the growth of epitaxial electro-optic and superconducting thin films." A substrate is an underlying template that lines up the atoms of a crystalline thin film grown on it, much as a waffle iron confers a grid pattern on batter poured into it while hot.

The FLC award specifically recognizes the ORNL scientists' research and development involving single crystals of magnesium oxide (MgO) for a wide range of uses and the development, patenting, and licensing of a new family of thin-film substrates based on the cubic-perovskite material, potassium requirements: It must have a crystalline structure that matches that of the thin film and that aligns the film's structure so that electrons or light can be conducted through the film. The substrate should also be chemically compatible—that is, when the film is deposited on the substrate at an elevated temperature, the substrate should expand at the same rate as the film when both are heated; if the thermal expansion rates are different, the substrate could break or strain the film.

Few compound crystals can meet these criteria in general, but single-crystal MgO is an excellent substrate that is used with barium titanate for optical modulators and switches, with yttrium-barium-copper oxides (YBCO) for superconducting thin films, and with other oxides as a substrate for optical waveguide films. However, for some devices, the typical MgO crystal size has previously been too small.

Through a three-year cooperative research and development agreement (CRADA), ORNL and its industrial partner succeeded in perfecting techniques for the reproducible growth

Dramatic increases in the average size of high-quality, arc-fusion-grown magnesium oxide single crystals (see photos above and at right) have resulted from a cooperative research and development agreement between ORNL and Commercial Crystal Laboratories, a small U.S.-owned crystal-growth company in Naples, Florida.

The result of the ORNL CRADA was the growth of large optical-quality MgO crystals at … the size that the customers sought.

of larger single crystals of MgO. The crystal industry had been making and marketing MgO crystals up to about 2.5 centimeter (1.0 inch) in diameter, but some customers wanted larger substrates in order to develop new electronic and optical devices. The result of the ORNL CRADA was the growth of large optical-quality MgO crystals at least 5 to 7.6 centimeter (2 or 3 inch) in diameter—the size that the customers sought (see photographs). This new MgO crystal-growth technology will help U.S. high-technology firms avoid total reliance on foreign suppliers of MgO substrates.

Large MgO substrates for thin films of various materials could be used for devices based on high-temperature superconductors and for optical switches and modulators for light-based communication networks and all-optical computers. Because infrared light from heat sources can be passed through MgO at high temperatures (and is absorbed by most other crystals at the same temperature), MgO windows and lenses can be used for chemical analysis (infrared spectroscopy) and for satellite sensors for remote detection of heat-producing processes on the earth. Other existing and potential applications of large MgO single crystals include optical components in the aerospace and defense industries and as filters and monochromators in DOE-supported neutron-science research.

Crystals of potassium tantalate/niobate grown at ORNL have been shown to make excellent substrates to support thin films of superconducting material such as YBCO. As a result, these new substrates received an R&D 100 Award in 1996 (see photograph and announcement on pp. 88–84) and the technology for producing these crystals has been patented and licensed to Commercial Crystal Laboratories of Naples, Florida.

Potassium tantalate is an excellent substrate because it is mechanically stable (it provides good support to thin films) and it is chemically stable (it doesn't react with thin films during deposition or with water vapor in the air prior to film growth). As an atomic template, it properly arranges the film's atomic structure through epitaxial growth so that the ferroelectric, metal, or superconducting films can exhibit good electronic and optical properties.

In some of his early experiments while doing research in Lausanne, Switzerland, Boatner added elemental dopants such as calcium and barium to the potassium tantalate crystals. He

found that the addition of various amounts of these impurities made the crystalline material semiconducting. Therefore, the substrates could be made in either an insulating or conducting form.

By adding niobium, it is also possible to turn the crystal into a ferroelectric material. Such a material exhibits a polar separation of positive and negative electrical charges and properties that can be switched when an electric field is applied.

These new substrates are useful because of the important applications of devices made using the thin films that are grown on them. High-temperature superconducting films are currently being developed for a variety of electronic devices such as magnetic sensors for medical, geological, and industrial applications; microwave components for radar and communication technologies; and ultrafast switches, interconnects, and current leads. Additionally, potassium tantalate can be used as a substrate for dielectric and ferroelectric materials, such as barium titanate and lead titanate, or for electro-optic materials such as pure potassium niobate. Applications for these materials include miniature "super" capacitors, digital circuitry devices for information storage, and integrated and hybrid optical components.

Potassium tantalate substrates can be produced as large wafers—with a diameter of 5 centimeter (2 inch) or more—because of the crucible-based fabrication method employed. In contrast, other candidate substrate materials, such as strontium titanate, require a flame-fusion fabrication process, which generally limits the crystal size to 2 centimeter or less (less than 1 inch in diameter). The larger wafer size of potassium tantalate substrates is advantageous because it reduces the fabrication cost of thin-film devices that are grown on the substrate material. Commercial Crystal Laboratories has developed improved ways to prepare epitaxial-quality surface finishes on these substrates and is currently marketing the material for commercial and research applications.—*Carolyn Krause*

Licensed Technologies Will Help Produce Diagnostic Radioisotope

Patients afflicted with heart, lung, liver, or brain disorders and the U.S. health care industry may soon be benefiting from new ORNL technology if a Knoxville company has its way.

On December 23, 1996, two licensing agreements were signed by Lockheed Martin Energy Research Corporation, which manages ORNL for DOE, and DeRoyal Industries, Inc., a Knoxville-based health care products manufacturer. DeRoyal Industries was granted rights to two new ORNL technologies for concentrating solutions of the technetium-99*m* radioisotope, the most widely used diagnostic radioisotope in nuclear medicine.

More than 36,000 diagnostic tests using technetium-99*m* agents are conducted daily in the United States (10 to 12 million tests annually). These agents are used for imaging the heart, liver, lungs, brains, and most other major organs in the body. The use of technetium-99*m* allows the diagnosis of many conditions, such as blockages of arteries of the heart or poorly functioning organs. Unlike techniques such as magnetic resonance imaging and X-ray scans, radioactive diagnostic agents such as technetium-99*m* can be used to evaluate tissue function rather than only the anatomical changes of diseased tissues. Because of the technetium isotope's short half-life, the patient's exposure to radiation is very low.

DeRoyal Industries, which was founded by Pete DeBusk in 1973, employs about 2000 people at its facilities in 38 countries. DeRoyal's international sales, which are in excess of $250 million, primarily involve soft goods such as operating room procedure trays, surgical accessories, and critical care and wound care products. The company also produces computer software for hospitals.

The new ORNL technologies are simple, efficient concentration methods that are required when dilute technetium-99*m* solutions are obtained from radionuclide generators. A generator is a device that contains a parent radioisotope and the decay product it yields. Technetium-99*m* solutions are prepared from the decay of the molybdenum-99 parent radioisotope, which is most often conventionally produced in a nuclear reactor as a byproduct of the fission of uranium-235.

Currently, the U.S. supply of molybdenum-99 comes from an aging Canadian reactor. To ensure a reliable future supply, DOE plans to produce the isotope using facilities at Los Alamos and Sandia national laboratories. There, stainless steel tube interiors will be coated with highly enriched uranium and irradiated in a reactor. The tubes will be opened, the enriched uranium coating dissolved, and the molybdenum-99 extracted from numerous fission products. The problem with this process is the large amount of radioactive waste that is generated.

In the envisioned Oak Ridge approach, an enriched molybdenum-98 product would be produced in ORNL's calutrons at the Oak Ridge Y-12 Plant, which separate stable isotopes electromagnetically. The molybdenum-98 would be placed in ORNL's High Flux Isotope Reactor (HFIR), where it would capture a neutron, forming molybdenum-99. This product would then be introduced into large-scale radionuclide generators from which

ORNL's radionuclide generator technology for producing technetium-99m produces no highly radioactive waste that requires special storage and disposal.

dilute technetium-99*m* solutions would be extracted and concentrated. The generators and concentrators would be built by DeRoyal Industries near the HFIR.

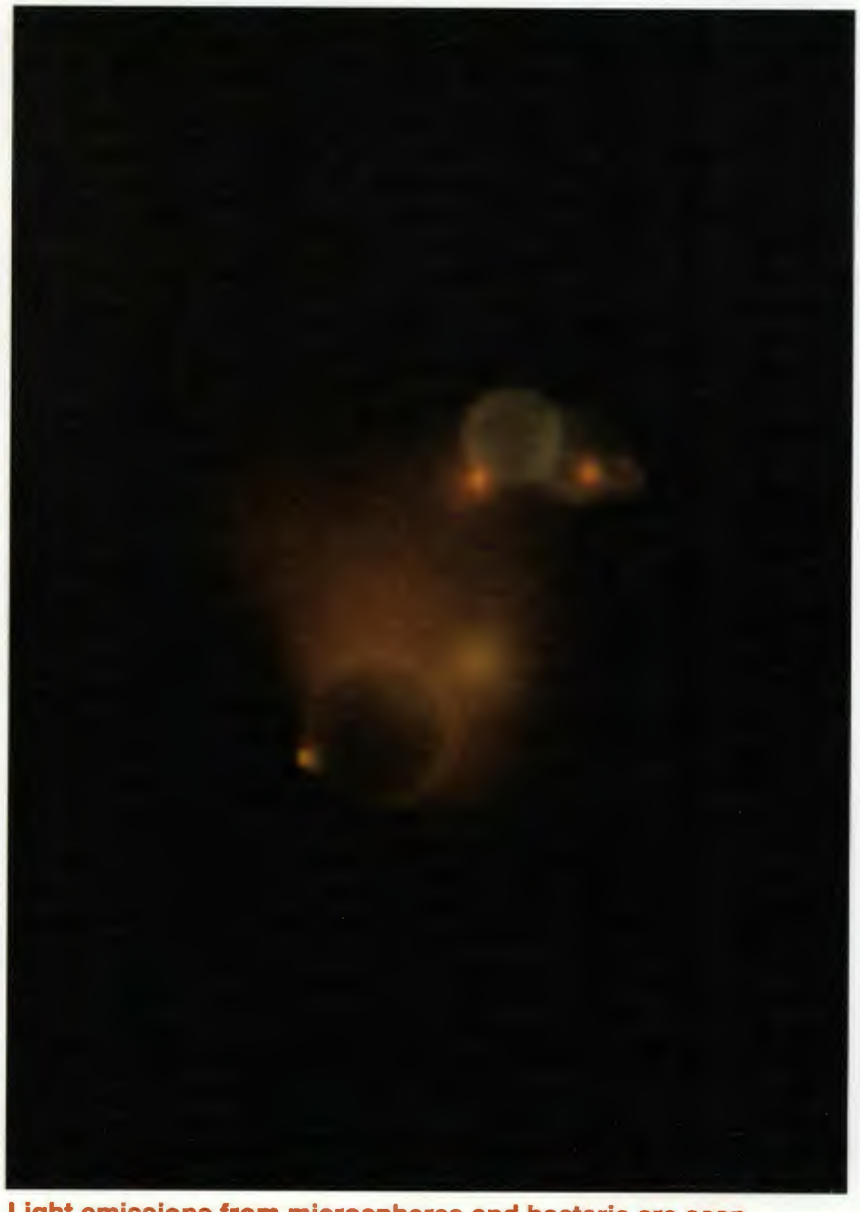
ORNL's radionuclide generator technology offers several advantages over the conventional technology planned for producing technetium-99*m*. It is simpler and faster. Highly enriched uranium is not required as the starting material. Perhaps most important, it produces no highly radioactive waste that requires special storage and disposal.

The new technology will require approval from the U.S. Food and Drug Administration prior to clinical use. It could make use of the HFIR and several other reactors in the United States, enabling the nation to avoid reliance on imports of molybdenum-99 from foreign sources.

Inventors for one patent for technology developed between ORNL's Chemical Technology and Life Sciences divisions for which exclusive rights were granted to DeRoyal Industries are Saed Mirzadeh, F. F. (Russ) Knapp, Jr., and Emory Collins. The inventors on a second patent for which non-exclusive rights were given for technetium-99*m* concentration technology are ORNL Nuclear Medicine Group members Knapp, Arnold L. Beets, Mirzadeh, and Stefan Guhlke, from the Clinic for Nuclear Medicine in Bonn, Germany, who worked with the Nuclear Medicine Group as a postdoctoral fellow for six months through July 1996.

Pete DeBusk, DeRoyal Industries president and chief executive officer, expects to develop a global market for this technology. He estimates that approximately 30 persons will be employed in the Oak Ridge area for production of the generator and concentrator units. Production is expected to begin within 2 to 3 years. Annual sales could reach about $75 million. DeRoyal also announced plans to invest $5 million to $10 million in the construction of a new processing facility at ORNL near the HFIR.

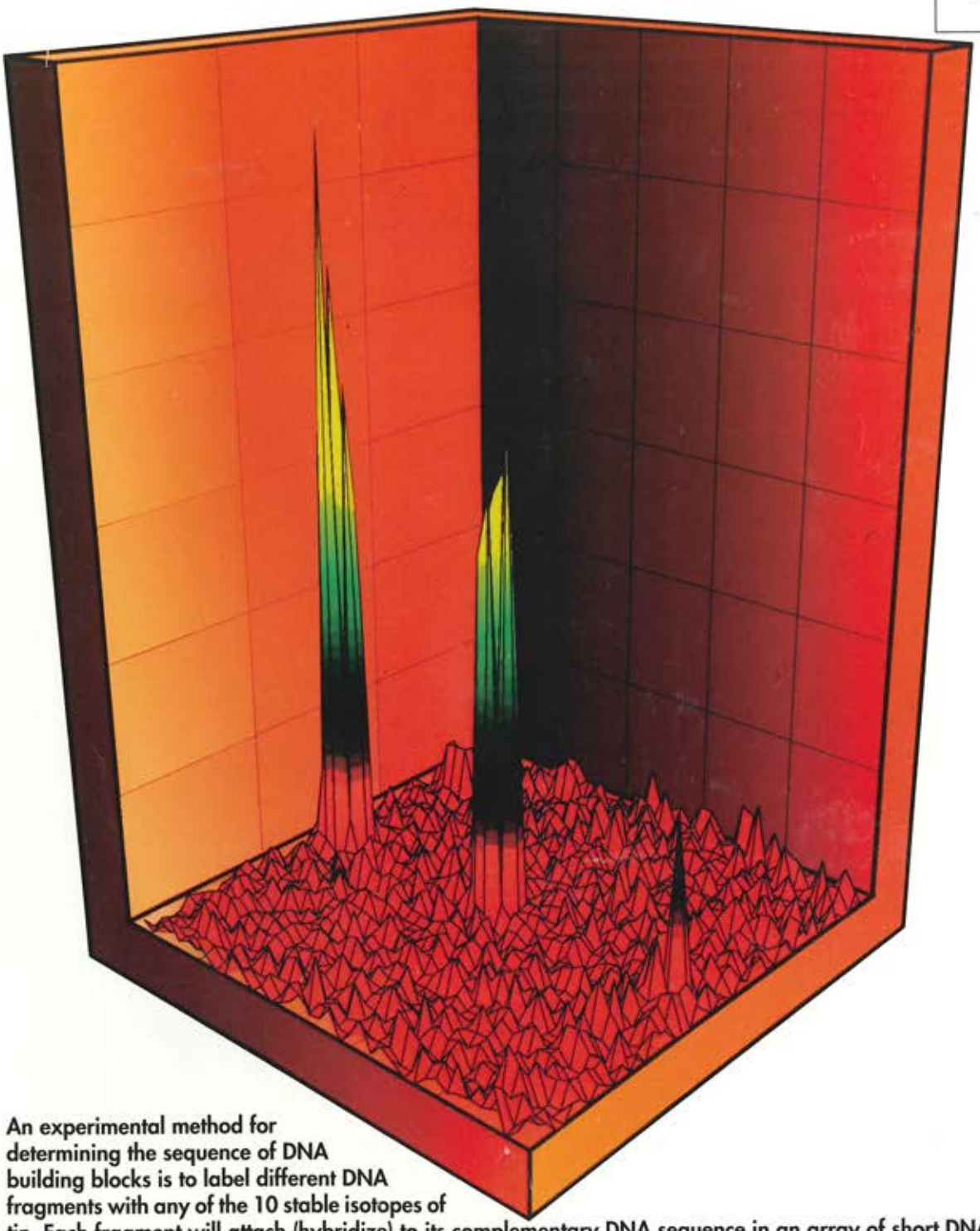
Glowing Spheres



Light emissions from microspheres and bacteria are seen through a fluorescence microscope. Shown are red-fluorescing *S. aureus* bacteria bound to 6.5-μm spheres and one yellow orange-fluorescing *E. coli* bound to the larger 10-μm sphere. For more details, see column 3 on p. 54 of the article "Biosensors and Other Medical and Environmental Probes."

OAK RIDGE NATIONAL LABORATORY *REVIEW*
P.O. Box 2008, Oak Ridge, Tennessee 37831-6144

U.S. Postage
PAID
BULK RATE
Oak Ridge, Tenn.
Permit No. 3



An experimental method for determining the sequence of DNA building blocks is to label different DNA fragments with any of the 10 stable isotopes of tin. Each fragment will attach (hybridize) to its complementary DNA sequence in an array of short DNAs on a nylon surface. Along with other atoms removed by laser from the surface, the tin atoms are obtained and then ionized selectively by laser and separated in a mass spectrometer. By measuring the concentration of each tin isotope, the relative order of DNA bases can be determined. The graphic above shows the relative concentrations of hybridized DNA sequences labeled with tin-118. At other sites on the nylon surface, the tin-118 concentration is negligible. For details, see p. 64 of the article "Biosensors and Other Medical and Environmental Probes."