Oak Ridge National Laboratory
REVIEW
• MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY •

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Back to the Future: Nuclear Energy Research

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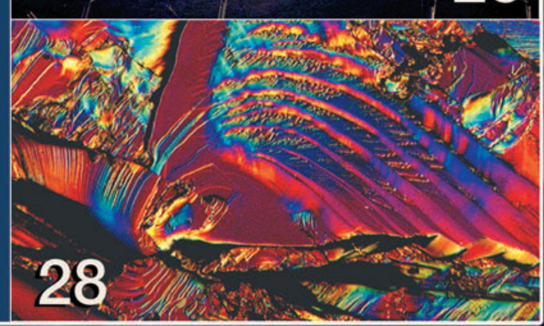
Features



COVER: Overhead view of ORNL's High Flux Isotope Reactor pool after shutdown. Reactor personnel push poles into the pool to prepare the reactor for refueling.

BACK TO THE FUTURE

Nuclear Energy Research at ORNL

The widespread concern over the role of carbon dioxide in global warming has led to a growing realization that nuclear energy is the only commercially available, carbon-free form of large-scale energy production. Thus, a broad consensus has emerged that nuclear energy must remain a vital part of the energy mix for our nation. As a result, the current administration featured nuclear energy prominently in the Energy Policy Document issued in 2001. Furthermore, Congress is currently debating a new energy policy that envisages a larger role for nuclear energy research in the future and authorizes research into advanced reactors for hydrogen cogeneration and the nuclear fuel cycle.

In response to this growing national interest in nuclear energy, Oak Ridge National Laboratory formed the Nuclear Science and Technology Division (NSTD) in October 2001 to consolidate the nuclear capabilities at the Laboratory. As the Laboratory's largest research division, NSTD, together with the unparalleled materials development expertise in ORNL's Metals and Ceramics Division, provides the basis for ORNL to be a leader once again in nuclear-related research. Many of today's nuclear reactor challenges call upon ORNL's past experience and expertise in particle fuels, materials, nuclear power systems, and gas centrifuge technologies—giving our work a "back to the future" theme.

Four main issues impede the development of nuclear energy: economics, waste, nonproliferation, and safety. ORNL is engaged in programs that address all of these issues in either current or future nuclear systems. This issue of the *ORNL Review* highlights a broad spectrum of programs that utilize ORNL's unique capabilities to address these issues. Nonetheless, some significant areas of nuclear work performed at ORNL (for example, research related to nuclear medicine and nuclear security) are not included. Although most of the programs described here rely on unique ORNL technologies and capabilities, such as particle fuels and gas centrifuges, many of the programs are collaborative in nature. Our research partners include commercial entities such as the United States Enrichment Corporation, other national laboratories, and various National Aeronautics and Space Administration facilities.

As the country reinitiates research and development efforts aimed at producing a new generation of nuclear technologies that address the key issues for nuclear energy, the cooperative efforts of the whole nuclear infrastructure in the United States will be needed to make this a successful endeavor. An increasing amount of international cooperation will be required. Exactly how these partnerships will develop is unclear, but develop they will. Because of its combination of critical technologies, dedicated staff, and long-established experience of cooperation with both domestic and international partners, ORNL is well positioned to help lead the nuclear renaissance.

David J. Hill
Associate Laboratory Director
Energy and Engineering Sciences

NUCLEAR POWER AND HYDROGEN PRODUCTION

FABRICATING FUELS

ORNL is improving the process of producing reliable coated-particle fuels for advanced gas-cooled nuclear reactors that will provide electricity and hydrogen.

Over the past decade, increased public pressure to provide more electricity, reduce air pollution, and slow the rate of global warming has led many Americans to revisit the potential of nuclear power to meet anticipated demands for more energy. The Department of Energy and others in the scientific community are interested in adapting the gas-cooled reactor for use both in producing hydrogen for fuel cells to power cars and buildings and in supplying electricity competitively.

Studies indicate that these advanced reactors—which would operate at a much higher temperature than the water-cooled reactors that produce 20% of our nation's electricity—could convert 43% of their fuel-core heat into electricity, much higher than the 31% efficiency of today's reactors.

Oak Ridge National Laboratory is contributing to this effort by improving how coated-particle fuels are made. According to David Williams of ORNL's Nuclear Science and Technology Division (NSTD), these nuclear fuel particles—some 4 billion in each reactor—must be able to withstand the reactor's high temperature and neutron radiation from heat-generating fission reactions.

"Regulations allow a fuel failure rate of only 1 in 100,000 particles," he says, explaining that maintaining the integrity of the particle coating is the key to avoiding fuel failure. "To ensure protection of workers and the public, only a small fraction of fuel failure is tolerated, to minimize the amount of radioactivity released to the coolant."

Perfect Spheres

The fuel being perfected for gas-cooled reactors would provide an additional level of safety. The meltdown-proof fuel particles would function as miniature reactors with their own containment. Each unit of fuel is a dark gray uranium bead shrouded in black carbon-containing coatings that trap and retain radioactive fission products, preventing their escape into the environment. The coated fuel particles—as small as ballpoint pen balls—would be compacted into fuel sticks embedded in a graphite block, which would moderate the neutrons and enable passage of the coolant, helium gas.

Since the early 1960s ORNL researchers have made important strides in developing and testing coated-particle fuel for high-temperature, gas-cooled reactors. Funding levels for this research that dropped after the 1979 accident at the Three Mile Island nuclear power plant have risen again. Drawing on four decades of experience, ORNL's modern researchers are taking advantage of state-of-the-art instrumentation, microwave technology, and computer modeling to create and produce efficiently the best possible coated fuel particles for advanced gas-cooled reactors.

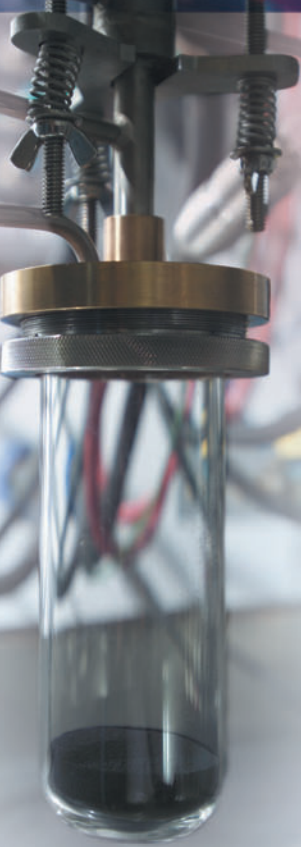
In the late 1970s, ORNL's Milt Lloyd learned about a type of sol-gel process called internal gelation from its inventor, M. E. A. Hermans of the Netherlands. Lloyd brought back this knowledge to ORNL's sol-gel group. Today, chemist Jack Collins has become ORNL's expert on using the hexamethylenetetramine (HMTA) internal gelation process, which begins with black pellets of depleted uranium dioxide and ends with perfect black uranium dioxide beads. Collins and Rodney Hunt, both of NSTD, will eventually produce beads enriched to 20% in uranium-235.

In the early 1980s, Lloyd, Collins, Paul Haas, and others were interested in using internal gelation only to make different sizes of fuel spheres. "We are tailoring the chemistry to make beads of one size with the right density and smooth surfaces so the coatings won't have structural flaws," Collins says of their efforts today. "The goal is to determine a fail-safe formula that consistently produces the desired kernel product and a process that can be scaled up by the chemical engineers."

In the bead-making process perfected by Collins, pellets of uranium oxide are mixed with nitric acid to make acid-deficient uranyl nitrate, which is cooled, combined with a chilled HMTA and urea solution, and dispatched to an injector system. This chilled stream (0°C) is dispersed into perfect drops of uniform size, with the help of controlled vibration, and is caught in a veil of silicone oil. The temperature difference causes the droplets to precipitate into perfect solid spheres and to flow with the oil without coalescing. The oil maintains the spherical shape of individual droplets.

As they leave the column, the gel spheres travel through a few yards of plastic tubing. The beads are then collected in a stainless-steel, wire-mesh basket and washed with tricholoroethylene (TCE), to remove the surface layer of silicone oil, and with dilute ammonia solution, to remove unwanted reaction products from the spheres. The spheres are heat-treated

Yellow air-dried hydrous uranium oxide beads produced at ORNL are then sintered to make black uranium oxide beads of high density. The sintered spheres are then coated using an ORNL-developed process.



Coated fuel particles are collected after carbon-containing gases are flowed up through a heated "funnel" into which uncoated particles are poured, in a process called fluidized-bed chemical vapor deposition.

to form a dense ceramic "kernel" that is used as the starting point for the coating process. NSTD staff plan to work with Terry White of the Fusion Energy Division to use a microwave furnace to heat the chilled broth to form the gel spheres. In this way, the hot silicon oil and TCE steps can be eliminated.

Coatings and Characterization

During irradiation, the nuclear kernel will undergo fission, causing it to swell and give off fission products that span the periodic table, including radioactive gases. Each uranium kernel will be coated at ORNL to form a tiny pressure vessel.

Rick Lowden is in charge of coating the nuclear fuel kernels, John Hunn heads the group characterizing the fuel particles' coatings, and Peter Pappano compacts the coated particles into graphite fuel sticks that are inserted into the large holes in a hexagonal-graphite fuel element block; the small holes encircling the large ones allow the helium coolant to flow. All three researchers are with ORNL's Metals and Ceramics Division.

"Each fuel particle is coated with four layers, starting with an inner carbon buffer layer, followed by a pyrolytic carbon coating, a silicon carbide layer, and an outer pyrolytic carbon layer," Lowden says. "Each layer has its own function. The buffer layer consists of porous carbon derived from a gas mixture containing acetylene, typically used in cutting and welding torches. The mixture produces a very soft, porous coating that accommodates fission product recoils from the kernel surface, provides a space for the fission gas released from the kernel, and accommodates kernel swelling without transmitting a force to the outer layer. The second 'sealant' layer, which is made of hard, dense carbon, helps trap the fission products inside and protects the fuel kernel from chlorine generated during the deposition of the next coating.

"Because the silicon carbide layer does not change much during irradiation and is impervious to gaseous fission products, it serves as the primary structural component of this miniature pressure vessel. The silicon carbide also protects the inner layers from an accidental introduction of air—carbon will burn up in oxygen. Additionally, because ceramics are brittle and could be susceptible to damage during handling and compaction, another hard carbon layer is added to the outside to protect the silicon carbide layer."

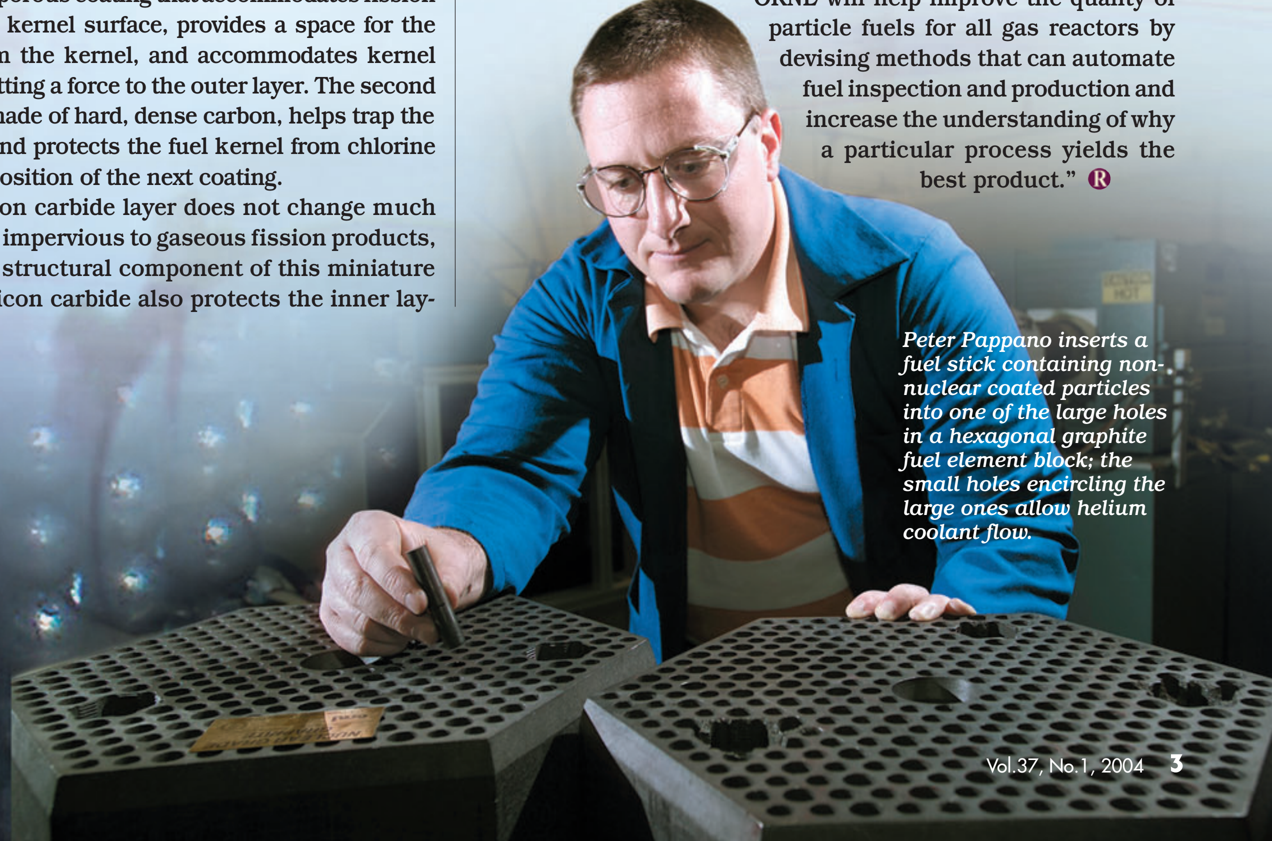
The coatings are produced using a fluidized-bed chemical vapor deposition process first investigated at ORNL some 40 years ago. Uncoated or partly coated kernels are poured into a funnel inside a heated furnace. Fluidizing and reactant gases are flowed from the bottom up, "stirring up the particles, like the Ping Pong balls in a lottery machine," Lowden says. Different gas mixtures are used to deposit carbon and silicon on the fuel kernels.

"We are improving this process by incorporating advanced process monitoring and control techniques developed in other industries," Lowden explains. "Full automation removes human error from the process."

ORNL is also taking advantage of the computer models developed to examine other applications of fluidized beds, such as combustors or chemical digesters. "The combination of a well-controlled and instrumented furnace and computer modeling will help us to improve the process and, it is hoped, make better fuel," Lowden says. "This approach should also simplify the scale-up of the process."

John Hunn's team is tasked with characterizing the kernels and coated particles. Intimate knowledge of the microstructure and properties of the kernel and coatings is paramount to understanding the relationships among processing, product, and irradiation performance. Like Lowden, Hunn is exploiting recent advancements in materials characterization techniques and exploring new methods, to more fully understand the behavior of the various components.

"We're also looking at developing a higher-temperature fuel or fuel for reactors with a different neutron spectrum in which, for example, silicon carbide is replaced with zirconium carbide or titanium nitride," says Lowden. Says NSTD's David Williams: "ORNL will help improve the quality of particle fuels for all gas reactors by devising methods that can automate fuel inspection and production and increase the understanding of why a particular process yields the best product." Ⓡ



Peter Pappano inserts a fuel stick containing non-nuclear coated particles into one of the large holes in a hexagonal graphite fuel element block; the small holes encircling the large ones allow helium coolant flow.

FUTURE REACTOR MATERIALS

CAN THE NEXT GENERATION TAKE THE HEAT?

ORNL is the U.S. leader in developing materials for 21st-century, high-temperature nuclear plants that will produce power and hydrogen.

Advanced materials that will be used in components of Generation IV reactors must be able to survive intense neutron exposures, corrosive environments, and high temperatures.

Oak Ridge National Laboratory has long been a world leader in materials research, and now with the resurgence of interest in nuclear energy, ORNL has a leading role in developing and selecting materials for the next generation of nuclear power plants. According to the vision of the U.S. government for 2015 and beyond, these plants will produce hydrogen as well as electricity, efficiently providing clean energy for the next generation of cars, trucks, homes, and factories. To achieve the vision, the Department of Energy has called upon ORNL to help cross one huge hurdle: finding materials that can withstand high temperatures, high radiation levels, high pressures, and harsh chemical conditions.

As the National Technology Director for Materials for DOE's Generation IV Reactor Program, ORNL's Bill Corwin understands the challenge. DOE's Office of Nuclear Energy, Science and Technology, has the U.S. lead for the International Generation IV Nuclear Energy Systems Initiative, which includes 10 partners from 9 other nations, as well as the European Union.

Corwin is building a team to resolve the materials issues for the four reactor concepts that DOE favors out of the 122 concepts considered in a recent international road-mapping process. The four selected concepts are the Very High Temperature Reactor (VHTR), the leading candidate for hydrogen production; the Gas-Cooled Fast Reactor (GFR); the Lead-Cooled Fast Reactor (LFR); and the Supercritical Water-Cooled Reactor (SCWR), a much-higher-efficiency variant of the boiling-water reactor.

"We understand that a limiting factor for these reactors will be the materials used in their operation," Corwin says. "Reactor materials will be exposed to very high temperatures, intense neutron radiation, and corrosive environments—in many cases, all three at once."

DOE's goal for Gen IV nuclear energy systems is a 60-year life rather than the 40-year life of today's light-water reactors. Because some of these reactors will produce process heat for hydrogen generation, the equation for materials compatibility changes.

"In a future hydrogen production plant, a reactor may be connected by a long pipe to a chemical plant to produce hydrogen, using the reactor's heat to drive a thermochemical separation cycle. The best heat transfer medium must be selected to get the process heat from the reactor to the chemical plant. Some of the reactants used to make the hydrogen at high temperatures are really nasty."

Producing Hydrogen Economically

To produce hydrogen economically, a reactor must operate at extremely high temperatures. Thus the VHTR has been selected for future hydrogen production plants. "The VHTR has the highest priority among the U.S. reactor concepts," Corwin says, "because it fits into the President's plan for the hydrogen economy."

In the envisioned hydrogen economy, hydrogen will be used in fuel cells to propel automotive vehicles and power buildings. By making hydrogen the fuel of choice for transportation and building sectors, the nation will be less reliant on imported fossil fuels and will, subsequently, reduce its emissions of climate-altering carbon dioxide. Because most hydrogen today is obtained from natural gas, producing significant greenhouse gases as a by-product, DOE plans to use nuclear reactors to produce hydrogen in an environmentally friendly fashion.

DOE's Office of Nuclear Energy plans to build a VHTR, also called the Next Generation Nuclear Plant (NGNP), by 2015 or soon thereafter. "Between now and 2009 it will cost about $200 million to answer the research questions about different materials and to select or develop and then qualify the needed materials for the NGNP," Corwin says.

ORNL principal investigators (PIs) working on materials research and development (R&D) for the selected advanced reactor types are Randy Nanstad, radiation effects; Bob Swindeman, high-temperature materials and alloys; Roger Stoller, microstructural analysis and modeling; Jim Corum (retired) and Tim McGreevy, high-temperature design methods; Tim Burchell, graphites; Lance Snead, ceramics; James Klett, carbon-carbon composites; and Dane Wilson, materials compatibility. As National Technology Director for Gen IV Materials, Corwin, working with ORNL PIs and representatives from other national laboratories responsible for leading the design activities for the various reactor concepts, has put together an integrated plan for materials R&D for the four reactor concepts.

For the NGNP, ORNL researchers are examining existing materials because of the tight deadline. They are considering candidate materials they developed for DOE's fusion and fossil energy programs because they can survive higher temperatures. Those materials include 9 chrome-1 moly vanadium steel and tungstenvanadium steel (developed by ORNL's Ron Klueh as a reduced activation alloy for fusion devices) and a variant on the Hastelloy material developed primarily at ORNL years ago for nuclear reactor components.

"We are trying to identify a material that might be used in a compact heat exchanger, which could consist of thin, closely spaced, parallel layers containing alternating, perpendicularly oriented micro-channels," Corwin says. "The helium cooling the reactor would pass through the module in one direction and transfer its heat to, say, molten salt passing through in the other direction on its way to the hydrogen production plant."

Graphite Structure

Unlike the other three reactor concepts, the NGNP will have a graphite structure to contain the fuel and moderate its neutrons to sustain heat-producing fission reactions. "We are working with graphite manufacturers to help them make graphites that are sufficiently similar to nuclear-qualified graphites produced in the 1970s," says Tim Burchell of ORNL's Metals and Ceramics Division. "We want to show that the VHTR graphites behave in a predictable manner during irradiation, based on knowledge from the past 40 years. Then we'll develop fundamental materials-physics models so we can predict with confidence the material properties in the new graphites."

Many of the metal components used inside current reactor vessels would not survive the 1200°C temperatures that might occur during an accident. Carbon-carbon composites could be candidates for these components, but ORNL researchers must determine how well they will perform under long-term radiation exposure and long-term and short-term oxidation. One potential problem is that if air enters the hot reactor internals, the composites would be converted to carbon dioxide. Silicon carbide is also being studied for potential use in control rods, which absorb the reactor's neutrons.

As they race the clock to meet America's energy needs, Corwin and his team members are absorbed by the challenging project of finding materials that can take the heat of a 21st-century nuclear reactor. Ⓡ

A REVOLUTIONARY REACTOR CONCEPT

A revolutionary nuclear reactor concept, based partly on ORNL's past coolant and fuel research, could be an economical source of hydrogen. Called the Advanced High-Temperature Reactor(AHTR), it would cost only half as much as current gas-cooled reactor concepts.

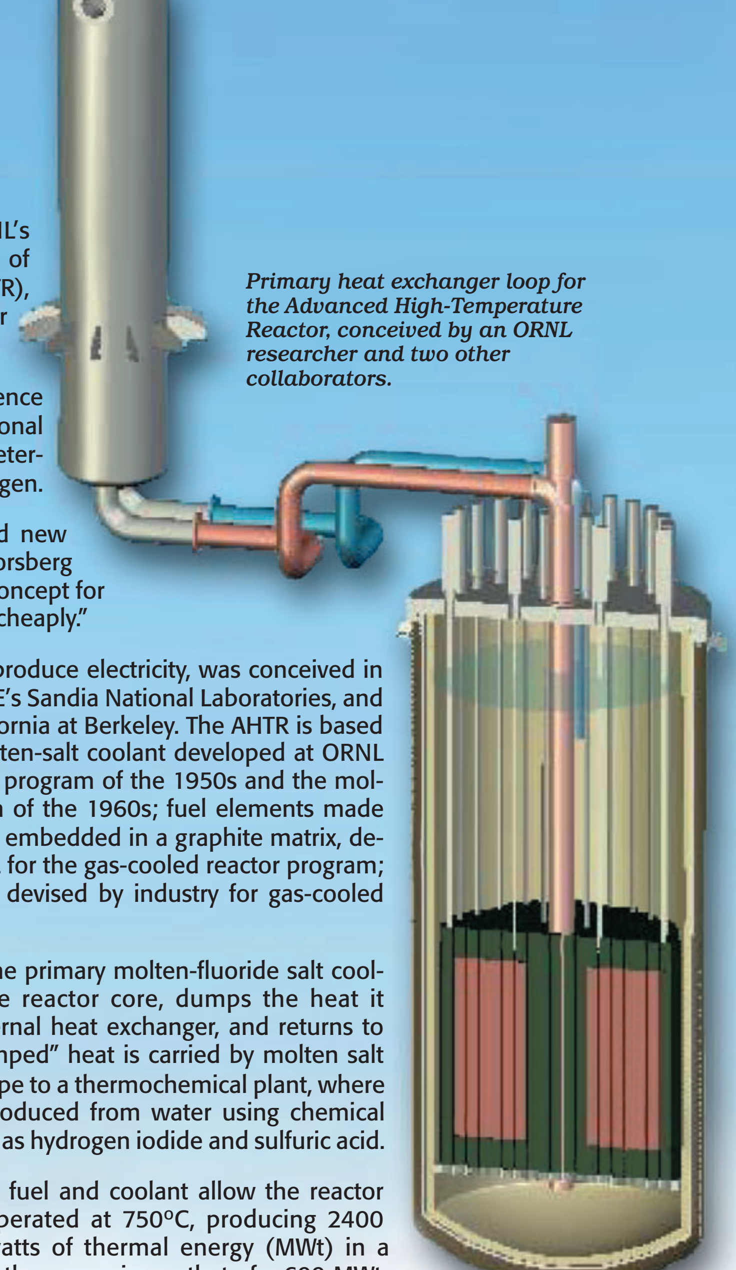
In January 2003, Charles Forsberg of ORNL's Nuclear Science and Technology Division explained the AHTR to the National Academy of Sciences. The Academy is interested in determining the most economical ways to produce hydrogen.

"More than 30 years have passed since a brand new nuclear reactor concept has been proposed," Forsberg says. "The Academy is very interested in our concept for making larger quantities of hydrogen more cheaply."

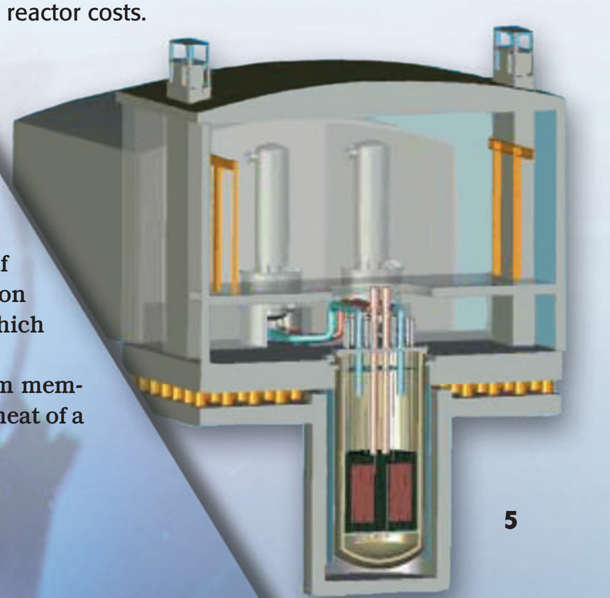
The AHTR, which could also be used to produce electricity, was conceived in 2001 by Forsberg, Paul S. Pickard of DOE's Sandia National Laboratories, and Per Peterson of the University of California at Berkeley. The AHTR is based on three technological feats: a molten-salt coolant developed at ORNL for the nuclear aircraft propulsion program of the 1950s and the molten salt breeder reactor program of the 1960s; fuel elements made of coated nuclear fuel particles embedded in a graphite matrix, developed in the 1970s at ORNL for the gas-cooled reactor program; and passive safety systems devised by industry for gas-cooled and liquid-metal reactors.

In the AHTR concept, the primary molten-fluoride salt coolant flows through the reactor core, dumps the heat it picks up on an external heat exchanger, and returns to the core. The "dumped" heat is carried by molten salt through a long pipe to a thermochemical plant, where hydrogen is produced from water using chemical reagents such as hydrogen iodide and sulfuric acid.

The AHTR's fuel and coolant allow the reactor to be operated at 750°C, producing 2400 megawatts of thermal energy (MWt) in a vessel the same size as that of a 600-MWt gas-cooled reactor. Its molten-salt coolant enables reactor operation at atmospheric pressure, avoiding the need for an expensive high-pressure reactor vessel, albeit with increased corrosion concerns. The liquid coolant transfers heat more efficiently than high-pressure gas. The combination allows the use of passive safety systems in a large reactor, lowering the AHTR's costs per unit output to 60% of gas reactor costs.



Primary heat exchanger loop for the Advanced High-Temperature Reactor, conceived by an ORNL researcher and two other collaborators.



URANIUM ENRICHMENT

COMING FULL CIRCLE

The resurrection of gas centrifuge technology for uranium enrichment—a dream come true for many Oak Ridge researchers—has brought the largest CRADA ever to ORNL.

From neckties to popular music, numerous trends and ideas identified with the 1970s are finding their way back into the American mainstream more than two decades later. The phenomenon extends to the world of technology, where the gas centrifuge method for making fuel for nuclear power plants, after a 20-year hiatus, is once again on center stage.

The uranium enrichment technology using spinning rotors was largely developed in Oak Ridge; highlights were the successful operation of the first cascade of 35 centrifuges in 1961 and the startup of the Centrifuge Test Facility in 1975. Centrifuge technology was shelved in 1985 by the Department of Energy in favor of the now-abandoned atomic vapor laser isotope separation (AVLIS) technology. At the time, fiberglass centrifuges were being built for a DOE-sponsored centrifuge enrichment plant at Portsmouth, Ohio. The plant closed in 2000. Research on AVLIS continued at DOE's Lawrence Livermore National Laboratory.

"The uranium enrichment market was nonexistent in the mid-1980s because nuclear power was not seen as the energy source of the future," says John Shaffer of ORNL's Nuclear Science and Technology Division. "Interest in centrifuge technology for uranium enrichment in the United States lay dormant until 1999."

By then, DOE had turned over the agency's enrichment facilities—two gaseous diffusion plants—to a new private company, the United States Enrichment Corporation (USEC). USEC, which has one-third of the world's enriched uranium market, obtains one-half its product from down-blended Russian weapons material and half from the gaseous diffusion plant in Paducah, Kentucky.

Because a gas centrifuge plant uses only 5% as much electricity as is consumed by a diffusion plant, USEC determined that the best chance to remain competitive with URENCO—a British, Dutch, and German consortium that uses centrifuge plants—was to resurrect the centrifuge technology. USEC turned to the "priesthood" of American centrifuge technology, Oak Ridge researchers and retirees.

Since July 2002 ORNL researchers have been working on the centrifuge program as part of a five-year, $125-million cooperative research and development agreement (CRADA) with USEC. Some $28.5 million worth of centrifuge research in Oak Ridge is directly funded by USEC as part of the CRADA, the largest in ORNL history.

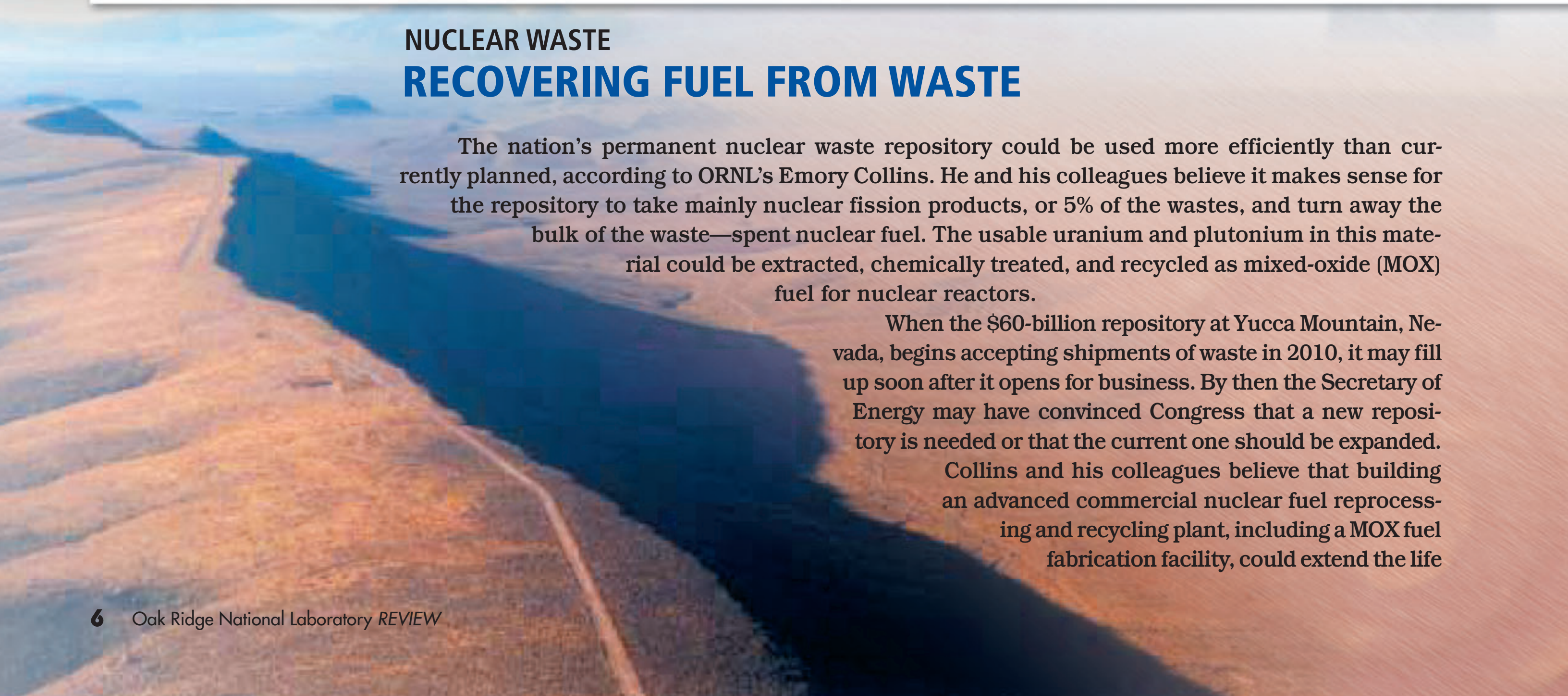
Materials, Motors, Modeling

Since the mid-1980s, advances in materials, motors, controls, and modeling have made possible the improvement of technology developed in the 1960s and 1970s in Oak Ridge. The advances are enabling the development of centrifuges that can be manufactured more economically and produce nuclear fuel with greater efficiency.

A group led by Shaffer developed carbon-fiber composites to replace the fiberglass used for the 1985 rotor. "Our new centrifuge material is lighter and stronger, so the rotor can spin faster without falling apart," Shaffer says. "As a result, more enriched uranium can be produced by each machine for a longer time."

While the centrifuge program lay dormant in the 1980s and 1990s, carbon-fiber composite technology moved from a laboratory curiosity to a mature technology. "These materials are being used anywhere high strength and light weight are needed," Shaffer says. "They are found in racing cars, rocket motors, submarine hulls, missiles, bridges, space satellites, telephone poles, and sewer pipes."

A group led by Don Adams of ORNL's Engineering Science and Technology Division has developed small motors operated by power electronics for the centrifuges. "The new motors are smaller and cheaper than the 1985 motors and the use of power electronics will simplify the control of the centrifuge motors," Shaffer says. In recent years, Adams and his colleagues have been adapting the technology for use in American automakers' development of hybrid gasoline-electric cars.



NUCLEAR WASTE

RECOVERING FUEL FROM WASTE

The nation's permanent nuclear waste repository could be used more efficiently than currently planned, according to ORNL's Emory Collins. He and his colleagues believe it makes sense for the repository to take mainly nuclear fission products, or 5% of the wastes, and turn away the bulk of the waste—spent nuclear fuel. The usable uranium and plutonium in this material could be extracted, chemically treated, and recycled as mixed-oxide (MOX) fuel for nuclear reactors.

When the $60-billion repository at Yucca Mountain, Nevada, begins accepting shipments of waste in 2010, it may fill up soon after it opens for business. By then the Secretary of Energy may have convinced Congress that a new repository is needed or that the current one should be expanded.

Collins and his colleagues believe that building an advanced commercial nuclear fuel reprocessing and recycling plant, including a MOX fuel fabrication facility, could extend the life

More than 15 years ago, Oak Ridge researchers developed computer models to optimize the centrifuge design. The design's geometry had to be precise to balance the high-speed rotating equipment. The speed had to be increased to improve the flow of uranium hexafluoride (UF_6) gas. The goal is to locate the most fissionable uranium-235 into the middle and out the top of the rapidly spinning centrifuge as it separates from the heavier and much more abundant uranium-238, which migrates toward the rotor wall.

"In the 1980s we needed weeks or even months to do these tricky, intensive calculations on the CRAY supercomputer," says Doug Craig, who leads the ORNL effort in the CRADA. "Now, running fluid dynamics and other codes can be done in a few days on a desktop computer."

The question now becomes, "Can ORNL help USEC reduce the cost of manufacturing a centrifuge from $100,000 to $50,000?"

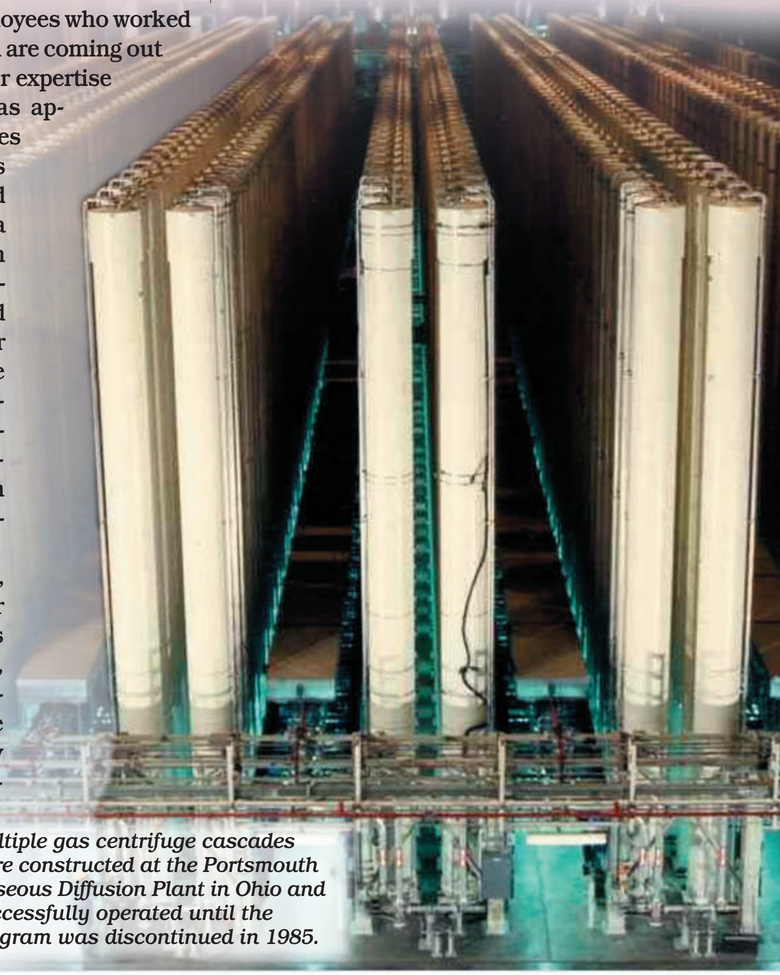
Cutting Costs

"ORNL is working out the techniques for making more economic centrifuges using carbon-fiber composites." Craig says. "Shaffer is helping USEC employees learn how to fabricate the components at the Boeing facility USEC is leasing in Oak Ridge. Shaffer's group is leading the manufacturing of test centrifuges for a demonstration program at Building K-1600 at the East Tennessee Technology Park in Oak Ridge. The project, which will involve the experimental operation of centrifuges using UF_6, is funded by USEC and overseen by DOE."

"The CRADA allows us to refresh and reinvigorate the enrichment technology base with new people," Craig says. "The younger folks can get hands-on experience with the technology that hasn't been used in Oak Ridge since 1985. It's great to have an opportunity to train a new generation of centrifuge researchers and transfer the technology to USEC."

Former ORNL employees who worked in the centrifuge program are coming out of retirement to lend their expertise to USEC, which now has approximately 100 employees in Oak Ridge. The retirees are helping USEC build 200 test centrifuges for a lead cascade plant in Portsmouth. The centrifuges will be installed and operating by 2005 under the watchful eye of the Nuclear Regulatory Commission. USEC's longer-range plans include construction of a modern commercial centrifuge enrichment plant by 2012.

Not surprisingly, USEC's chief scientist for the centrifuge project is a former ORNL employee, Dean Waters, who received an E. O. Lawrence Award from DOE, largely for his centrifuge innovations. Like Shaffer and his ORNL colleagues, Waters is helping transfer the centrifuge technology he developed during much of his career. Former and present ORNL researchers are excited. As they bring their old ties out of the closet after two decades, they also are making an invaluable contribution that will help sustain America's uranium enrichment program.



Multiple gas centrifuge cascades were constructed at the Portsmouth Gaseous Diffusion Plant in Ohio and successfully operated until the program was discontinued in 1985.

of the repository. "It could receive wastes for hundreds of years rather than fill up when it opens," Collins says.

Here's the vision of Collins, Charles Forsberg, Dennis Benker, Kevin Felker, G. D. "Bill" DelCul, Barry Spencer, Ron Canon, and David Williams, all of ORNL's Nuclear Science and Technology Division, and personnel at four other national laboratories performing research for the Advanced Fuel Cycle Initiative of the Department of Energy's Office of Nuclear Energy.

A 2000-ton-per year commercial reprocessing and recycling plant, including a MOX fuel fabrication facility, is designed, built, and operated. The spent fuel that has cooled for as long as 40 years at power plant sites is transported in government-approved casks to the safeguarded plant. Using the UREX process, the uranium in the spent fuel is separated from radioactive fission products and heat-emitting isotopes of cesium and strontium. The liberated isotopes are shipped in special packages to the waste repository.

At the plant, plutonium and neptunium are separated from the uranium and fission products using an ORNL-developed process that makes neptunium stay with the plutonium, so it cannot easily be diverted for use in a nuclear weapon. The neptunium has a decay daughter, protactinium-233, which emits an easily detected gamma ray that could signal that stolen plutonium is about to be smuggled past plant portals and entrances.

"We showed that a plutonium-neptunium product can be recovered in high yield from light-water-reactor spent fuel," Collins says. "We demonstrated that this product is sufficiently purified of fission products and can be made into MOX fuel for use in a fast reactor or a current commercial power reactor."

The envisioned plant could also make reactor control rods containing "burnable poisons" like americium-241, from long-cooled nuclear waste. When americium-241 absorbs reactor neutrons, it forms plutonium-238, which can be used in MOX fuel.

Randy Nanstad examines the setup for a fracture toughness test of a stainless steel cladding specimen from the Davis-Besse reactor pressure vessel head.

NUCLEAR SAFETY

STAYING IN THE COMFORT ZONE

ORNL has provided the Nuclear Regulatory Commission with valuable scientific data and computer codes to help the agency decide whether individual nuclear power plants can continue to operate safely.

America's nuclear power plants, which provide 20% of the nation's electricity, have operated relatively safely since the startup of the first plant in 1957. To ensure the continuity and improvement of these facilities' safety records and to avoid accidents such as the 1979 loss-of-coolant (LOCA) accident at the Three Mile Island plant, the watchdog of the nuclear power industry—the Nuclear Regulatory Commission (NRC)—relies partly on the work of ORNL researchers.

NRC's research program at ORNL, led by Julie Simpson, addresses newer as well as older threats to the safe operation of U.S nuclear power plants. The new threats include electromagnetic interference from wireless technologies and attacks by terrorists and computer hackers. The traditional threats include lightning, human error, and challenges to the integrity of reactor pressure vessels (RPVs), such as corrosion, pressurized thermal shock, and irradiation.

License To Keep Operating

Of the nation's 103 nuclear power plants, 18 plants that currently have 40-year operating licenses have had their licenses extended by NRC, allowing them to operate another 20 years. Data and modeling by ORNL researchers have helped guide the NRC in making these decisions.

Researchers in ORNL's Heavy-Section Steel Irradiation Program, led by Tom Rosseel and Randy Nanstad, both of the Metals and Ceramics (M&C) Division, have analyzed whether the steel in different RPVs has become too embrittled from neutron irradiation to continue safe operation. "Based on our test data and computer modeling," Nanstad says, "it looks like many of the nation's RPVs could last 60 to 80 years instead of the expected 40 years."

"We write reports that help NRC understand the damage mechanisms in irradiated steel containing various elements, such as copper and nickel," Rosseel says. "In this way, NRC can develop standards, codes, and regulations to make sure that nuclear power is safe for the public."

Electric utilities seeking license renewal must convince the NRC that their RPVs are not susceptible to brittle fracture even though the vessel walls have reduced ductility and fracture toughness after exposure to neutron radiation at operating temperatures of about 288°C (550°F) for 40 years. One concern is that if the RPV walls are overcooled by a sudden drop in water coolant temperature during a pressurized thermal shock (PTS) event, small flaws in the wall and/or its welds could grow into cracks that propagate through the wall, introducing the possibility of RPV failure.

A re-evaluation of the NRC's stringent PTS rule could result in earlier nuclear plant license renewals. An updated ORNL computer code is being used for this re-evaluation. Called the FAVOR (Fracture Analysis of Vessels: Oak Ridge) code, it was developed by Terry L. Dickson of the Computational Sciences and Engineering Division (CSED) for ORNL's Heavy-Section Steel Technology (HSST) Program. NRC engineers applied FAVOR to three pressurized-water reactors for which license renewals have been sought.

"Our preliminary results show that conservatisms in the current PTS rule can be reduced while continuing to provide reasonable assurance that public health and safety are protected," Dickson says.

Hole in a Head

HSST researchers have been involved in analyzing a recent nuclear power plant incident. On February 16, 2002, during an outage for refueling, workers making an NRC-required inspection at the Davis-Besse

Nuclear Power Station in Ohio found long cracks in three control rod drive mechanism (CRDM) nozzles penetrating the RPV head, the dome-shaped upper portion of the ferritic steel vessel housing the nuclear core of the pressurized water reactor (PWR). Upon further inspection of the outside of the RPV head, the workers observed a buildup of white powder, identified as boric acid deposits. They also found that the cracks in the CRDM nozzles allowed the boric-acid-containing cooling water to leak outside the vessel.

After the powder was removed on March 7, workers identified a cavity 5-in. wide and 6-in. deep between two nozzles (through which control rods are withdrawn to start up the reactor and returned to shut it down). What caused this irregularly shaped cavity to develop?

Investigation found that, because boric acid is corrosive to the ferritic steel forming the RPV wall, the leaked water ate its way through the 6-in.-thick wall until it reached the backside of the austenitic-steel layer that protects the inside of the RPV wall from corrosion by the borated cooling water. This stainless-steel cladding (with a nominal thickness of 0.24 in.) was pushed outward into the cavity by the high pressure—2165 pounds per square inch (psi)—of the 600°F water inside the vessel. The thin cladding deformed but did not break, holding the cooling water within the vessel. It was remarkable that the cladding held up so well because it was later discovered that the thin stainless-steel layer was flawed—it contained defects with an estimated average depth of 0.05 in.

Today the Davis-Besse reactor remains shut down. NRC is investigating the structural integrity of reactor vessel heads at 69 PWRs.

After these discoveries, NRC sought analytical and experimental assessments from Paul Williams and B. Richard Bass, both of CSED, and Wallace J. McAfee of the M&C Division. "NRC wanted to know how close the reactor vessel head was to failure," Bass said. "What were the probabilities of failure based on what can be ascertained from the conditions?"

The HSST Program is supporting an accident sequence precursor assessment to identify the factors contributing to the event. HSST researchers are also trying to determine whether the flawed cladding would have failed by ductile tearing or plastic collapse and what would have been the size of the rupture.

Williams is developing analytical computational codes to calculate probabilities concerning how and when the Davis-Besse RPV would have failed with continued operation. In addition, McAfee is conducting a series of 14 high-pressure clad-burst experiments on flawed clad disks that will be completed in 2004. Bass says that these ORNL large-scale tests provide essential data against which model predictions can be compared, thereby improving analytical tools for predicting the likelihood of failure.

ORNL has a growing nuclear safety research program, and it's safe to say that the Laboratory is providing useful answers to NRC's challenging questions. Ⓡ

Spent nuclear fuel cask

GETTING CREDIT

When nuclear fuel is irradiated, or "burned," in a reactor, its reactivity drops as the uranium fuel is consumed and fission products accumulate. The less reactive the burned, or spent, fuel removed from the reactor, the less likely that the fuel can go critical, or sustain a chain reaction.

Until recently, however, the licensing approach used to certify spent fuel transportation packages did not use the credit from the reactivity decrease caused by burn-up (i.e., burn-up credit). ORNL researchers and others have shown that, if burn-up credit were utilized, spent nuclear fuel could be safely packed in more dense arrays, dramatically reducing the cost of transporting, storing, and disposing of spent fuel from nuclear power plants.

"With burn-up credit, casks designed for truck shipment can carry twice as much spent fuel, and casks designed for rail shipment can carry up to one-third more spent fuel," says Cecil Parks of ORNL's Nuclear Science and Technology Division. "You could put 32 spent fuel assemblies in a rail cask with burn-up credit but only 24 spent-fuel assemblies without."

In 1999, the Nuclear Regulatory Commission (NRC) asked Parks to lead a project to investigate and resolve outstanding technical issues related to burn-up credit and then provide a recommended basis for issuing regulatory guidance on the subject. The project combined ORNL staff experience in cask design and operations, reactor physics, criticality safety, and regulatory practice.

An ORNL-developed code system called SCALE, for "Standardized Computer Analyses for Licensing Evaluation," was used to help understand how reactivity decreases in spent fuel vary with reactor conditions, time after discharge from the reactor, the level of knowledge regarding the spent fuel isotopic contents, and cask conditions. Parks says, "We have clarified technical issues and impacts on cask design of burn-up credit and the amount of inventory allowed in the cask."

In September 2002, after ORNL completed its technical documents, NRC published new guidance that established recommended approaches for applicants to use when requesting burn-up credit as a part of the safety basis for cask designs. Currently, a cask vendor is seeking a license from NRC that asks for burn-up credit, referencing the ORNL documents.

REACTOR POWER IN SPACE

SHOOTING FOR THE MOONS

ORNL has lead roles in a new NASA program to build a nuclear reactor power system that will enable future missions to our solar system's outer planets.

Exploring planets beyond Mars will require a power source different from those now deployed in American spacecraft. Radioisotope thermal generators and solar energy cannot meet the challenges posed by proposed missions to the cold, dark regions of our solar system. ORNL engineers are convinced nuclear fission power will.

"To understand why nuclear reactors are needed in space, we must understand the size of our solar system and the distances involved in interplanetary space exploration," says Sherrell Greene of ORNL's Nuclear Science and Technology Division. "A radio signal requires 35 minutes to travel from Earth to Jupiter and 5 hours is required for a signal to travel from Earth to Pluto. The distance to Jupiter from Earth is 4 times the distance between Earth and the sun."

Because these distances are so large, the intensity of sunlight shining on each planet is greatly reduced as we travel outward from Earth toward the edge of the solar system. The intensity of the sun's light shining on Jupiter is only $1/27^{th}$ its intensity on Earth.

"There isn't much light getting out to Jupiter," Greene says. "It's cold and dark there. For spacecraft carrying scientific instruments beyond Mars, solar energy is not an option, and command and control are more complicated."

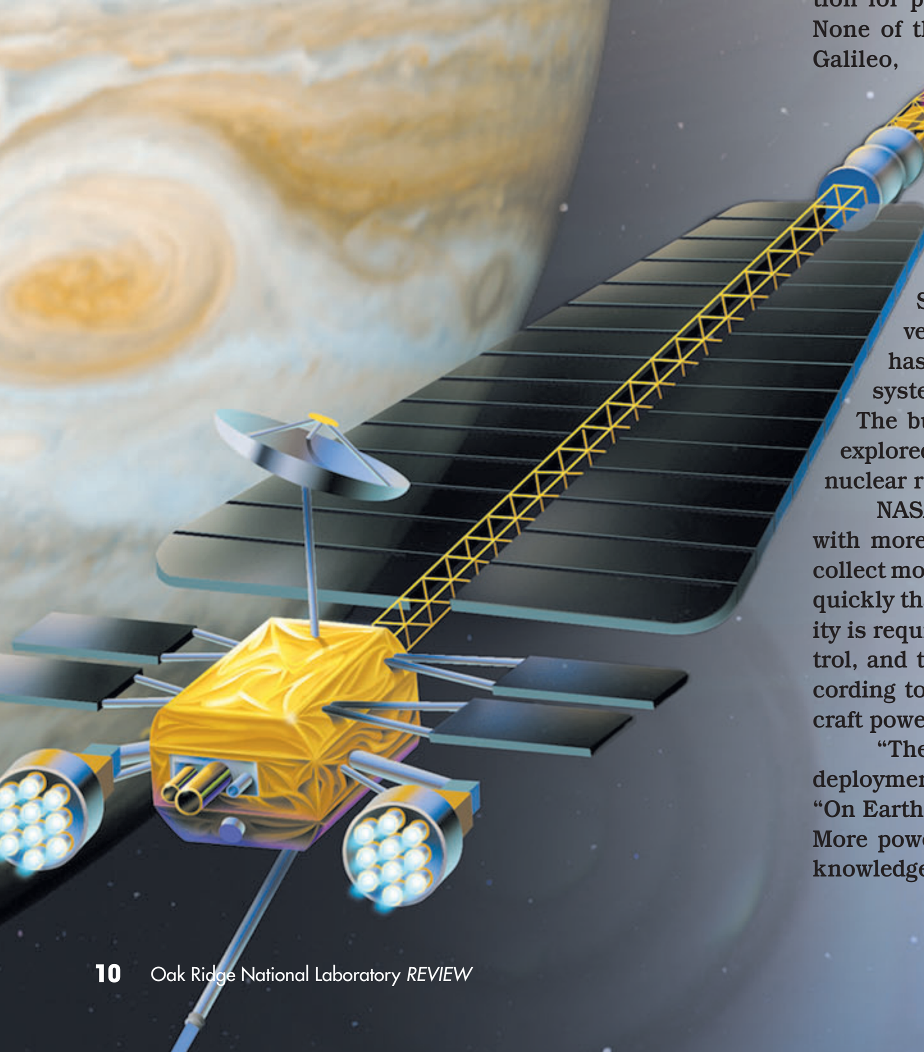
The traditional approach of mounting solar cells on unmanned spacecraft works well for voyages to Venus, Mercury, and Mars. However, beyond Mars this approach is not practical because the sunlight's intensity is so low that the space probe cannot capture enough solar energy without huge, unwieldy arrays of photovoltaic cells.

"As we move beyond Mars, we need an alternative source of electrical power," Greene explains. "Radioisotope thermal generators are a very good option for providing low levels of electrical power. None of the space probes, such as Voyager, Galileo, and Cassini, has had even 1 kilowatt (1 kW) of power. Most have had only a few hundred watts of power. The beautiful photos of the planets and the data collected there were obtained with less power than is required to blow-dry your hair.

"The National Aeronautics and Space Administration (NASA) has done marvelous things with one kilowatt, but NASA has just about exhausted its options for solar system exploration with current power sources. The bulk of the solar system simply cannot be explored in any meaningful way unless we employ nuclear reactors in space."

NASA desires to go to different planets (and their moons) with more robust spacecraft that can maneuver around moons, collect more data, and communicate the information to Earth more quickly than can be done with current technologies. More electricity is required to operate science packages; power command, control, and telemetry systems; and provide electric propulsion. According to Greene, these needs can be met only by using spacecraft powered by nuclear reactors.

"The future of science in space depends on the successful deployment of space-based reactor power systems," Greene says. "On Earth knowledge is power, but in space, power is knowledge. More power means more destinations, more observations, more knowledge, and quicker data return."



NASA's unmanned Jupiter Icy Moons Orbiter will require 100 kilowatts electric to fly to Jupiter and orbit around and take data on three of its moons.

Exploring Jupiter's Moons

Greene leads a team that is working on a NASA-approved mission called JIMO, for Jupiter Icy Moons Orbiter. The unmanned spacecraft, designed to do science, will require 100 kW of electrical power to move out to Jupiter, spiral into the huge planet, and then fly out and maneuver in orbit around three moons—Callisto, Gannymede, and Europa. Next to Mars, solar system scientists believe Europa to be the most desirable destination in our search for life, because this moon is thought to host a vast, ice-covered ocean. JIMO will be the first space probe to orbit around and collect data from three moons.

JIMO will be powered by a reactor—the second reactor launched into space by the United States. The first, called SNAP-10A, orbited Earth in 1965. Since that time, the Russians have launched more than 30 Earth-orbiting space reactors, mostly for military purposes, in reconnaissance satellites. JIMO would fly in the early part of the next decade. The JIMO mission is led by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, and is funded by NASA's Office of Space Science. The Office of Nuclear Energy has been the lead DOE organization, but officials recently announced that the National Nuclear Security Administration (NNSA) Office of Naval Reactors will eventually take over as DOE's supporting agency.

Two NASA centers are supporting JPL—Marshall Space Flight Center and Glenn Research Center. Also collaborating in this project are two DOE labs— Los Alamos National Laboratory and ORNL.

Greene attributes ORNL's success in becoming a supporting organization for JIMO partly to the existence in Oak Ridge of hundreds of old files and documents. Some were written in the 1950s for ORNL's Aircraft Nuclear Propulsion Program, which spawned nuclear and materials technologies that formed the backbone of today's nuclear enterprise. Fortunately, these ORNL documents, including Robert W. Bussard's 1953 visionary report on "Nuclear Energy for Rocket Propulsion," were not destroyed.

"Our ability to locate, secure, access, and digest those documents has contributed greatly to our success in bringing this work to ORNL," Greene says. "ORNL is a major element of our nation's 'institutional memory' in the space nuclear power arena. We're working hard to help ensure successful implementation of our nation's next nuclear-powered space mission."

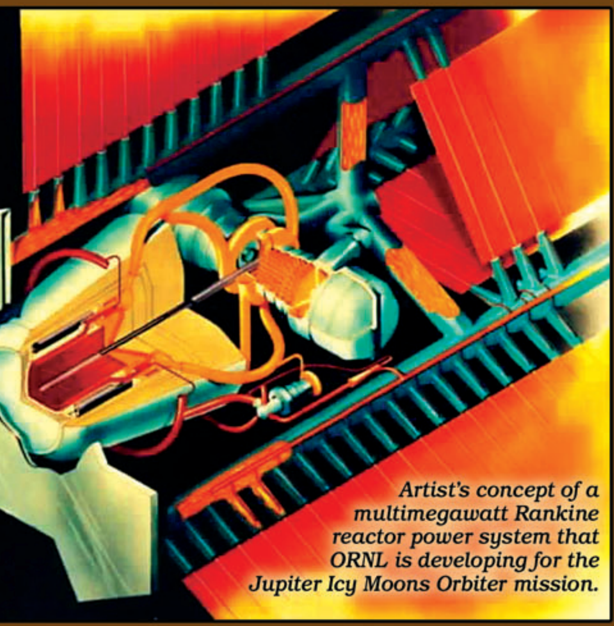
Lab's Lead Roles

ORNL has several important roles on the government's team. The Laboratory has the lead in developing advanced materials and refractory metal technologies needed to enable the reactor system to operate at the high temperatures required to minimize its size and mass. ORNL also is coordinating the development of the autonomous reactor control, strategies, and control-system concepts required to enable the JIMO reactor to deal with its environment and changing power demands without human intervention (and the associated time delays). ORNL's third lead role is to provide nuclear safety assurance for the space probe, both in flight and on the ground. "ORNL will estimate the probability and consequences of various potential accidents involving the reactor and recommend approaches to ensure safe performance of the mission," Greene says.

ORNL also will guide the design of the reactor's nuclear shield, which protects the spacecraft's electronics, controls, and science packages from radiation emanating from the reactor. "The government will develop its own design for this complicated shield so it can be a 'smart buyer' of shield components," Greene explains.

ORNL has the lead role in estimating the cost and schedule for the JIMO program's nuclear part. The Laboratory also has a support role for the JIMO mission: providing technical support and implementation for National Environmental Policy Act compliance activities in building the JIMO spacecraft on the ground."We're excited about the roles ORNL is playing in advancing knowledge of our solar system," says Greene, "Space really is the fission frontier!"

AHEAD OF THEIR TIME



Artist's concept of a multimegawatt Rankine reactor power system that ORNL is developing for the Jupiter Icy Moons Orbiter mission.

A space reactor power technology first championed by ORNL some 40 years ago is receiving attention again as NASA seeks improved, high-performance space power technologies. In 2002, ORNL competed for and won a NASA research grant to develop a liquid-metal Rankine power conversion system concept for use in space. The new project is led by Grady Yoder of ORNL's Nuclear Science and Technology Division.

The Rankine power conversion approach, which is employed by virtually every power reactor, uses a liquid coolant that is boiled by energy from the reactor. The resulting vapor is fed to a turbine-alternator combination to produce electricity. Unlike terrestrial reactors, which use water as the working fluid, space reactors would employ liquid metals such as lithium, potassium, or cesium.

"The focus of ORNL's research project is to design and fly a small-scale Rankine power conversion 'phenomenology demonstrator prototype' in space," says Sherrell Greene, who leads ORNL's space fission power activities. "If successful, the project will demonstrate that two-phase, or liquid-vapor, phenomenology inherent in the Rankine cycle can be managed and controlled in the microgravity climate of space. A second goal is to update the design of space Rankine power conversion systems first pioneered by Art Fraas and others at ORNL during the 1960s. The roots of this project go back to SNAP-50 and ORNL's Medium Power Reactor Experiment in the 1960s. Art and his team were just ahead of their time."

New Horizons in Science Briefing

For the past 41 years the Council for the Advancement of Science Writing—a group of distinguished American journalists and scientists committed to improving the quality of science news reaching the general public—has annually held a four-day New Horizons in Science Briefing. It's about scientific and medical developments deemed likely to become newsworthy in the coming months.

On October 26-29, 2003, Oak Ridge National Laboratory and the University of Tennessee hosted the briefing in Knoxville and at ORNL. The Laboratory and UT were honored that the Council's executive director, Ben Patrusky, selected eight ORNL researchers and four UT faculty members as speakers at the conference, which was attended by more than 100 science writers, including several from nationally recognized newspapers, magazines, radio news programs, and television news networks. The following 10 pages describe the groundbreaking research presented by the local speakers.

CARRYING YOUR WEIGHT

In pursuit of a super-strength suit, ORNL's François Pin helped identify an energy source and devise a wearable exoskeleton "foot" interface to amplify the wearer's physical strength.

In Iraq last summer, while enduring blistering heat from the desert sun, young American soldiers sometimes struggled to move while carrying 125-pound backpacks. Last spring, soldiers on aircraft carriers hoisted bombs into fighter jets using long attachments called hernia bars. It seems possible that many of these soldiers will someday undergo hernia, shoulder, and back surgeries.

"In an age of advanced technological developments that has brought satellites, missiles, unmanned aerial and ground vehicles, and high-tech aircraft and weapons, we have put too little emphasis on helping humans in such tasks as lifting heavy objects," says François Pin, an ORNL robotics scientist whose team once developed a robot that enabled a person exerting 10 pounds of force to lift and control a 5000-pound payload. "Many of our construction, manufacturing, and military personnel carry extremely heavy loads. We are injuring our work force. Those injuries are costing the nation billions of dollars in health care and disability insurance."

Pin believes the answer lies in wearable robotics, an emerging technology that could lead to the exoskeleton and ultimately the "super-strength suit." He thinks it is time to focus technological development on human assistance and amplification.

"In just a few years, we could have robots that will help humans in materials handling, manufacturing assembly operations, and rescue operations, such as rubble removal and casualty evacuations," he says. "Wearable robotics will be used to improve the strength and stability of human movements. The technology can help the elderly get out of their chairs more easily and give the handicapped more control of their bodies."

He points out that surgeon-assist robotics are already in use for eye and plastic surgeons to ensure that their movements during surgery are precise, controlled, and tremor-free. In eye surgery, automated laser equipment is used to make precise cuts.

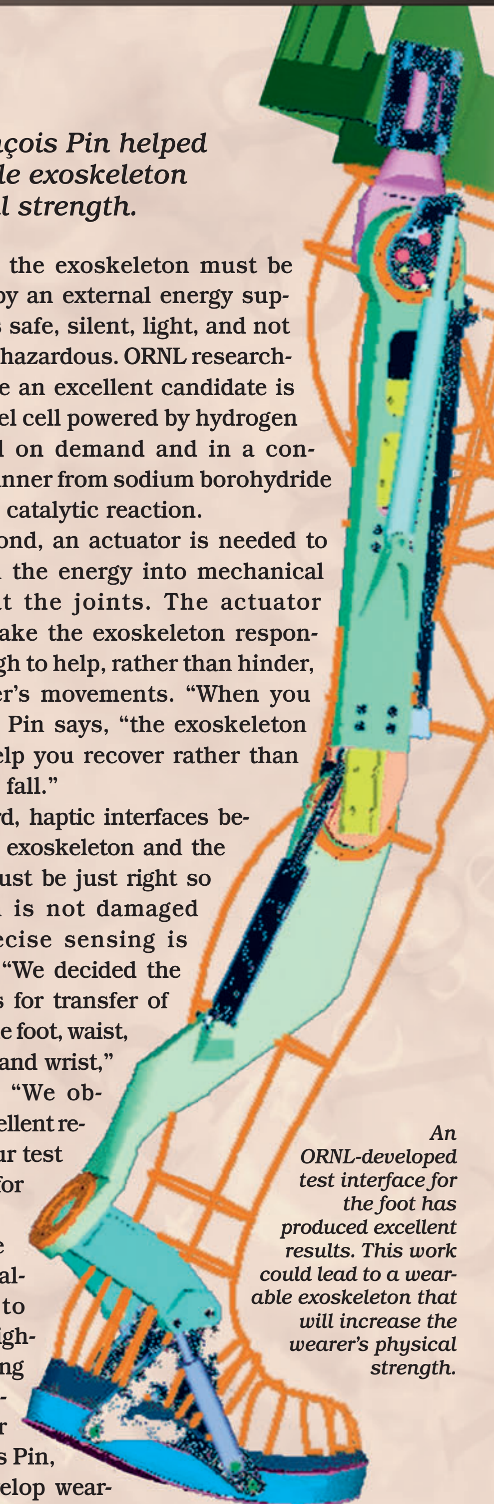
Pin and his colleagues have received funding from the Department of Defense to conduct research toward designing an exoskeleton to make each soldier faster, stronger, and tougher. Building a workable exoskeleton, he says, will require solutions to challenging technological problems.

First, the exoskeleton must be powered by an external energy supply that is safe, silent, light, and not too hot or hazardous. ORNL researchers believe an excellent candidate is a small fuel cell powered by hydrogen generated on demand and in a controlled manner from sodium borohydride through a catalytic reaction.

Second, an actuator is needed to transform the energy into mechanical motion at the joints. The actuator should make the exoskeleton responsive enough to help, rather than hinder, the wearer's movements. "When you stumble," Pin says, "the exoskeleton should help you recover rather than make you fall."

Third, haptic interfaces between the exoskeleton and the human must be just right so that skin is not damaged while precise sensing is achieved. "We decided the best areas for transfer of load are the foot, waist, shoulder, and wrist," Pin says. "We obtained excellent results in our test interface for the foot."

The fourth challenge is to develop high-tech sensing and controls. "Our goal," says Pin, "is to develop wearable robotics that are 'transparent' in the sense that they will augment a human's physical abilities without either being felt or hindering any other function. Our experimental results with our new controls test stand show very smooth tracking of the human's limbs and complete stability during accidental impacts or intentional contacts, such as foot steps, even when carrying backpack loads as heavy as 200 pounds. These results are extremely promising for a variety of applications, particularly smart prosthetics and materials handling." Ⓡ



An ORNL-developed test interface for the foot has produced excellent results. This work could lead to a wearable exoskeleton that will increase the wearer's physical strength.

DEFINING THE "MACHINES OF LIFE"

New, automated analytical and computational approaches and tools are needed to rapidly identify and characterize protein complexes. Michelle Buchanan and others have made ORNL a leader in "genomes to life" research involving characterization and imaging of these molecular machines.

The biology revolution launched by the Human Genome Program is not over yet, according to Michelle Buchanan, director of ORNL's Chemical Sciences Division and DOE's Center for Molecular and Cellular Systems. Knowing the sequence of the DNA bases in the human genome and the location of its genes is just a small step toward understanding life itself.

"Any protein encoded by a single gene is estimated to have up to 200 types of variations," Buchanan says. In a cell, a protein can be modified in different ways—by errors resulting from genetic mutations or post-translational modifications, for example. Proteins seldom act alone in cells but form complexes, which are the molecular machines of life.

"Protein complexes are the key to biological function," Buchanan says. "Our job is to identify normal and modified proteins; learn how protein complexes assemble; and determine the levels, cellular location, and dynamics of protein complexes. We must understand the network of reactions that occur in sufficient detail to predict, test, and comprehend the response of a biological system to changes."

ORNL, other Department of Energy national laboratories, and universities are using DOE funding to bring to the biology community the best information on protein complexes. Achieving this goal requires interdisciplinary teams of biologists, chemists, and computational scientists and the best available analytical and computational tools that DOE can offer.

DOE is interested in protein complexes because they are present in microorganisms related to the department's missions—energy production, environmental protection, and homeland security. The research is being conducted for DOE's Microbial Genome and Genomes to Life programs.

Buchanan is leading a multi-lab partnership (including four DOE labs and two universities) to study protein complexes in two types of bacteria, using several approaches. "Mass spectrometry will be a huge workhorse for protein complex identification," Buchanan says. "It is already being used for proteomics—identifying proteins and revealing their amino-acid sequences to get the parts lists—analogous to finding the order of DNA bases in gene sequencing."

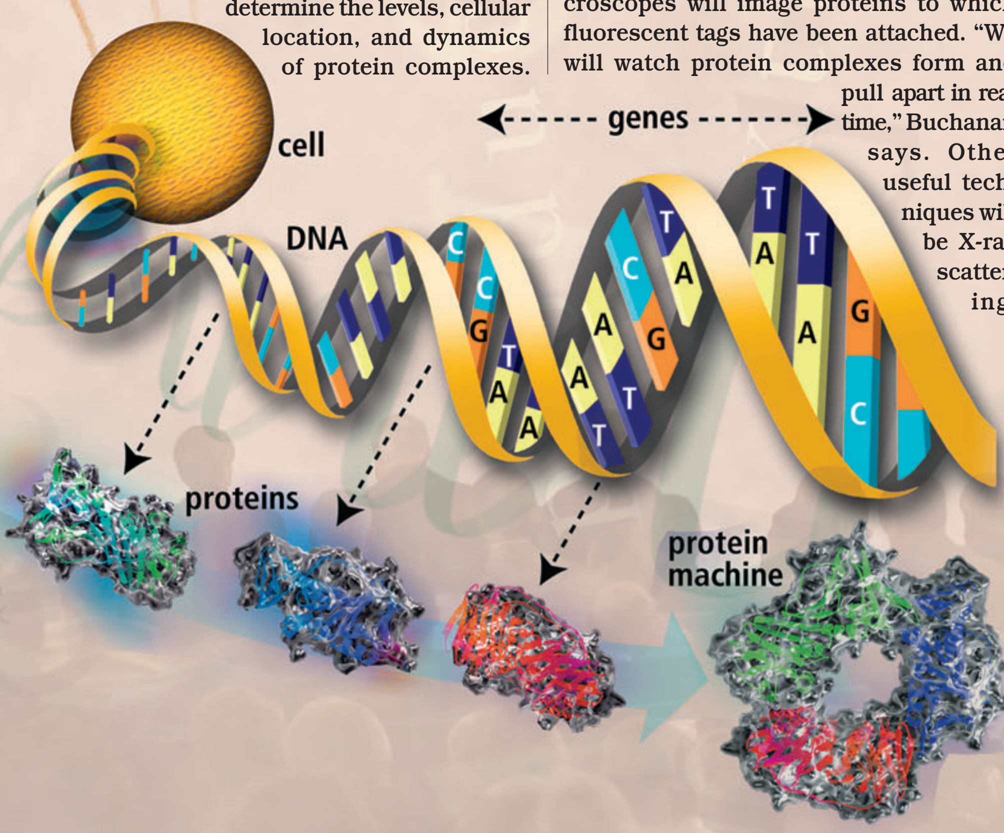
Other tools will also be important for the pilot project. For example, optical microscopes will image proteins to which fluorescent tags have been attached. "We will watch protein complexes form and pull apart in real time," Buchanan says. Other useful techniques will be X-ray scattering, nuclear magnetic resonance spectroscopy, and neutron scattering. In 2005 ORNL's High Flux Isotope Reactor will have the world's best small-angle neutron-scattering facility, the Center for Structural Molecular Biology, which is funded by DOE's Office of Biological and Environmental Research.

As an energy research agency, DOE focuses on microbes that produce clean fuels, such as methane, methanol, and hydrogen. Buchanan's project is studying *Rhodopseudomonas palustris*, whose talents include hydrogen production. Another microbe being studied is *Shewanella oneidensis*, which can turn soluble metallic compounds in soil and water into insoluble compounds. Scientists hope that soluble uranium can be converted into insoluble uranium on DOE sites so it will stay in the soil or sink into sediments, rather than dissolve in water where it could be transported off site. Because of its environmental restoration mission, DOE is interested in this microbe and other microbes that convert organic pollutants into less toxic materials.

The project partners are working to improve technologies for fishing protein complexes out of bacteria using affinity tags and reagents and isolating the complexes for analysis by mass spectrometry. ORNL's "lab on a chip" technology might make this pipeline more efficient. The partners are also improving high-throughput computational tools for rapidly analyzing, interpreting, and communicating on web sites the volumes of data on, for example, five novel proteins that the partners discovered during research on *R. palustris*.

One long-term objective is to provide high-quality data on protein complexes to the biological community, much like the data large sequencing centers provided during the Human Genome Program. Meeting this goal will require developing whole new technologies, as well as improving and automating current state-of-the-art but labor-intensive technologies.

"This project is an extreme challenge for analytical chemists and computational scientists," Buchanan says. "But it will be a definite boon for biologists." Ⓡ



Genes contain instructions for making proteins, which assemble to form complexes to do the work of the cell. These complexes, also called protein machines, are being characterized at ORNL. Image courtesy of BWXT Y-12 Graphic Design Services.

NANOFLUIDICS AND THE ARTIFICIAL CELL

ORNL's Mike Ramsey, a pioneer of the "lab on a chip," has moved from microfluidics to nanofluidics in pursuit of an artificial cell for rapidly sensing chemicals and sequencing DNA.

When ORNL Corporate Fellow Mike Ramsey proposed the "lab on a chip," he helped start the field of microfluidics, which now has its own annual international conference. He co-founded Caliper Technologies, Inc., a California company that in 2002 sold $30 million worth of lab-on-a-chip technology. Caliper's devices promise to spur the pharmaceutical industry's development of more-effective therapeutic drugs at lower cost.

When Ramsey learned that DOE's Office of Nonproliferation and National Security was seeking small devices to detect trace amounts of materials related to weapons of mass destruction, he combined two ideas. "I had seen a miniature gas chromatograph fabricated on a silicon wafer using the same tools that make semiconductor chips possible," says Ramsey. "A contemporary from graduate school at Indiana University had invented the technique of capillary electrophoresis. So my idea was to microfabricate a network of channels in a glass chip to do fluid experiments, rather than gas-phase experiments, and to use electric fields to move fluids and the ions and molecules contained within them." Ions of various types migrate at different rates when driven electrokinetically, allowing their physical separation.

Ramsey pitched the idea of a miniature device for separating molecules and measuring chemical reaction rates using very small liquid samples. Compared with conventional chemical separation technologies, a microfluidics device, he argued, would use smaller samples, separate chemicals much faster, produce less waste, and cost much less. Eventually, the concept won DOE funding.

Ramsey fabricated the first microfluidic chip in 1991 and performed the first viable experiments in 1992-93. In 1994 the chip concept was patented and described in a scientific journal. The chip's applications include process and environmental monitoring, clinical diagnostics, combinatorial discovery, and high-throughput experimentation.

The first lab-on-a-chip device available for sale was the Agilent 2100 Bioanalyzer, the only desktop device that can analyze DNA, RNA, proteins, and cells. For example, the device can determine the molecular weight of proteins and help identify chemical compounds that might be useful therapeutic drugs. Biotechnology researchers using the device simply load multiple microliter-sized samples on the chip, press a button, and minutes later view the resulting data on a laptop computer.

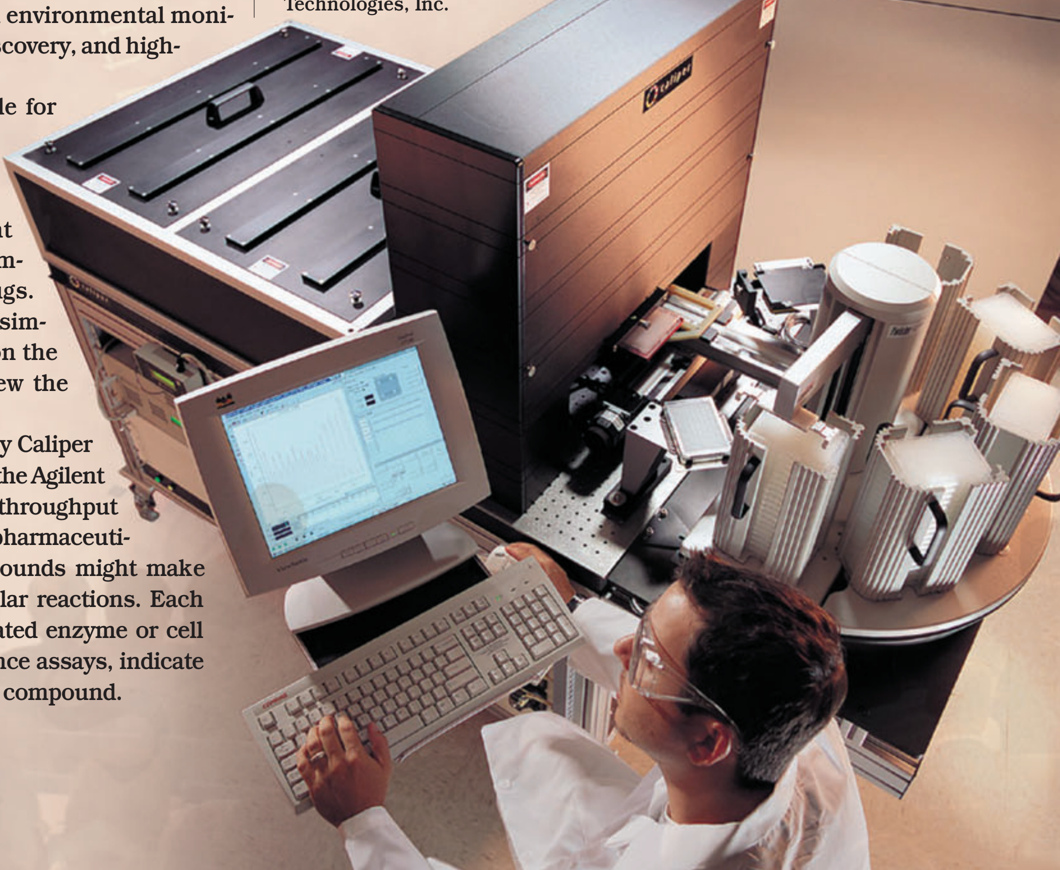
Other lab-on-a-chip devices marketed by Caliper are the ASME 90, a high-throughput version of the Agilent 2100 Bioanalyzer, and the HTS 250, a high-throughput machine that helps determine which of the pharmaceutical industry's millions of synthesized compounds might make effective drugs, based on molecular or cellular reactions. Each test compound is reacted with a disease-related enzyme or cell on the chip; results, typically from fluorescence assays, indicate the potential therapeutic effectiveness of the compound.

"The advantage of Caliper machines over conventional assay methods is that they make very precise measurements," Ramsey says. "Ten of the Caliper 250 HTS systems can perform approximately one million assays a day while consuming a mere microgram of protein."

By shrinking down the widths and depths of the fluid paths etched into glass chips, Ramsey's group has moved into nanofluidics. "We have found a number of interesting effects not observed at the microscale, such as anomalously high electrical conductivity of fluid in nanochannels compared with in the bulk," Ramsey says.

With funding from the Defense Advanced Research Projects Agency, Ramsey's group is building a chemical sensor based upon nanofluidic components. The device, an artificial cell made of layers of silicon and silicon oxide, has an array of ion channels and nanopores drilled by a focused ion beam system. The nanopores, coated with target attractors, are crossed by electrical currents. The current signature changes if target molecules stick inside a nanopore. How long or how much the current is reduced is correlated with the characteristics of the nanochannel and the target molecule, allowing chemical identification.

By moving from lab chips to nanofluidics and artificial cells, Ramsey is becoming a nanoscience pioneer. ®



Caliper Technologies' microfluidics-based high-throughput instrumentation allows millions of compounds to be rapidly tested at the nanoliter scale with high precision to determine the suitability of drugs for treating disease.
Courtesy of Caliper Technologies, Inc.

IMITATING NATURE

Nanobioscientists like Mike Simpson aim to harness or imitate the complex abilities of bacteria and other single cells to make implantable sensors and actuating devices.

Put a biologist, a physical scientist, and an electrical engineer in the same room, and you have a recipe for an interesting collaboration in nanobioscience. Become a fly on a wall of that room and you might hear statements common to systems biology, invented by physical scientists applying systems analysis tools to biological problems. And you might learn a little about synthetic biology—methods for applying biology's lessons to device design.

What you might hear in that room: "Living cells work using the information processing of gene circuits and networks." "We need to find out how these circuits and networks are built and interconnected to make cells and organisms function." "Let's put the intelligence in genes on an electronic chip." "Our funding agencies want us to create engineered systems that closely mimic the size and functional complexity of biological systems, such as bacteria and other single cells."

In the mid-1990s, ORNL electrical engineer and nanobioscientist Mike Simpson heard University of Tennessee biologist Gary Sayler give a presentation. Simpson and Sayler then talked, and a collaboration began. The result was a silicon chip harboring bacteria engineered to light up in the presence of their favorite food—a pollutant called toluene. The light from an activated fluorescent protein triggered an electronic response. The "critters on a chip" sensor, formally labeled a bioluminescent bioreporter integrated circuit (BBIC), was licensed to Micro Systems TECH for homeland security uses.

Based on research by Simpson's and Sayler's groups and funded by the National Institutes of Health, ORNL recently patented a method for using an implantable BBIC sensor chip for glucose detection. "Sayler's group engineered human mammalian cells to emit light to the circuitry our group designed for an implanted sensor," Simpson says. "The amount of light is related to the glucose level. We have suggested that incorporating our glucose-sensing capability in a closed feedback loop with an implantable insulin pump could lead to an artificial pancreas."

Simpson is intrigued by the information-processing capabilities that are packed into single cells. "If you compare the information-processing ability of a piece of silicon the same size as an *E. coli* bacterium, the bacterial cell wins by a lot," says Simpson, who has a joint appointment at the University of Tennessee and Oak Ridge National Laboratory..

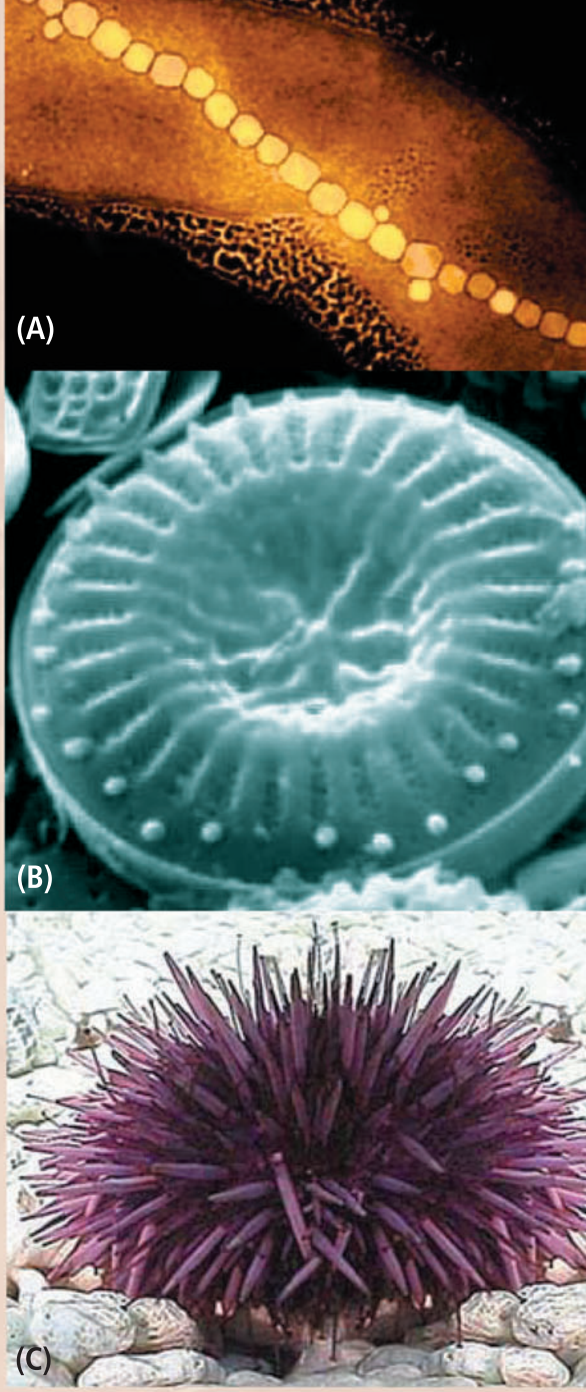
He is fascinated by magnetotactic bacteria, which are found in aquatic environments. These aquatic bacteria gather materials to make nanomagnetic particles, assemble them into a rod that aligns itself with the earth's magnetic field, and then start up a protein motor that enables the bacteria to travel, following the magnetic field's curvature. "These bacteria use the magnetic field to guide them down into water where the dissolved oxygen level is just right," Simpson says.

Another micro-organism of interest is the diatom, which builds an elaborate silicon structure in which it lives until the structure divides into two diatom cells. Each of the daughter cells inherits half the structure and must manufacture the other half.

"I am interested in these cells because they perform exquisite controlled synthesis and directed assembly of nanoscale materials," Simpson says. "Understanding how their genetic and biochemical circuits and networks make possible their complex functionality could teach us how to create engineered systems with similar abilities."

Simpson's group, including Tim McKnight and Anatoli Melechko, is collaborating with Mitch Doktycz's group in biomimetics—mimicking cell structure and function in engineered devices. They can grow an array of vertically aligned carbon nanofibers in any pattern they choose. Thus, they can imitate a cellular membrane by controlling the spacing between the nanofibers so that small molecules will pass through, while larger molecules are excluded. They demonstrated this capability by transporting fluorescently labeled latex beads of different sizes down a microfluidic channel intersected with a stripe of nanofibers and detecting a buildup of the larger beads at the intersection.

For nanobioscientists, Mother Nature is a role model. Ⓡ

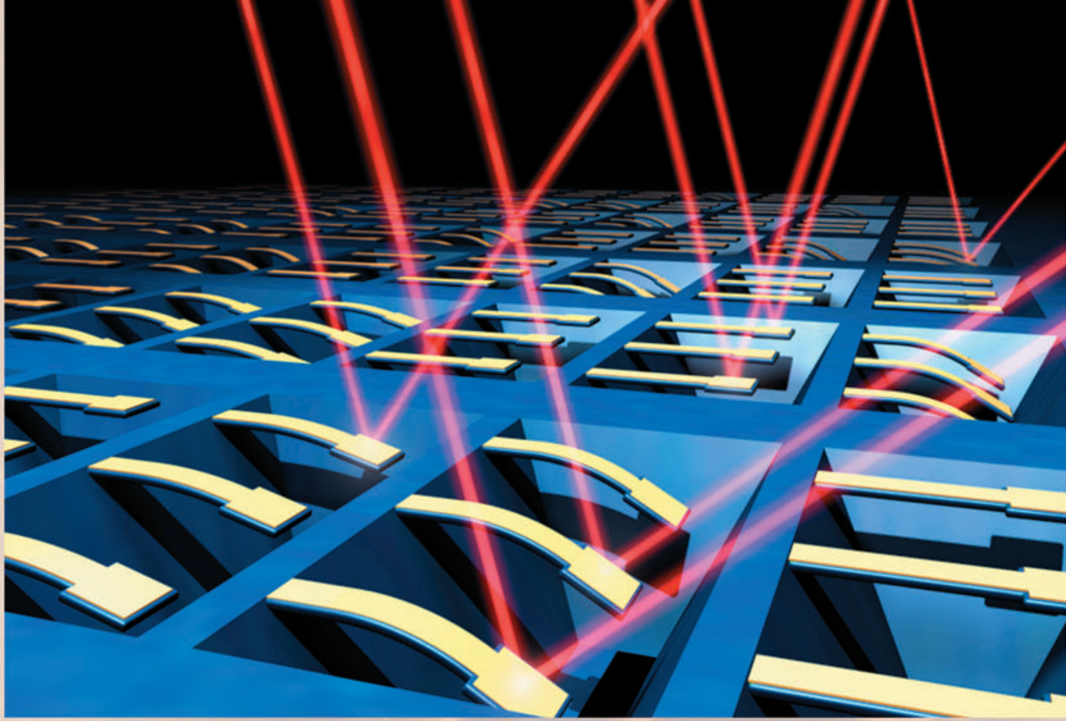


(A): *This magnetotactic bacterium exhibits one-dimensional ordering of a nanostructure.*
(B): *This diatom is a single-cell eukaryote that exhibits three-dimensional (3D) ordering with a complex but static structure using one material.*
(C): *The sea urchin is a multi-cell organism that has 3D ordering with a complex and dynamic structure that uses many materials. Scientists study these cells because they perform exquisite controlled synthesis and directed assembly of nanoscale materials.*

CASW

TINY DETECTORS

The microcantilever sensor invented by Thomas Thundat is the heart of numerous emerging physical, chemical, and biological sensors, including a compact airport explosives detector and a more sensitive detector of early-stage prostate cancer.



Microcantilevers coated with a material that attracts molecules of a target substance will bend more when near that substance, changing the angle at which incoming laser light will be deflected. Courtesy of Arun Majumdar and Kevin Lin, University of California at Berkeley.

In 1991, Thomas Thundat observed an anomalous effect while conducting an experiment with an atomic force microscope (AFM) in his ORNL lab. He had performed the same experiment a few months earlier when he was a postdoctoral researcher at Arizona State University. Strangely, the AFM cantilever at Arizona State had been stable, whereas the one at ORNL kept drifting, ruining the experiment.

"Eventually, I realized that because it rains a lot in Tennessee, my lab's humidity level often went up, so the cantilever drifted," Thundat says. "There was no variation in the cantilever in Arizona, where it is always dry. Then it occurred to me that the silicon nitride cantilever could be a sensor for humidity, because water vapor adsorbs on silicon nitride."

Thundat then developed a mercury sensor using a microcantilever, which resembles a tiny diving board. He deposited a layer of gold on a cantilever and exposed it to mercury vapors. Because mercury has an affinity for gold, mercury in the air binds with the gold layer, causing the cantilever to bend. Thundat says the cantilever is a sensitive detector because of mechanical forces induced by chemical binding between probe and target molecules. In 1996 Thundat and his colleagues extended the sensor concept to physical sensing and demonstrated an infrared detector and an infrared camera based on a bimetallic cantilever.

In the 1990s Thundat's group fabricated many different cantilever chemical and biological sensors by coating them with special chemicals that attracted and captured molecules of a target material. They made sensors that can detect not only trace amounts of environmental pollutants but also weapons of mass destruction.

Collaborating teams led by Thundat at ORNL and Jesse Adams at the University of Nevada recently devised a much more compact cantilever-based airport explosive sensor that could detect trace amounts of TNT. The innovation was reported in a paper in the October 2, 2003, issue of *Nature*; the paper's lead author, Lal Pinnaduwage, is a member of Thundat's team. The paper proposed distributing microsensors in airport ventilation systems to detect nitrogen-containing explosive molecules wafting through the air.

In each microsensor, a tiny voltage would be applied to an embedded piezoresistive heating element, which would heat the cantilever to 1000°C for 0.1 sec. The adsorbed TNT molecules undergo nanoexplosions when the cantilever is heated very rapidly. Consequently, the cantilever would bend down, squeezing a zinc oxide crystal embedded below in a piezoelectric sensor-actuator. An electric charge would be produced, alerting airport officials to the location of an explosive. "This new device overcomes a number of limitations associated with conventional microcantilever sensors," Thundat says. "The process uses integrated elements on each cantilever, consumes 10,000 times less electricity, and allows for an array structure that simplifies the simultaneous use of many cantilevers."

Pinnaduwage and Thundat also developed a coating that, when applied on a cantilever, can very sensitively detect explosives, such as the PETN explosive used by the would-be "shoe bomber." "This sensor can detect PETN within 10 seconds at 1 part per trillion sensitivity," Thundat says.

Thundat found that a cantilever coated with double-stranded "probe" DNA will deflect when it hybridizes with a complementary DNA target, say, from a disease bacterium. He also showed that cantilevers can detect glucose levels in blood.

Recently, Thundat and Arun Majumdar of the University of California at Berkeley fabricated cantilevers coated with an antibody to the prostate-specific antigen (PSA). They showed that this technique in which PSA binds with the antibody coating on the cantilever, causing it to bend, detected early signs of prostate cancer in serum samples with 10 times higher sensitivity than conventional techniques.

Using ink-jet printing techniques, Thundat and Majumdar have developed a parallel array of 500 DNA- and antibody-coated cantilevers. Stacked charge-coupled device camera images show which cantilevers deflected after exposure to disease proteins. If this array could rapidly detect in body fluids any one of 100 different cancer markers, such as elevated or depressed levels of antibodies and enzymes, it could be the heart of a hand-held device for fast disease diagnosis. Ⓡ

A NEUTRON MICROSCOPE

New knowledge and novel materials and products will arise from cutting-edge research at DOE's Spallation Neutron Source at ORNL, according to Thom Mason, SNS Project leader.

The next frontier in materials science may be viewed on Chestnut Ridge in Oak Ridge, Tennessee. The 80-acre wooded site is the location of the Department of Energy's Spallation Neutron Source (SNS) currently under construction at Oak Ridge National Laboratory. The SNS, an accelerator-based source of pulsed neutrons for research, will offer ~10 times the peak neutron flux of its leading competitor. Combined with ORNL's steady-state High Flux Isotope Reactor, the SNS will make ORNL the world's leading center for neutron science.

The leader of the SNS project is Thom Mason, a condensed matter physicist who has used inelastic neutron scattering to study the magnetic dynamics of superconductors and novel magnetic materials. "Understanding complicated materials requires sophisticated scientific tools," he says, noting that humankind has moved from simple materials—such as bronze, iron, steel, and silicon—to mastering more complex materials, such as polymers, proteins, nanomaterials, and superconductors.

Compared with other facilities, the SNS will provide more comprehensive information about materials, using smaller samples. Neutrons produced in the SNS will reveal more details about the magnetic structure of nanoscale materials.

"The SNS is one of the largest science projects under way in the world and is the largest science project in DOE's Office of Science," Mason says. "It also will be the largest materials research user facility in terms of investment. The project will be ready in 2006, and a lot has been happening in terms of design and construction.

"The scope of research at SNS will be tremendously broad, so it will have a big impact on many areas in science," Mason explains, listing superconductivity, magnetism, inorganic chemistry, solid-state chemistry, polymer chemistry, life sciences, and engineering. "The SNS will revolutionize our understanding of the structure and dynamics of proteins, plastics, and engineering materials."

Structure determines the properties of a material, he says, noting that three forms of carbon—graphite, diamonds, and buckyballs— have different properties because of their unique structures. "Knowledge of structure and dynamics suggests ways to make a better material," Mason says.

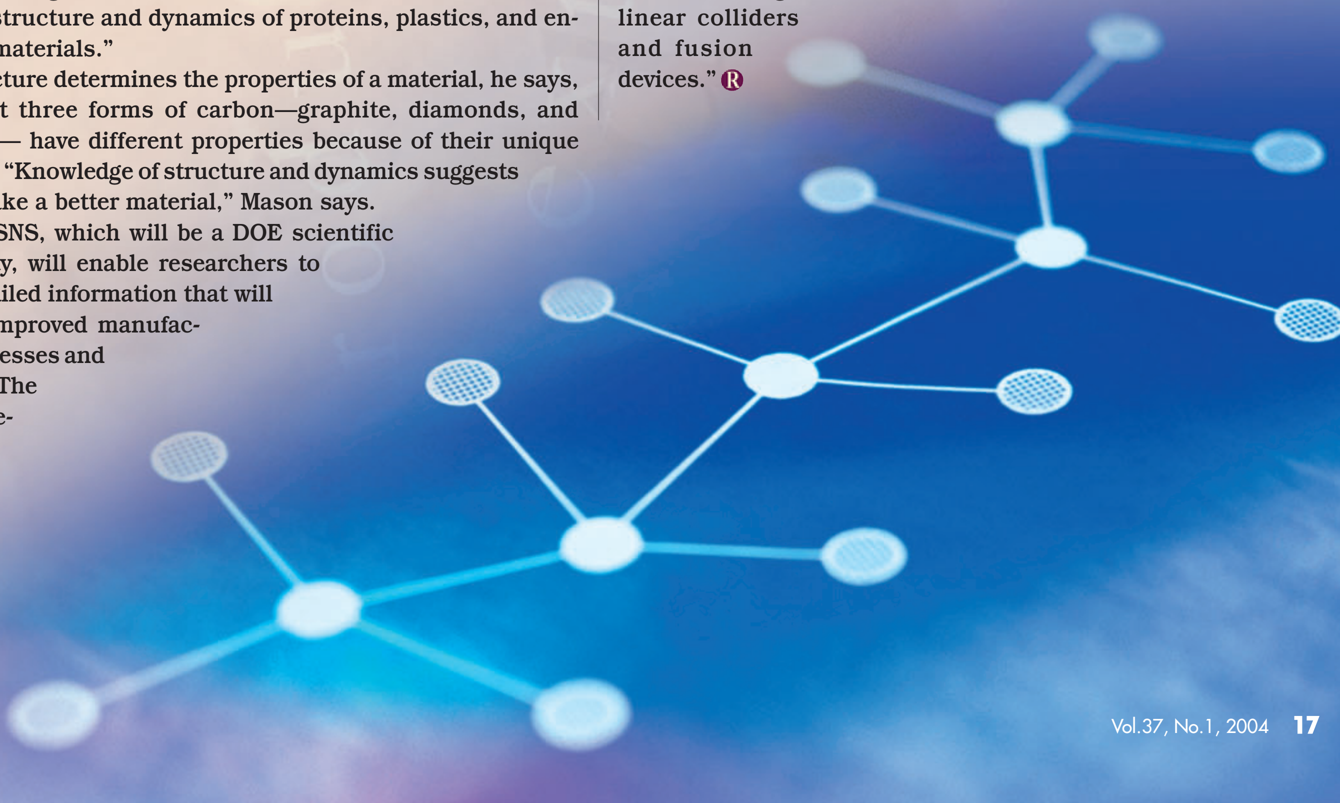
The SNS, which will be a DOE scientific user facility, will enable researchers to obtain detailed information that will result in improved manufacturing processes and products. "The SNS will reveal the origins and mechanisms of behavior that become important in materials that go into real products and real industries," Mason says. "These could be magnetic devices for information storage, or chemical products that go into latex paints or better plastics or high-strength alloys or composite materials—things that eventually wind up in cars, airplanes, and computers and data storage units."

The SNS, he adds, will enable studies of residual stresses and other features of matter in a realistic environment. Residual strains in intact engineering components can be measured using the VULCAN instrument at the SNS. Researchers will be able to detect subtle shifts in the position and motion of atoms in, for example, a mineral that is squeezed in a diamond anvil pressure cell at the Spallation Neutron and Pressure, or "SNAP," beam line.

Pending the construction of a second target station, in 20 years the SNS should be operating approximately 45 best-in-class neutron science instruments with two differently optimized target stations and total beam power in the 3- to 4- megawatt range. Scientists at the SNS will be able to address such questions as, why is a material failing, how can a certain manufacturing process be improved, or why do some compounds contract when heated and expand when cooled?

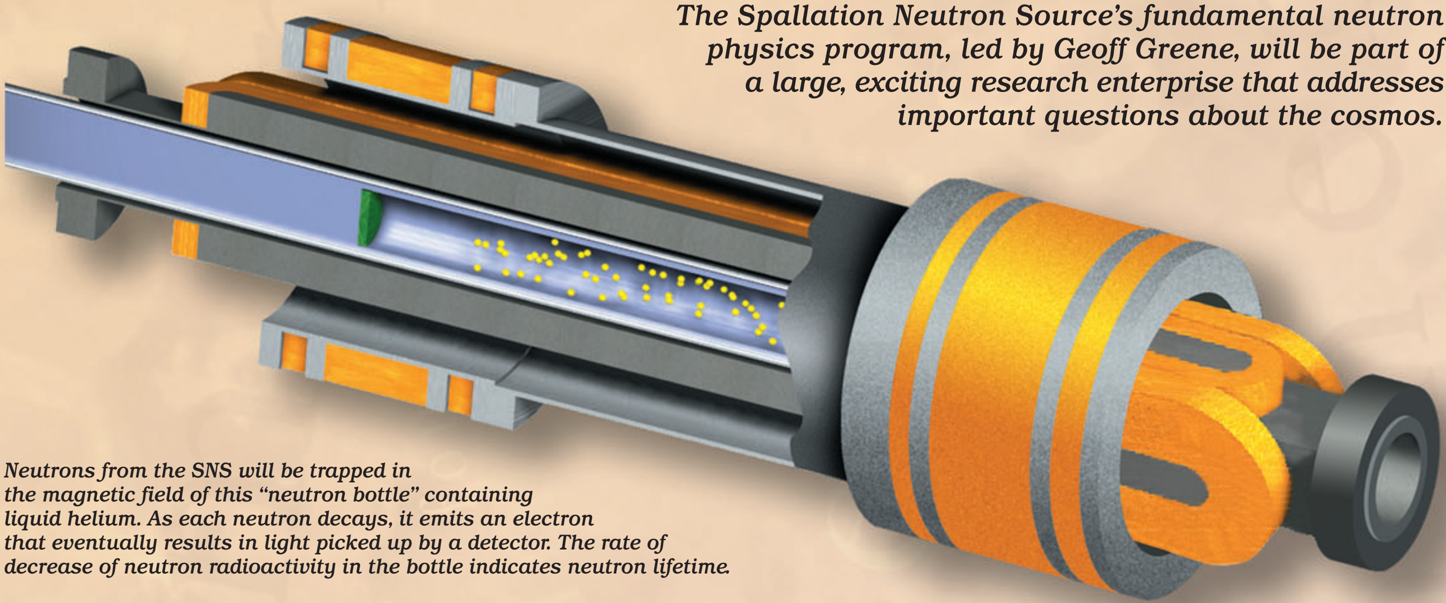
"The SNS will have the capability to advance the state of the art in spallation neutron source technology," he adds. "Research and development work will be conducted on accelerators, targets, and neutron scattering instruments to keep SNS at the forefront."

"The SNS will not only be breaking new scientific ground," says Mason, noting that the project is interesting from a sociological standpoint because it is being built as a multilaboratory partnership. "The project is a model for major facilities of the future, such as next-generation linear colliders and fusion devices." Ⓡ



NEUTRON CLUES

The Spallation Neutron Source's fundamental neutron physics program, led by Geoff Greene, will be part of a large, exciting research enterprise that addresses important questions about the cosmos.



Neutrons from the SNS will be trapped in the magnetic field of this "neutron bottle" containing liquid helium. As each neutron decays, it emits an electron that eventually results in light picked up by a detector. The rate of decrease of neutron radioactivity in the bottle indicates neutron lifetime.

Geoff Greene wants to know what makes the universe tick, so he follows the best neutron sources around the world. Now, he's preparing to study the fundamental characteristics of the neutron at what will be the world's best neutron science facility. Greene came to ORNL in 2002 through a joint faculty appointment with the University of Tennessee. In collaboration with colleagues from ORNL and several other institutions, he is designing two instruments for the Fundamental Neutron Physics Beam Line at the Department of Energy's Spallation Neutron Source at ORNL, which will be completed in 2006.

Greene has conducted research at neutron sources in France, at DOE's Los Alamos National Laboratory, and at the National Institute of Standards and Technology (NIST). "I came here because of the SNS," he says in his ORNL office. "There's no question that the next big thing is up the hill."

Why is he interested in studying the nature of the neutron at the SNS? "Some large questions concerning the universe can be addressed by studying the neutron," he says, giving these examples. Why does the universe discriminate between matter and anti-matter? How were elements made during the first few minutes of the Big Bang? How much energy is produced in the sun? What is the nature of the weak nuclear interaction between quarks? Why does the universe apparently show a "preference between left- and right-handedness," an effect known as parity violation?

Measurements of neutron lifetime could shed light on this last question. "Our neutron measurements will complement the findings of researchers in high-energy physics, nuclear physics, theoretical physics, cosmology, astronomy, and astrophysics," Greene says.

Neutron scattering researchers see the neutron as a point-like object that interacts simply with matter, providing an attractive probe for understanding complicated materials. To nuclear and particle physicists, the neutron is a much more complicated object, made of "spinning" quarks and filled with a host of "virtual" particles and anti-particles that are being continuously created and annihilated.

"Although the neutron exhibits all the complexity of an atomic nucleus, it is really much simpler," Greene says. "From a nuclear and particle physics standpoint, the neutron is complicated enough to be interesting but simple enough to be understandable."

Greene and his colleagues from Harvard, NIST, Los Alamos, and Germany's Hahn-Meitner Institute will try to determine more precisely how long the unstable neutron lives before decaying. "The free neutron has a 'half-life' of about 10 minutes," he says. "When a neutron decays, it releases enough energy to be observed in a sensitive detector."

Pulses of neutrons from the SNS will pass through cold liquid helium before entering a magnetic "neutron bottle" containing liquid helium. Because neutrons are tiny magnets, they can be trapped in a non-homogeneous magnetic field created by a superconducting magnet.

Each decaying neutron produces an energetic electron that disrupts the helium atoms, causing a flash of ultraviolet light that is converted to visible light and detected. These light pulses count the neutron decay rate in the bottle as a function of time. The rate of decrease of neutron radioactivity in the bottle indicates the neutron lifetime.

"We expect the SNS to give us 100 times the count rate of the current neutron lifetime experiment," Greene says. Such an increase will allow significant improvement in the measurement of the neutron lifetime.

"It is an astonishing fact that the universe seems to make a big distinction between right and left," Greene adds. "We don't really know why radioactivity is left-handed, meaning that when a radioactive nucleus decays, it emits more electrons in one direction than another. Nuclear radioactivity is really the decay of a neutron within the nucleus. The study of the decay of the free neutron may help us better understand the origin of parity violation." And it will help Greene and his colleagues better understand the universe. Ⓡ

UNCOVERING THE EVIDENCE

ORNL's Arpad Vass found that a dead body lying on the surface or in a shallow grave emits more than 400 different chemical vapors, some of which attract cadaver dogs.

Human body odor historically has a bad name, but for ORNL's Arpad Vass, determining the chemical composition of human body odor after death could lead to the invention of a desirable "electronic nose." Such a detector could help police more quickly find bodies buried in hidden, shallow graves.

A tool that mimics a cadaver dog's nose is high on the wish list of law enforcement agencies. The wish is a goal for Vass, who is close to developing a superb training tool for cadaver dogs and eventually a detector of clandestine graves.

Vass, an expert at determining how long someone has been dead, is also developing a way to calculate "time since death" by reading the peaks of activity of different microbes associated with human decomposition. Recently, he developed a chemical technique for pinning down the day that any murdered victim dies, provided that medical examiners send him organ tissues for the analysis of amino acids and neurotransmitter breakdown products.

The FBI's technology-assisted search teams are deployed many times each year looking for clandestine graves of alleged murder victims, based on tips from informants. The teams use ground-penetrating radar and cadaver dogs in a sometimes futile but always expensive search over a large area.

"It is reported that cadaver dogs can find human remains hundreds of years old and can differentiate human bones from animal bones," Vass says. "However, these dogs are difficult to train, expensive to maintain, and easily distracted. If we could develop a detector that does what cadaver dogs do well, the costs to and efforts of law enforcement would be significantly reduced."

Police could use a tool for quickly distinguishing between human and animal bones because bones are brought to them frequently. "They need to know whether it's a chicken bone or a bone of a dead infant and whether the bone is evidence of a murder," Vass says. "One possible tool we are testing that may detect differences in the elemental composition of human and animal bone is laser-induced breakdown spectroscopy."

At the University of Tennessee Anthropological Research Facility (dubbed the Body Farm), Vass and his colleagues found that donated dead bodies lying on the surface or buried in shallow graves emitted more than 400 different volatile compounds. The researchers are honing in on groups of chemicals that are consistently emitted for each stage of decomposition: fresh, bloated, decayed, and skeletonized.

"We identified fluorinated compounds coming out as vapors from buried bodies," Vass says. "Since Americans drink fluorinated water, it may be possible that, as dead bodies decompose, fluorine combines with hydrocarbon compounds, generating an odor. We'd like to test whether cadaver dogs key in on these compounds."

At the UT facility, ORNL researchers collect vapors from a 2.5-ft-deep grave outfitted with perforated pipes, sampling ports, a video camera for visual monitoring of a body as it decomposes, and a capture hood containing a triple-sorbent trap system developed in ORNL's Chemical Sciences Division—a metal cylinder loaded with carbon granules that bind lightweight, medium-size, and large molecules. The collected vapors are desorbed from the carbon trap and analyzed by a gas chromatograph–mass spectrometer at ORNL.

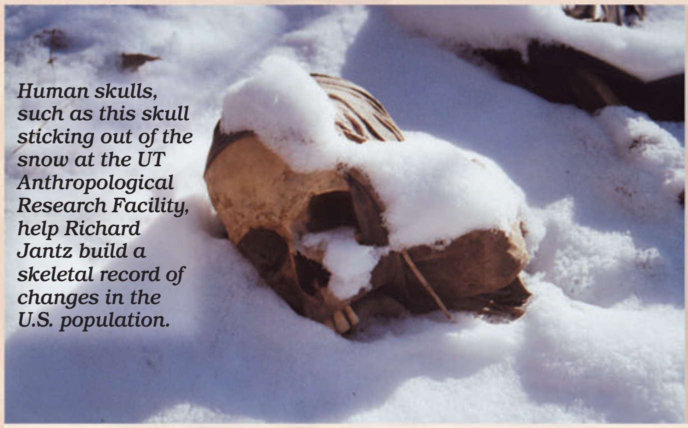
"We found that a human body in a shallow grave decomposes eight times slower than a corpse left on the surface," Vass says. "Some reasons may be that bacterial decay in the body slows down because of the lack of oxygen, and insect infestation of the body is minimal."

If the chemicals that attract cadaver dogs can be identified, then one type of detector that ORNL researchers could build would use polymers that react with specific chemical vapors wafting by. A reaction changes each polymer's electrical conductivity enough to produce an electronic signal. Thus, a specific group of signals from the electronic nose could alert law enforcement that a shallow grave is nearby.

From this research, Vass and his colleagues hope to complete a "DOA" database, where DOA stands for "decomposition odor analysis," not "dead on arrival." Ⓡ

The task of finding a body in an unknown shallow grave is difficult and time consuming. ORNL research to determine a decaying body's chemical signature may lead to rapid detection of clandestine graves.

by Laura Buenning,
University of Tennessee-ORNL Science Alliance



Human skulls, such as this skull sticking out of the snow at the UT Anthropological Research Facility, help Richard Jantz build a skeletal record of changes in the U.S. population.

BONE DIARIES

As UT's Richard Jantz reads skeletons, he finds that modern Americans exert less effort and eat more nutrients than their ancestors.

University of Tennessee Anthropology Professor Richard Jantz likes to read biographies, but not the kind you might think. What he likes best is the history recorded in the human skeleton.

"You write your biography on your skeleton," says Jantz. "Like a diary, it records all kinds of bumps in the road. "

Jantz scrutinizes the structural variations in modern Americans for clues to the long-term effects of nutrition and physical activity on the skeleton. His opinions on the much-publicized

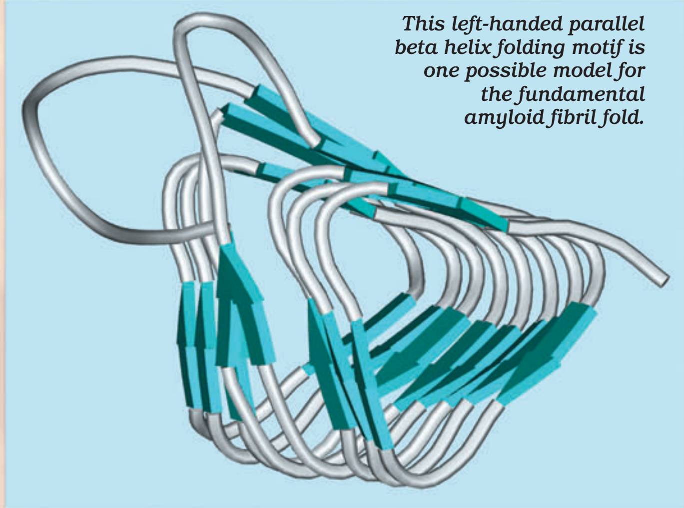
FROM EXOTIC TO EXTINCT

UT's Daniel Simberloff studies the effects of exotic plants and animals that destroy native species.

Invasive species intrigue Daniel Simberloff, professor of ecology and evolutionary biology at UT. Some 7000 exotic species have been introduced into the 48 contiguous United States. About 700 of these are considered invasive, because they destroy native species. For example, ladybugs native to the United States are being replaced by exotic ladybugs from Asia and Europe. "Dozens of native species here are rare, but introduced species are common," Simberloff says.

Another example is the Small Indian Mongoose, which sugar cane growers introduced to the West Indies in 1872, to Hawaii and Fiji in 1982, and later to islands in the Indian Ocean and Adriatic Sea. Brought in to control rats, the mongoose "turned out to be a huge pest," Simberloff says. "It caused the extinction of more than 30 species of birds, mammals, reptiles, and amphibians native to these islands.

"Most introduced species do not become a major problem, but some do. And so we ask, 'Why?' You add a new species to a group that has been co-adapting and co-evolving for a long time and suddenly you have a whole new entity in the mix. Studying its impact



This left-handed parallel beta helix folding motif is one possible model for the fundamental amyloid fibril fold.

PROTEIN FOLDING GONE AWRY

UT's Ron Wetzel seeks to develop molecules that can block the formation of amyloid fibrils common to several deadly diseases.

Many unknowns surround the diseases typified by deposits of amyloid fibrils inside body tissue. But, to UT Professor of Medicine Ron Wetzel, nothing is more mysterious than how the process starts.

Alzheimer's, Lou Gehrig's, Parkinson's, Huntington's, and prion diseases such as Creutzfield-Jacob Disease—the diseases are many and the proteins forming the amyloid fibrils differ. However, the fibrils are alike because all are composed of similarly misfolded proteins. Nearly insoluble in water, the fibrils tend to aggregate and make deposits, complicating efforts to manage their

UNFOLDING THE ANSWERS

Experiments with mice by UT's Alan Solomon and colleagues showed that a monoclonal antibody could be made to remove amyloid fibrils .

Diseases stemming from deposits of abnormally folded proteins could be the most serious medical problem facing society in the 21st century. So says Alan Solomon, UT professor of medicine and American Cancer Society clinical research professor.

Schooled in the chemistry of proteins, Solomon knows the tragic consequences of proteins that fail to fold along their normal pathways. Many of the devastating diseases caused by misfolded proteins affect the elderly. No effective treatments are available for these diseases, which include Alzheimer's disease, diabetes, and rheumatoid arthritis.

One of the most common and deadly of protein-misfolding disorders is amyloidosis. This pathologic process involves the deposition of any one of at least 24 different proteins as amyloid fibrils in the body.

While attending a national amyloid meeting in 1995, it occurred to Solomon that the body might not recognize the fibrils as being foreign tissue. He decided to test whether fibrils obtained from human tissue could be eliminated by mice. Experiments in Solomon's lab showed mice developed antibodies that eliminated the human amyloid. A monoclonal antibody created in Solomon's lab dramatically hastened removal of the amyloid.

debate on Kennewick Man and the origins of the first Americans have been broadcast on *NOVA* and British television, and he has been quoted in the *Washington Post* and the *New York Times*.

"Modern Americans live in a unique environment," he says. Never before has over-nutrition been a bigger problem than under-nutrition, or have humans exerted as little effort as we do now. We have bigger bodies. And infant mortality is far below what it used to be."

As studies at the Jamestown reconstruction project and similar projects elsewhere in America have shown, colonial Americans experienced quite the opposite. While struggling to survive, many actually starved to death.

As conditions improved, the body responded in unique ways, according to Jantz. "We're taller than we were more than 100 years ago. The shape of the skull is higher, narrower, and longer. The teeth and jaws, like the rest of the skeleton, are experiencing less stress, so they are becoming smaller."

Jantz and Doug Owsley of the Smithsonian Institution are assembling a skeletal record of Americans since colonial times. Their goal is a 300- to 400-year skeletal history of both black and white modern Americans. Jantz is director of UT's Forensic Anthropology Center, which includes the Anthropological Research Facility, dubbed the "Body Farm." Founded in 1972 by Dr. William M. Bass, this facility is a laboratory for ORNL's Arpad Vass, who seeks clues from decomposition to determine precisely how long someone has been dead. Ⓡ

should tell us quite a bit about the forces that determine which species can coexist and how they accommodate one another."

During his early years on the national board of the Nature Conservancy (1986 to 1997), Simberloff came to realize how serious were the societal and environmental problems caused by introduced species."As one of the few scientists on the board, I talked to many land stewards," he says. "It became clear over a three- or four-year period that about half their problems had to do with introduced species. That was when I began to see this as not just an interesting, arcane academic phenomenon, but a societal and economic concern." Ⓡ

Ladybugs native to the United States are being replaced by exotic ladybugs from Asia and Europe, such as this one.

associated diseases."Understanding how fibrils form and grow by bringing more molecules into the structure could help us design inhibitors to block the process," Wetzel said. His group focuses on Alzheimer's and Huntington's diseases.

Each disease has its own protein that runs into trouble during normal folding. "The protein goes down an alternative folding pathway," he says. "Once started, the process is often self-sustaining."

According to Wetzel, some conditions may result from the deposition of masses of fibrils that can interfere with tissue structure. But other diseases may involve relatively small numbers of fibrils that may directly kill specific types of cells.

Using electron microscopes, Wetzel's group has found that amyloid fibrils from any protein resemble short, relatively rigid, twisted ropes. Higher-resolution methods, such as X-ray crystallography and nuclear magnetic resonance, fail to resolve fibril structure for various technical reasons.

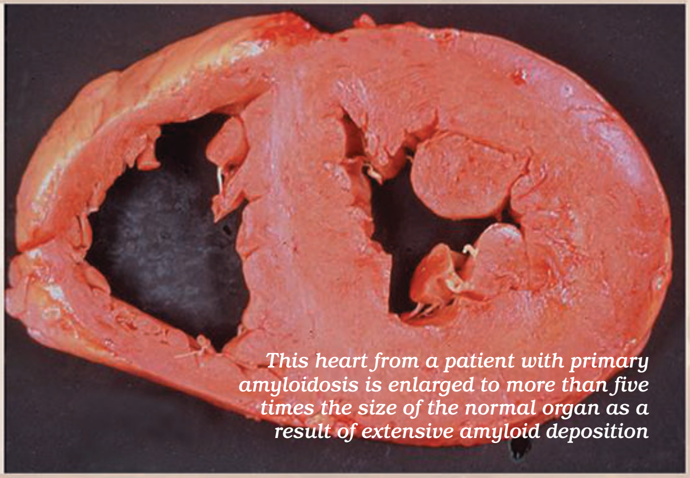
To overcome this barrier to understanding how different proteins evolve to form different shapes and how they get tangled up to form highly stable amyloid structures, Wetzel's lab fell back on classical methods of piecing together misfolded proteins. They have excelled at growing in the test tube amyloid fibrils and aggregates associated with Alzheimer's and Huntington's diseases.

Wetzel seeks to understand how molecular "chaperones" designed to eliminate protein misfits can interfere with amyloid formation in Huntington's disease. "This knowledge," says Wetzel, "could help us figure out how to make the disease process stop." Ⓡ

"It got rid of the human material five times faster, even before the mice could mount an immune response," Solomon says. However, his appeal to drug companies for help in developing this antibody in a form that could be tested in patients proved futile.

Fortunately, Solomon's appeal to a new National Cancer Institute program called RAID (Rapid Access to Interval Development) brought positive results. The RAID program is designed to translate into clinical practice those promising discoveries that often seem too expensive or risky for commercial development.

In 1998 RAID agreed to create a humanized form of the antibody. In June 2002 RAID decided to produce enough of the antibody for a clinical trial. Aging baby boomers at risk of developing amyloidosis may someday be able to knock out the disease, thanks to research conducted in Knoxville. Ⓡ



This heart from a patient with primary amyloidosis is enlarged to more than five times the size of the normal organ as a result of extensive amyloid deposition

PROFILE Jeff Wadsworth
New Director, *New Directions*

"Nano-bio-info: Built upon a foundation of scientific and operational excellence." That could be the title of the message ORNL Director Jeff Wadsworth frequently delivers in his speeches to the public. Nanoscience, biology, and large-scale computing are three research initiatives expected to dominate science and technology in this century, largely because of their promise for improving our lives. New facilities expected to be operating between now and mid-decade at ORNL will position the Laboratory to be a world leader in these three "thrusts," as Wadsworth calls them. He emphasizes that this leadership is possible only because of the very strong science and engineering foundation at the Lab. The Department of Energy is committing greatly increased funding in these areas, based on the Office of Science's 20-year facilities plan, announced November 10, 2003. Three of the 28 proposed facilities, including a second target station for the Spallation Neutron Source, would ensure ORNL's role as the world leader in neutron science for years to come.

Wadsworth is an internationally recognized metallurgist who came to ORNL in August 2003 after a year at Battelle's world headquarters and 10 years at DOE's Lawrence Livermore National Laboratory in senior management positions. He is excited by ORNL's future, which will include opportunities for the Laboratory to respond to problems of national interest, such as increasing homeland security, decreasing the odds of power blackouts, contributing to climate modeling, and spurring the economy through technology transfer. In this interview, he talks about ORNL's strengths and challenges.

Q. In light of your focus on technology transfer and homeland security while at Livermore and Battelle, will ORNL become more of an applied sciences lab and less of a basic science lab?

We will continue to do both basic and applied work. We have a terrific scientific foundation and we are competitive in the country's current research thrusts in nanoscience, life science, and large-scale computing. We are applying our capabilities to problems of national scale and the Department of Energy's main missions of national security, energy, and the environment. The content of each of those missions changes with time. Today the defense missions include homeland security and intelligence work. Twenty years ago, they were warhead design and underground testing. In energy, the recent blackout in the Northeast greatly increased interest in research to improve the power grid. Around the country a year ago, the grid wasn't a big deal, but it is now. Our scientific foundation and capabilities in thrust areas allow us to be flexible in supporting the important national missions of our time.

Q. Exactly, how might ORNL's research portfolio change?

I think national security is likely to grow, because right now the country has a huge concern about nonproliferation and homeland security. Economic development and technology transfer will receive increased emphasis, partly because of the new Battelle venture capital fund (to create and grow companies from technologies developed at ORNL and other Battelle-managed national labs). I hope to grow the biology program, and I'd like to give our important work in the environmental sciences more visibility.

Q. Will ORNL be able to compete effectively with DOE's weapons labs for funding from the Department of Homeland Security?

When I left Livermore in August 2002 and joined Battelle-Columbus, half of my assignment was to work with the White House transition planning office of the Department of Homeland Security (DHS). We studied carefully the capabilities of the DOE national labs. Oak Ridge and Pacific Northwest were seen as having capabilities in parts of homeland security that were more than competitive with the capabilities of the weapons labs—Livermore, Los Alamos, and Sandia. We have been named one of five DHS core labs. Because of our core capability in understanding isotopes, Oak Ridge's niche will be to lead efforts to find ways to detect radiation dispersal devices, or dirty bombs. We have contributions to make in chem-bio detection and information processing, which includes population models and work that requires massive computing, such as extracting meaningful information from complicated data sets. We are working with the other four labs on developing partnerships and plans in these areas.

Q. Some principal investigators and other researchers in small programs are concerned about funding levels in FY2005. What message do you have for them?

If the energy bill passes and provides the increased funding proposed for DOE's Office of Science, we can compete for more funding for small PI-driven research. Politically, the way the world works, people tend to get more excited about buying science in terms of large projects. Large-scale scientific signature facilities, such as the Spallation Neutron Source, distinguish national labs from industry and universities. DOE is not neglecting the smaller programs and the PI-driven research, but the agency is articulating its science future around major user facilities, which will impact the future of science. Under those facilities is a lot of PI-driven research.

Q. What is ORNL's future as an energy lab?

We have a large energy portfolio, one of the broadest in the country. At a recent DOE on-site review, we presented our vision for what ORNL can do to help the country in the next 5 to 15 years in terms of the power grid, nuclear energy, energy efficiency, fusion energy, and the hydrogen economy.

Q. What are ORNL's strengths and competitive advantages?

We have some very good scientific capability in the thrust areas the country is investing in—nanoscience, computing, and biology. We have an opportunity to become world-class in all three. I think we will be first in our neutron science capability under nanoscience. With our computing capabilities, our partnership with Cray, and a new building, we are well positioned to compete for a large supercomputer that may be in the federal budget. In biology we have a rich history with the mouse genomics program. We will work hard to win the DOE genome program facility for characterizing protein complexes. Other strengths are our support for the community and the political and business support we receive, which is second to none. Finally, our modernization program is just sensational. No other lab in this country has a modernization program that looks like ours. It's a huge advantage when it comes to winning new programs and recruiting new people.

Q. What are ORNL's most serious challenges?

Our safety record needs to improve. We have had problems in operating our facilities properly. These deficiencies are a huge distraction to us as we try to become the country's premier national lab. It's hard to overstate how important it is to run the lab safely and efficiently in order to be successful in our major science and technology missions. Another serious challenge we have is work force development. Over the next five years a significant percentage of the work force will become eligible for retirement. We will be hiring new people across the board. Ray Orbach, director of DOE's Office of Science, told us recently that, if we are successful in our ambitions to bring exciting new capabilities to the Laboratory, we must attract world-class scientific expertise. He wants us to aspire to be the Bell Labs of the 21st century, like the Bell Labs of the last century, when it was thought to be the place of great scientific discovery. We should try to make Oak Ridge the place where people naturally think to go for the best science in the country.

Q. What mark would you like to leave as director of the Laboratory?

I think this is a fantastic laboratory. I think it should be the world's best laboratory in our fields of endeavor. As employees we should strive to be as good as we can be. If we succeed in our ambitions to have a vibrant intellectual capability as a foundation stone; if we can operate safely, efficiently, and cost effectively; and if we can contribute to the nation's scientific thrust areas and solve national problems, we can indeed be the best in the world. R

CYBER SCIENCE

Through a high-speed national network connecting ORNL's neutron science facilities with supercomputers and data storage centers, valuable data will be rapidly accessed.

When ORNL becomes the world's foremost neutron science center, researchers from around the nation will be able to analyze the Laboratory's data both up close and at a distance. Thanks to a $3.9 million grant awarded by the National Science Foundation to the Department of Energy's Center for Computational Sciences (CCS) at ORNL, a network hub and high-performance network connections will be established to support access to ORNL's neutron science instruments across the TeraGrid.

A neutron scattering scientist at ORNL sends data from her experiment to a San Diego supercomputer for analysis. The calculation results are routed to Argonne National Laboratory, where they are turned into "pictures." These visualizations are transmitted in a matter of seconds to a scientist's workstation at Georgia Tech, one of UT-Battelle's core universities. Within minutes, the significance of an experiment is communicated to interested researchers, thanks to a high-speed network called TeraGrid.

The TeraGrid is part of a high-speed network that will provide scientists with extraordinary amounts of data from ORNL's High Flux Isotope Reactor and the $1.4-billion Spallation Neutron Source. When complete, the TeraGrid's network backbone will operate at 40 gigabits per second, making the research network the fastest in the world.

"This award is a wonderful illustration of the continuing partnership between NSF and the Department of Energy's Office of Science on the TeraGrid," says Raymond Orbach, director of the DOE office. "CCS will now be able to provide the nation's research community with expanded access to ORNL's extraordinary neutron science facilities."

The SNS, which will be the world's premier neutron scattering facility, is scheduled for completion in 2006. The High Flux Isotope Reactor is the world's most powerful source of thermal neutrons, used to unlock the molecular secrets of materials and to provide radioisotopes for a number of medical, industrial, and academic uses. Data from the two neutron sources will be made available through CCS.

The CCS is a DOE high-performance computing research center and a designated user facility whose mission includes helping to solve grand challenges in science and engineering. Housed in a new 170,000-ft^2 building with a 40,000-ft^{2}computer center, CCS is the nation's largest such facility for unclassified scientific research.

ORNL's winning proposal was one of three so awarded by the NSF. ORNL collaborated in writing the proposal with the University of Tennessee, Georgia Institute of Technology, Duke University, Florida State University, North Carolina State University, Virginia Polytechnic Institute and the University of Virginia.

The ORNL-led addition to the TeraGrid, called the Southeastern TeraGrid Extension for Neutron Science (SETENS), will allow scientists to use the massive computing and data storage resources on the TeraGrid to make rapidly detailed analyses and visualizations of data from neutron scattering experiments. The system will provide near real-time feedback.

SETENS represents a major commitment to the region and to economic growth in the Southeast. "This partnership will allow Georgia Tech researchers to explore pressing questions regarding the structure of complicated materials," says G. Wayne Clough, president of the Georgia Institute of Technology. "From a scientific perspective, this partnership has important ramifications in the fields of biotechnology, telecommunications, and environmental technology. From an economic development perspective, these resources show a continued commitment to build the intellectual capital of the Southeast—an investment that will reap benefits in terms of new business and research opportunities for decades to come."

The TeraGrid is a cornerstone in NSF's activities to develop a national cyber infrastructure to revolutionize the conduct of science and engineering research and education. The effort began in August 2001 with a $53-million award to four sites: the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign; the San Diego Supercomputer Center at the University of California; Argonne National Laboratory; and the Center for Advanced Computing Research at the California Institute of Technology in Pasadena. The consortium received another $35 million in October 2002 when the Pittsburgh Supercomputing Center joined the partnership.

The ORNL award will enable creation of a new TeraGrid hub in Atlanta, joining existing hubs in Chicago and Los Angeles. The hubs are connected by high-speed optical links in multiples of 10 gigabits. ORNL—the hub of the neutron science universe—will connect to the Atlanta hub at 10 gigabits initially and will work with Georgia Tech to equip, operate, and maintain the hub.—*Ron Walli, ORNL Communications Group*

RESEARCH

MODERNIZING THE GRID

ORNL researchers evaluate ways to make the U.S. electric system more reliable and less likely to experience a large blackout.

On August 14, 2003, during the largest electricity blackout in U.S. history, "communications were disrupted, traffic was snarled, elevators stopped, air conditioners quit, stores and businesses were forced to close, factories shut down, and hospitals and other vital facilities went to emergency power," according to a Department of Energy report.

"This blackout was largely preventable," said Secretary of Energy Spencer Abraham in his November 19 remarks announcing the U.S.-Canadian Power System Outage Task Force's *Interim Report* on causes of the blackout. The report, he added, "…showed that once the problem grew to a certain magnitude, nothing could have been done to prevent it from cascading out of control."

Two ORNL researchers—Brendan Kirby and John Kueck, both in the Engineering Science and Technology Division (ESTD)—served on the task force's Electric System Working Group. Kirby, an international expert on improving power-grid reliability and using electrical loads as a resource, said that he and Kueck interviewed employees of electric power systems in the Northeast and Midwest. They also analyzed tapes of telephone calls between operators at the control centers of the affected power systems.

"We found that the failure of power system operators to notice that an alarm system had stopped functioning and lack of human communication contributed to the blackout," Kirby says. "Multiple transmission lines failed, and the people who needed to know about these failures didn't find out until it was too late."

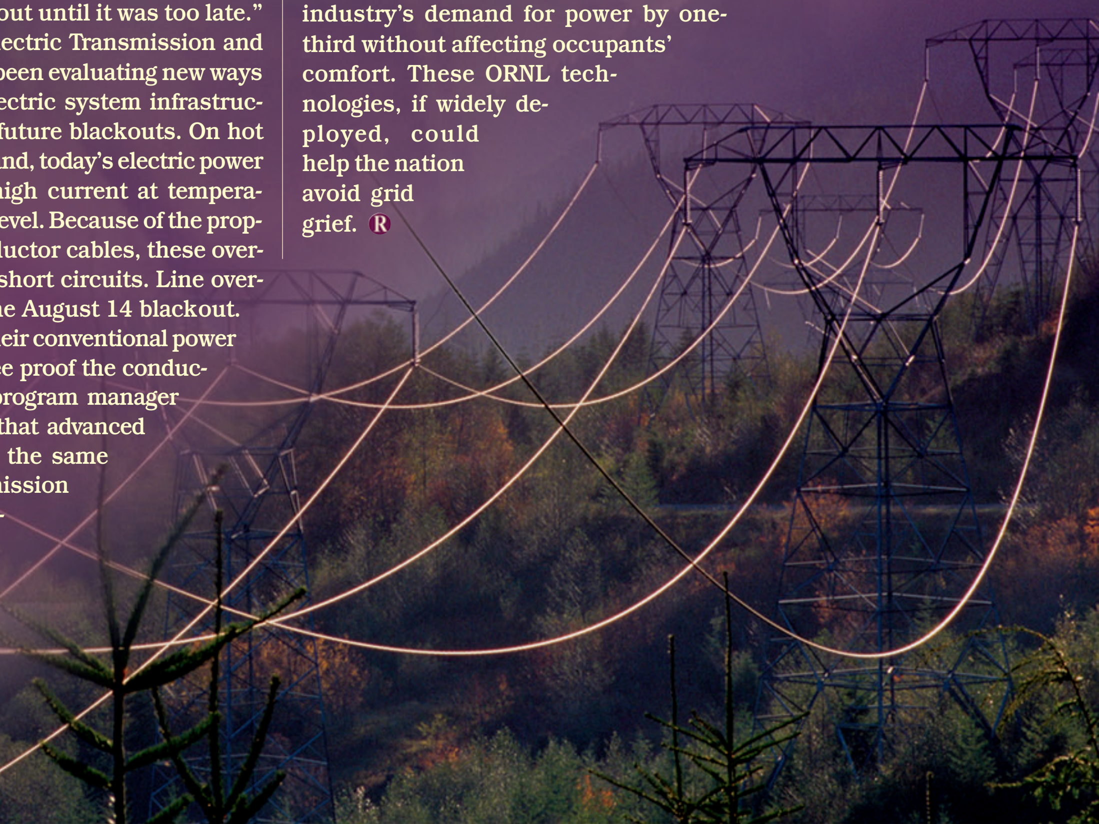
Researchers in ORNL's Office of Electric Transmission and Distribution Technologies Program have been evaluating new ways to reduce congestion on the nation's electric system infrastructure, improve its reliability, and prevent future blackouts. On hot days when air conditioning is in high demand, today's electric power lines can suddenly be forced to carry high current at temperatures higher than their normal operating level. Because of the properties of these steel-core-aluminum conductor cables, these overloaded lines can sag into trees, causing short circuits. Line overload and sagging became a problem in the August 14 blackout.

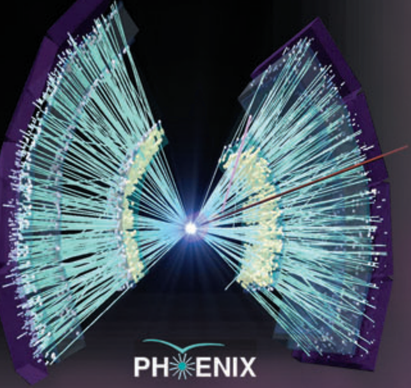
"Utilities may be willing to replace their conventional power lines with advanced conductors if they see proof the conductors have significant advantages," says program manager Bob Hawsey. "We can show them proof that advanced conductors carry more current without the same degree of sagging at the National Transmission Technology Research Center (NTTRC), operated by ORNL in partnership with the Tennessee Valley Authority."

At NTTRC's Powerline Conductor Accelerated Testing facility at ORNL, John Stovall and Tom Rizy, both of ESTD, have been subjecting advanced conductors to thermal, electrical, mechanical, and environmental "stress" tests while simulating 20 to 30 years of power transmission in several months of testing. They showed that 3M's composite-core conductor, which consists of ceramic fibers inside an aluminum-zirconium matrix, can carry 2.5 to 3 times the current of heavier conventional steel-core lines at 2.5 times the operating temperature before sagging the same amount.

Other technologies evaluated at ORNL that might have prevented the blackout are real-time communication and control technologies, including power electronics to control reactive power. These technologies could have made the operators of the affected systems aware of the location and impact of transmission-line failures and helped them respond quickly to prevent spread of the voltage collapse.

To improve electric reliability, Kirby advocates the concept of "spinning reserve" from responsive load instead of having generators standing by ready to provide reserve power. Several trial demonstrations of this concept are being developed in various parts of the nation by ORNL. One example is a rapid and temporary reduction of hotel and motel room air-conditioning loads when a problem develops within the power system. Demonstrations show that utilities can page a hotel's supervisory controls to turn off room heating or cooling systems for 10 to 30 minutes to drop the hospitality industry's demand for power by one-third without affecting occupants' comfort. These ORNL technologies, if widely deployed, could help the nation avoid grid grief. Ⓡ





ORNL'S IMPACT ON BIG BANG RESEARCH

Several ORNL physicists have played key roles in the search for one of the early universe's signature ingredients. Internal "seed-money" funding, the forerunner of today's Laboratory Directed Research and Development Program, allowed this ORNL physics program to flourish.

Researchers conducting experiments at the Relativistic Heavy Ion Collider (RHIC) at the Department of Energy's Brookhaven National Laboratory (BNL) may have come close to simulating the Big Bang. Whether they created a quark-gluon plasma, the signature of the first 10 microseconds of the universe's birth, ORNL physicists involved in these experiments are not ready to say.

"The good news is that it looks like Brookhaven has found an odd form of matter," says Glenn Young, director of ORNL's Physics Division. "What it is, we don't know. Science only disproves the existence of phenomena predicted by theory; it doesn't prove a theory correct. The hypothesis that a quark-gluon plasma could be produced at RHIC has survived this set of experiments."

At a Brookhaven colloquium on June 18, 2003, researchers announced that experimental results at RHIC, the world's largest facility for nuclear physics research, provided evidence they are on the right path to discovering a quark-gluon plasma—an elusive form of matter believed to have existed in the first microseconds after the universe was born. Quarks and gluons are thought to have roamed freely back then. As the universe cooled down, after 10 microseconds, the quarks and gluons "froze" into protons and neutrons, which make up the nuclei of atoms. Each neutron or proton is composed of three quarks held together by gluons.

Three types of experiments—gold-on-gold, deuterons-on-gold, and protons-on-protons—have been performed at RHIC. In each case nuclei in two beams are stripped of all their electrons, accelerated to almost the speed of light, and sent in opposite directions around a circular track. At several points along this track the beams are steered into each other, and detectors at those locations record the resulting collisions.

Occasionally quarks inside the nuclei of the two counter-circulating beams will collide head-on and create jets of particles that are emitted in back-to-back directions. "Quarks can't show up in the real world," Young says. "But if we visualize them as colliding invisible marbles, they shatter into fragments we can see." In gold-on-gold collisions many fewer jets were observed than expected, suggesting that some jets had to plow through dense matter that might have been a quark-gluon plasma. This phenomenon, called jet quenching, was one of the predicted signatures of the production of a quark-gluon plasma. Jet quenching was recorded by each of the four detectors at RHIC, including PHENIX, in which ORNL researchers played key roles

Proton-on-proton collisions were then measured, verifying the baseline expectations. Theoretical studies suggested that an effect other than quark-gluon-plasma formation could be responsible for the observed jet quenching. If so, a similar but smaller effect was predicted for deuteron-on-gold collisions. Significantly, this effect was not observed.

Nevertheless, Young says, "Many measurements are needed to see if RHIC has actually produced a quark-gluon plasma. We must look for muons, heavy electrons that come from the decay of heavy particles, like the J/psi particle, which is a charmed quark bound to its antiquark. We are using the muon identifier at the PHENIX detector at RHIC to find them. If quark-gluon plasmas are present, they would modify the production of J/psi particles, and the muon identifier should detect this change."

Young played a major role in getting ORNL involved in the RHIC experiment. In fact, it was Young's idea to build a muon iden-tifier at PHENIX. Young's colleague Paul Stankus suggested that PHENIX could

detect jets and jet quenching by focusing on rare, high-energy particles. Vince Cianciolo and Ken Read co-led the detailed design and 60-person crash construction of PHENIX's muon identifier. Cianciolo also spearheaded the development of its read-out electronics to find an occasional muon among thousands of other particles. Partly because of this work, he received a Presidential Early Career Award for Scientists and Engineers in 2002. Read is the PHENIX Detector Council representative responsible for the muon identifier, on which he has worked since 1993.

A photograph of PHENIX graced the October 2003 cover of *Physics Today*. The PHENIX collaboration has 400 physicists from 12 nations and 40 institutions.

"It all started with a seed money project back in 1989," Young says. "We got in the game of developing gamma-ray detectors called calorimeters when Brookhaven was starting its research program and accepting proposals for detector experiments on RHIC. I had learned about calorimeters from colleagues at BNL and ORNL. Before then, Frank Plasil, a member of our group, had a connection with a European group doing experiments in search of quark-gluon plasmas at the European Organisation for Nuclear Research (CERN) in Switzerland. So we offered to build calorimeters for that experiment. Our offer was accepted.

"We collaborated from 1986 through 1996 with Russian and German scientists in developing calorimeters using the Russians' lead-oxide bricks for experiments at CERN in Switzerland. These bricks stopped gamma rays, causing the emission of a 'shower' of electrons and positrons and changing their last bit of energy into visible light that can be detected by a photomultiplier. We developed electronics to read out the data, so we could figure out what was formed when nuclei collided in the CERN synchrotron. ORNL's Terry Awes became spokesman for the last CERN experiment."

ORNL wrote a set of winning proposals to work with the Russians and Germans to move the lead-glass calorimeter to PHENIX, with ORNL focusing on developing the electronics to read out and sort through the data to find meaningful signals. To develop the electronics for many subsystems at PHENIX, Young worked with electrical engineers in ORNL's Engineering Science and Technology Division; the project leads were Gary Alley, Chuck Britton, Bill Bryan, Miljko Bobrek, and Alan Wintenberg.

Stankus, who had worked on the last experiment at CERN in which ORNL was involved, pondered the problem of identifying jets at PHENIX. "Paul told the PHENIX collaborators that when quarks collide and shatter into lots of particles, the leading particle in the jet carries off most of the energy," Young says. "He proposed that some of the fastest leading particles could be pions, which could be detected by our calorimeter, because a pion, which is a quark-antiquark pair, decays into two gamma rays. He was right. Lo and behold they are easy to see and they came out clean as a whistle at PHENIX."

The collaborators detected jet quenching. "We saw only 20 to 30% of what we should see in pion decays," Young says. "Maybe some of the fragments had a real hard time pushing their way out when two quarks collided, because the matter they encountered looked like thick molasses. It was more opaque than a normal nucleus by a factor of 40 to 50. A quark-gluon plasma will be the densest form of matter ever seen, if it's actually found."

Young first reported on the data analysis of the results of the gold-gold collision experiment at a physics meeting in 2000.

Stankus oversaw the analysis and led the writing of the paper featured on the cover of the January 14, 2002, issue of *Physical Review Letters*.

More measurements using the muon identifier and the analysis of data already obtained will be needed to help verify whether the dense matter detected in the RHIC experiments actually is a quark-gluon plasma. The muon identifier consists of panels of steel that stop most particles—except muons—and detectors that produce current pulses when the gas inside them is ionized by particles passing through them.

The identifier's trigger electronics that Cianciolo helped develop will be key to finding the needles in the haystack—the muons that indicate the presence of a quark-gluon plasma. "It's like finding short scenes in a movie that could interest us the most and reviewing them many times to see if what we're looking for is there," Cianciolo says. If muons are seen, they will be the stars. R

PHENIX (shown here) is one of four detectors at Brookhaven National Laboratory's Relativistic Heavy Ion Collider. ORNL researchers have been involved in the development and operation of PHENIX.

...and the WINNERS are...

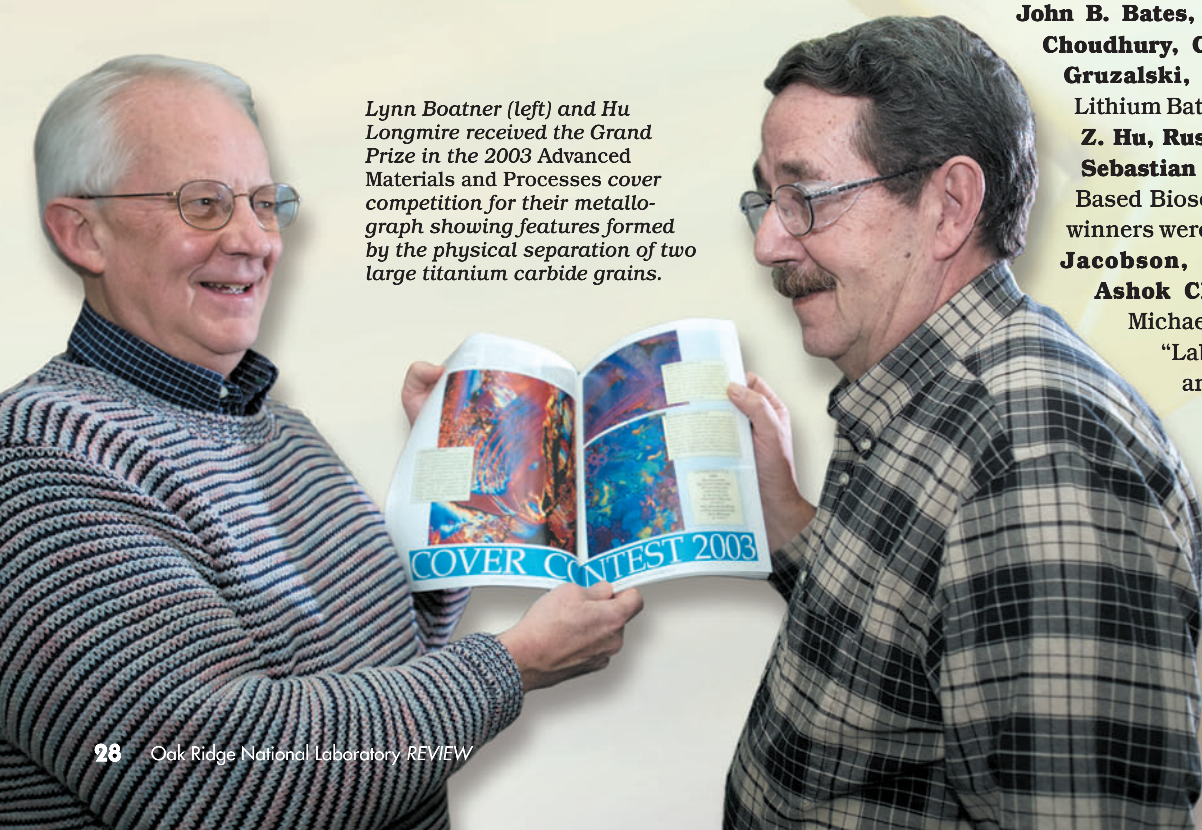
Accomplishments of Distinction at Oak Ridge National Laboratory

ORNL Corporate Fellow **Lynn A. Boatner** received the **AACG Crystal Growth Award**, the highest honor bestowed by the American Association for Crystal Growth, for "novel research in the area of crystal growth that has advanced the application of single crystalline materials and enhanced the appreciation of crystals both scientifically and aesthetically." **Boatner** and **Hu Longmire** received the **Grand Prize** for their entry in the 2003 Cover Competition of *Advanced Materials and Processes*, an ASM International publication (see image on this page). An entry by **Boatner**, **Allison Baldwin**, and ORNL Corporate Fellow **Stan David** in the 2003 ASM/IMS International Metallographic Competition received the **First Place Award** in the Light Microscopy Category; their paper is titled "Three-dimensional Metallographic Reconstruction of Solidification Microstructures in Stainless Steel Single Crystals."

Michael Ramsey, an ORNL corporate fellow, earned the **2003 American Chemical Society Division of Analytical Chemistry Award in Chemical Instrumentation**. The award, sponsored by the Dow Chemical Foundation, recognizes valuable contributions and achievements in analytical chemistry.

The Welding Institute of the United Kingdom presented an award to **Sudarsanam Suresh Babu** for his contributions to the advancement of welding technology.

Robust wireless technologies for extreme-environment communications, developed at ORNL, received the ***Excellence In Technology Transfer Award of the Year*** at the Southeastern Region of the Federal Laboratory Consortium awards ceremony, held in September 2003 in Charleston, South Carolina; the Southeast Region covers nine states and more than 40 federal laboratories. The winning researchers were **Stephen F. Smith, Gregory R. Hanson, Michael R. Moore, John P. Jones, Jr., Roberto Lenarduzzi, Michael S. Emery, Gary W. Turner, Milton N. Ericson, Timothy E. McKnight, James O. Hylton, James A. Moore, Alan L. Wintenberg, William B. Dress,** and **Paul D. Ewing**. There were four other ORNL winners. Recognized for ***Excellence in Technology Transfer*** were **Nancy J. Dudney, John B. Bates, Bernd J. Neudecker, Ashok Choudhury, Chris F. Luck, and Greg R. Gruzalski,** for "Thin-Film Rechargeable Lithium Batteries," and **Thomas Thundat, Z. Hu, Russ Miller, Protiveris Rep, and Sebastian Kossek,** for "Microcantilever-Based Biosensors." ***Honorable Mention*** winners were **Michael Ramsey, Stephen C. Jacobson, Roswitha S. Ramsey, and Ashok Choudhury,** all of ORNL, and Michael R. Knapp of Caliper, Inc., for "Lab-On-A-Chip," and **Baohua Gu** and **Gilbert M. Brown**, for "New Ion Exchange and Regeneration Technology for Water Treatment." Ⓡ

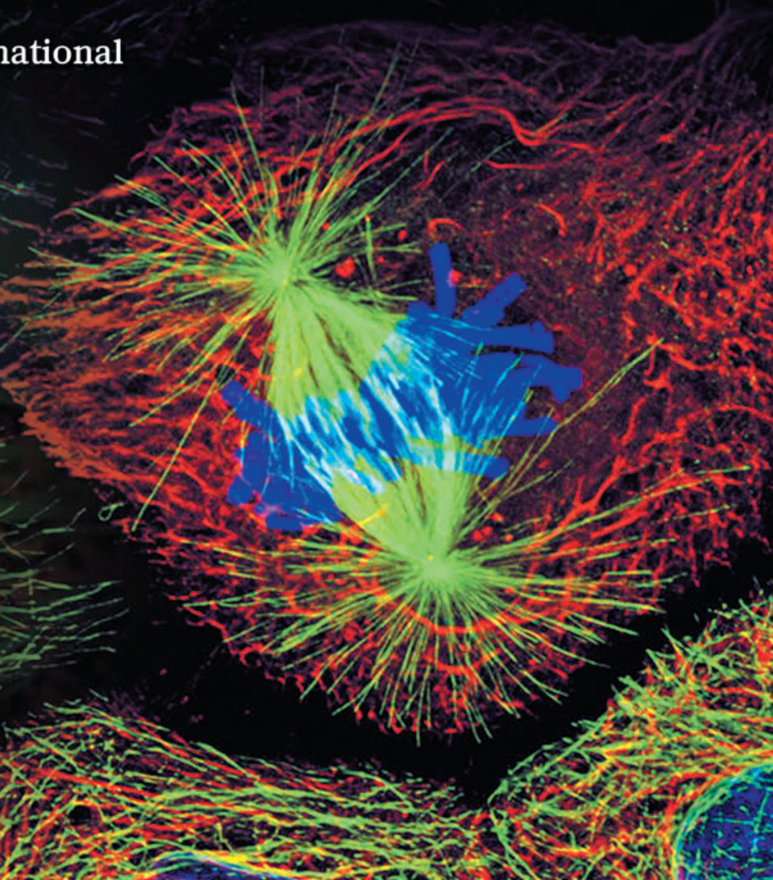


Lynn Boatner (left) and Hu Longmire received the Grand Prize in the 2003 Advanced Materials and Processes *cover competition for their metallograph showing features formed by the physical separation of two large titanium carbide grains.*

Next Issue:

Genomics

- Experiments at ORNL's new mouse vivarium will steer the recently sequenced mouse genome toward better therapies for people.
- ORNL researchers characterize and image bacterial protein complexes using mass spectrometers, microscopes, and ORNL-developed "lab on a chip" devices.
- High-performance computing is identifying the structure and biological role of genes and proteins.
- "Gene chips" define gene functions and their regulatory networks in microorganisms.
- Researchers are evaluating the international project to sequence the first tree genome.



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