Science & Technology
REVIEW

October 2002

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

This Year's R&D 100 Awards

Also in this issue:

- **50th Anniversary Highlight: Supporting National Security and Contributing to the Country's Well Being**

Lawrence Livermore
National Laboratory

Making History
Making a Difference

1952-2002

About the Cover

This issue showcases the Livermore technologies that received R&D 100 Awards for 2002. The five winners are represented on the cover. Clockwise from the top, a transcutaneous electrical nerve stimulator is attached to the body to treat pain; the world's most powerful solid-state laser; the deposition platter (in gold) and sputter source (black metal) of a thin-film coating system for extreme ultraviolet lithography of computer chips; an array of laser diodes (next to coin for scale) cooled by silicon microchannels to increase the power output of the diodes; and a cell subjected to the in situ rolling circle amplification technique, which reveals its damaged (red) and normal (green) genes.

Cover design: Lew Reed

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Science & Technology REVIEW

October 2002

Lawrence Livermore National Laboratory

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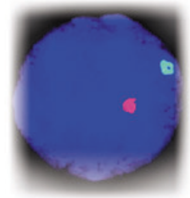

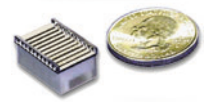

50th Anniversary Highlight

Departments

Stardust theory may not hold

Scientists study grains of dust that predate the solar system to obtain insight into the early evolution of the Sun. Nanodiamonds (also known as stardust) recovered from meteorites have been thought to be the most abundant type of presolar dust. If that is true, then nanodiamonds should be at least equally abundant in comets, which are also made of presolar material.

Understandably, the experts were puzzled when, in examining interplanetary dust particles that entered our atmosphere at speeds equivalent to those of cometary meteors, they found a dearth of nanodiamonds. Says John Bradley, director of the Livermore branch of the Institute of Geophysics and Planetary Physics (IGPP), "We presumed that if we studied [micro]meteorites (also known as interplanetary dust particles) from comets further out in our solar system, we would find more nanodiamonds. But we're just not seeing them. One theory is that some, perhaps most, nanodiamonds are formed within the inner solar system and are not presolar after all." An alternative explanation offered by the study is that all meteoritic nanodiamonds are presolar, but their abundance decreases the farther they are from the Sun.

The study and its conclusions were published in July 2002 in *Nature*. Bradley was one of the study's authors, which was conducted by IGPP in conjunction with scientists from the Georgia Institute of Technology, the University of Washington, the Goddard Space Flight Center of the National Aeronautics and Space Administration, and the Natural History Museum in London.

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Pufferfish DNA helps identify more human genes

An international research consortium led by the Department of Energy's Joint Genome Institute (JGI) reported that it has completed the draft sequence, assembly, and analysis of the genome of the Japanese pufferfish, *Fugu rubripes*. Fugu is a delicacy in Japanese cuisine that can be poisonous if improperly prepared. Its scientific value, however, comes from its compact genome. Fugu has roughly the same number of genes as the human genome, without the "junk" DNA that fills much of the human sequence. Furthermore, nearly three-fourths of the genes in the human genome have identifiable counterparts in fugu, highlighting the anatomy and physiology common to all vertebrates.

By comparing the human and pufferfish genomes, researchers have been able to predict the existence of nearly 1,000 previously unidentified human genes. Although their functions are largely unknown, the more complete determination of the existence and location of these genes will help scientists to characterize how the genes are regulated and function in the human body. "Comparative genomics research like the fugu project are a key to understanding the biology of the human genome," says JGI Director Eddy Rubin. "The fugu is kind of a Cliffs Notes for a really complicated book, and it's telling us a lot of what we would not understand without it," he adds.

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After PEREGRINE comes Minerva

Laboratory researchers are developing a "daughter" method to PEREGRINE, the cancer therapy system that calculates radiation dosage accurately so that the maximum radiation dose can be directed at a tumor while damage to nearby healthy tissue is minimized. Christine Hartmann-Siantar, a principal developer of PEREGRINE, says that Minerva, the new method, is for planning treatment for molecular targeted radiotherapy, which is a type of treatment for metastasized cancer. "Metastastic cancer kills 35,000 Americans every month," notes Hartmann-Siantar, adding that 70 percent of all cancers are metastatic.

With the Minerva targeting method, scientists can inject molecules of radiation specifically diagnosed for individual patients into the body where the molecules attach onto spreading cancer cells. In addition to accurate targeting of the cancer cells, the therapy causes fewer side effects than chemotherapy.

Researchers are in the early prototype stages of developing the Minerva method and expect it to be available in a few years. PEREGRINE received FDA approval in 2000 and currently is installed and being tested at centers in the U.S., Canada, Japan, and various European countries.

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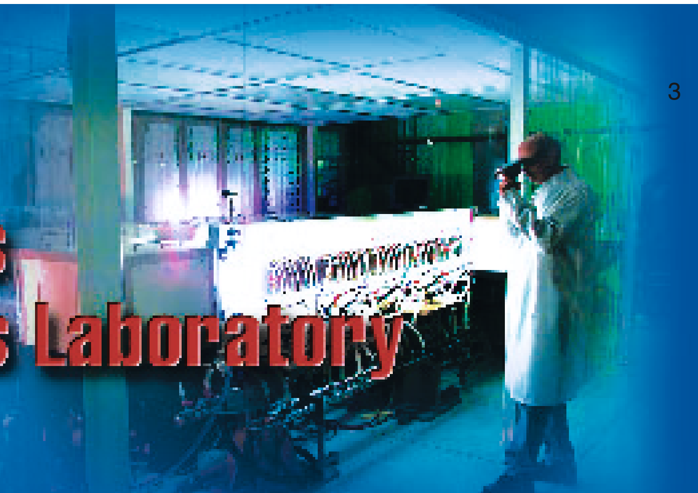
Applied Science Is a Hallmark of This Laboratory



THIS month's issue of *Science & Technology Review* highlights Livermore's success in applied science—taking scientific ideas and developing them into technologies and products that meet real-world needs. Engineers often refer to this process as "turning hand-waving into hardware." Ever since E. O. Lawrence founded this Laboratory, we have been directed by the nation, through Congress, to apply this process to a variety of missions, from designing nuclear weapons to designing instruments to rapidly detect chemical and biological agents released in terrorist attacks.

Underlying the applied science at Livermore is exploratory science, in which we research the fundamental aspects of physics, chemistry, materials science, and bioscience. This exploratory research produces the necessary foundation for developing scientific and technological solutions to national security problems. Among the results are nuclear weapons to support the U.S. deterrent, precision technologies for fabricating one-of-a-kind optics for lasers and telescopes, miniaturized DNA assays and instruments for quickly detecting biothreat agents, and x-ray and extreme-ultraviolet optics for making next-generation computer chips.

Every year, *R&D Magazine* selects the 100 most technologically significant new products and processes of the past year. Since 1978, Livermore has received 90 of these R&D 100 Awards. They provide independent confirmation of the Laboratory's excellence in applied science and technology. As with previous award-winning products and processes, this year's winners are derived from work carried out for our core missions, work demanding that we come up with creative science and technology answers to solve the nation's problems. These answers, in turn, have led to further inventions and creations with applications originally unimagined.

Three of this year's winners have origins in our laser program efforts. The solid-state heat-capacity laser, for instance, is a powerful but compact laser that has near-term defense applications as well as potential applications in industrial materials processing. The technology that made possible another winner, the small laser diode array, has obvious applications in industrial materials processing and promises to contribute to the field of laser surgery. Then there's the thin-film coating tool—developed for extreme-ultraviolet lithography for producing next-generation computer chips—which looks to have wider applications in the worlds of microelectronics and optics.

The other two winning inventions are grounded in bioscience but may have future roles in homeland security and nonproliferation as well. In situ rolling circle amplification shows great potential to help diagnose genetic disease and has potential applications in the fight against bioterrorism. The portable transcutaneous electrical nerve stimulation device has obvious benefits in improved medical treatments. Furthermore, this device and others developed as part of our program of cooperative threat reduction activities with the former Soviet Union continue to open doors for Russian scientists and engineers who once worked on Soviet weapons programs, helping them redirect their talents to civilian applications.

As the Laboratory embarks on its post–September 11 homeland security mission, its expertise in applied science is as important as ever. Science and technology play a critical role in defending the country against terrorism waged with weapons of mass destruction by providing new detection capabilities, better methods for emergency response and recovery, and, perhaps most important, improved information analysis and connectivity. In these areas and more, we build on our 50-year tradition of excellence in applied science. This excellence will let us fulfill our expanding and evolving national security missions in deterrence and nonproliferation and meet the needs of new missions in counterterrorism and homeland security. Success in developing some of the devices and technologies we are pursuing for homeland security might lead to recognition by *R&D Magazine* in future years.

■ Hal Graboske is acting deputy director for Science and Technology.

Sending Up Signals for Genetic Variation

THE Human Genome Project, the international research program to map and sequence all the human genes, is an immense scientific effort that has made demands on biological research techniques and led to new biological tools. Among the many developments resulting from genomic research is one by a Livermore team that can find minute changes in the DNA of individual cells and thereby significantly improve the detection of cancer and other diseases.

The new technique, called in situ rolling circle amplification (IRCA), is a fast and inexpensive method to precisely locate a damaged or abnormal gene that indicates the presence of or tendency toward a particular disease. IRCA can find a single cell containing an abnormal gene from among thousands of cells, making the technique ideal for tissue biopsies. The process is so sensitive that it can detect a mutation in a single DNA base, the smallest unit of genetic information. (An average human cell contains about 6.5 billion DNA bases.)

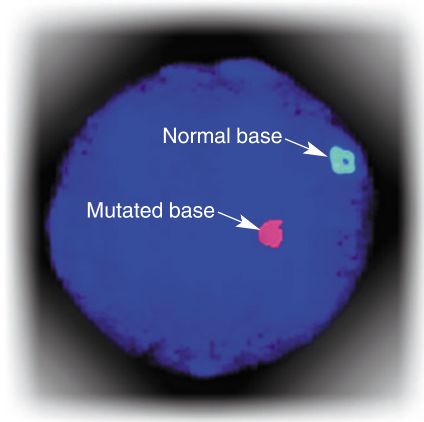
The technique involves locating the gene of interest in intact cells—in which fluorescent molecules have been incorporated—and massively amplifying (duplicating) critical sections of DNA so a fluorescent signal can be detected. No other method is available that can detect a single DNA or RNA base change within a cell or tissue.

“IRCA is a way of putting our newly gained knowledge of the human genome to beneficial use,” says team leader Allen Christian, a molecular biologist and chemical engineer. The discovery, he says, moves the research findings of the Human Genome Project from the laboratory to the clinic. “The genome project has given us the sequences of all the human genes. Our job as scientists is to apply that knowledge. We know that certain DNA sequence variations signal a diseased state, so we can use that information to diagnose disease at the earliest stages, when treatment is most effective.”

The Livermore research team, which worked for about a year on the process, included biologist Jim Tucker and technicians Melissa Pattee and Christina Attix. (Christian and Tucker were part of a Livermore team that won an R&D 100 Award last year for gene recovery microdissection, a process that identifies expressed genes—that is, genes that have been turned on—from a specific chromosome region.)

The Livermore breakthrough is a significant extension of rolling circle amplification (RCA), which was developed at Yale University in the mid-1990s. RCA is limited to identifying DNA that has been extracted from a cell. In contrast, the Livermore technique works inside cells, thereby preserving the chemical environment of the cell and its neighbors. In addition, IRCA provides answers in a couple of hours, compared to a wait of several days required with tests using traditional methods. The technique can also be used to detect and measure messenger RNA in single cells, something that could not be done previously. (Genes produce proteins with the aid of messenger RNA.)

The team that developed the in situ rolling circle amplification technique. From left, Allen Christian, Melissa Pattee, Jim Tucker, and Cristina Attix.



The in situ rolling circle amplification technique reveals a mutated tp53 gene in a human lymphoblastoid cell by coloring it red, whereas a normal gene is colored green.

Synthetic Probes Start the Process

The technique starts with the laboratory production of linear probes (or stretches) of DNA encompassing about 100 bases. The DNA has been treated to remove one of its double strands. The probes are applied to target DNA under study, which also have been made single-stranded. Because DNA prefers to be double-stranded, the probe will seek out a target whose DNA sequence is a counterpart to that of its own.

In the cell nucleus, the linear probe's two ends attach through hydrogen bonds to the target DNA and in the process wrap around that DNA to form a circle. An enzyme called a ligase then "padlocks" the circular probe onto the target DNA by forming chemical bonds that are much firmer than hydrogen bonds. In this way, the probe is prevented from detaching from the target.

Typically, two probes are applied to the target DNA: a normal sequence probe and a mutant sequence probe. The normal probe can only attach to the normal DNA sequence, and the mutant probe can only attach to a mutant sequence.

Each probe contains a DNA sequence that allows a short piece of DNA, called a primer, to initiate a reaction that quickly and repeatedly replicates the probe. The duplicating reaction is catalyzed by a polymerase enzyme, which rolls out hundreds or thousands of linear copies of the circular probe's DNA. The single strands of targeted DNA make it easier for the polymerase to make copies of the probe.

Every time the probe is replicated, a binding site for a fluorescently labeled molecule (or beacon) is created. Within a few seconds, enough beacon sites are created to allow the fluorescent signal to be seen under a microscope and permit a normal base to be distinguished from an abnormal base. "We're in essence sending up signal balloons that help us to detect the products of the polymerase reaction," says Christian.

The match between a normal probe and target produces a green signal after amplification, whereas a match between a mutant probe and target produces a red signal. If the probe and the target do not match, there is no signal because the ligase will not work.

Numerous Applications

IRCA has numerous medical applications, especially in the diagnosis and treatment of diseases that have genetic markers. Christian expects that one of the technique's first routine clinical uses will be as a fast, inexpensive assay for the presence of mutations that are relevant to a particular cancer. "IRCA will allow physicians and medical researchers to identify and localize genes that are known to be or strongly suspected of being responsible for causing certain cancers," says Christian. The technique will also help physicians to choose and customize cancer therapies for their patients and monitor the effectiveness of therapies.

Christian notes that many cancer diagnostic procedures currently in use involve the same dyes and stains that were first discovered more than 100 years ago. These dyes and stains cannot detect the subtle genetic changes that are believed to occur when tissue first becomes cancerous.

On a different application, IRCA could be used to identify the strain of bacteria infecting a person. This capability would enable physicians to select the most effective antibiotics. Similar approaches may work for detecting viruses ranging from the common cold to hepatitis, herpes, and HIV.

IRCA also has applications in agriculture, toxicology, pharmacology, and environmental science. The technique will assist scientists in rapidly identifying which strains of a plant, tree, or vegetable have desired genetic characteristics. In this way, IRCA has the potential to improve the quantity and quality of food. In basic cell research, the advance could help to determine the genetic composition of bacterial, plant, and human cells. For pharmacology, the technique will provide an important tool to test promising new drugs and measure cells' responses to them.

The technique may also have an important role to play in fighting bioterrorism. Portable detectors using IRCA may offer advantages over units using the polymerase chain reaction technology to amplify short stretches of DNA or RNA and thereby identify a potential bioagent.

Christian reports that the research team has been flooded with calls and e-mails from researchers across the country since the procedure was first described in a paper published in *Proceedings of the National Academy of Sciences* in 2001. The Laboratory is currently negotiating with companies to license the process.

Clearly, IRCA stands to improve human health and advance a large number of disciplines.

—Arnie Heller

Key Words: cancer detection, in situ rolling circle amplification (IRCA), R&D 100 Award.

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SiMM Is Anything But Simple

FROM delicate surgical procedures to cutting and welding metals, diode-pumped solid-state lasers offer a wealth of uses. A Livermore team has won an R&D 100 Award for a modular packaging technology for the smallest, most powerful, and least expensive laser diode pumps ever.

A silicon microchannel cooling system makes it possible. This technology, called SiMM for silicon monolithic microchannel, relies on photolithography and high-production etching techniques to produce thousands of miniscule, 30-micrometer-wide channels in silicon substrates. Water flowing through these microchannels cools the laser diode bars that are attached to the silicon, allowing the diodes to perform at higher average power than previously possible.

On each SiMM, a tiny package of 10 diode bars can be combined with as many microlenses—which collimate the laser light—to create a unit from which large diode arrays can be built. The microlenses attached to each package, developed and patented by Livermore scientists, give unsurpassed optical brightness. Livermore holds three other patents as well for new developments associated with SiMM.

To date, Livermore has fabricated arrays that put out power of up to 45 kilowatts. Yet these powerful arrays measure just 10 by 18 centimeters.

Cooling Is Key

“Because laser diode bar arrays are semiconductor devices, their performance suffers as their temperature increases,” notes physicist Ray Beach, who leads the team. Cooling is a challenging problem because laser diodes generate high heat intensity, yet must operate near room temperature. Efficient cooling is thus the cornerstone of any technology that proposes to increase the power output of laser diodes.

Although laser diodes are extremely efficient devices by ordinary laser standards, typically converting nearly 50 percent of their electrical consumption into light, the remaining 50 percent shows up as heat.

The use of silicon in the cooling system is critical. Because photolithographic and etching technologies are so well developed for silicon, arrays of precision microchannels can be easily and inexpensively fabricated in this material. Silicon makes it possible to place thousands of 30-micrometer-wide microchannels close to the heat-producing laser diode bar arrays. It also allows multiple bars to be located on a single substrate, with an equal number of cylindrical microlenses, all attached in a single fabrication step.

Members of the SiMM team are, from left, Larain DiMercurio, Joe Satariano, Jacqueline Crawford, Barry Freitas, Gary Loomis, Terri Delima-Hergert, Dave Van Lue, Ray Beach, Kurt Cutter, and Everett Utterback. Missing from the photo are Cathy Reinhardt and Jay Skidmore.

But why use silicon rather than materials with higher thermal conductivities, such as copper? In compact heat sink structures with flowing water, the best way to control the overall temperature rise is to minimize the thickness of the boundary layer where stagnant water meets flowing water. It is in this boundary layer that the largest temperature rise occurs. Because boundary-layer thickness scales relative to channel width for the flow conditions in the SiMM package, the best material for the cooling system is one that permits easy fabrication of narrow channels. With copper, the channels would have to be wider. It turns out that better thermal performance is gained by using a material that permits tiny microchannel fabrication—silicon—rather than a material with higher thermal conductivity.

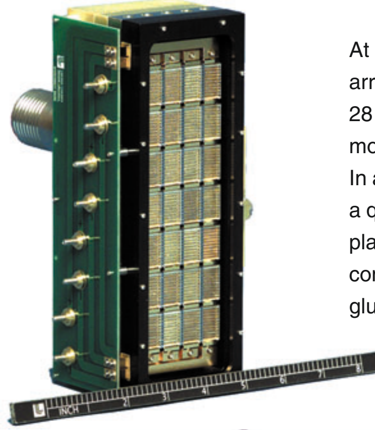
The laser diode bars can be precisely placed on the SiMM in V-shaped grooves etched on the front surface of the package. These grooves are generated with the same technology that creates the microchannels in the back side of the silicon. Because the V-shaped grooves are defined with a photolithographic process, the diode bars can be located with micrometer precision relative to one another over the entire SiMM package. Senior engineering associate Barry Freitas, lead developer of the SIMM package, is responsible for this innovative diode bar mounting technology.

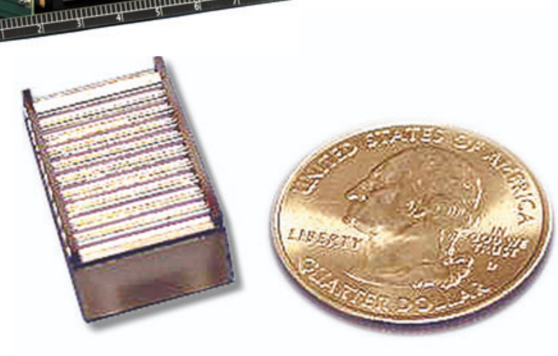
The cylindrical microlenses are located with the same micrometer precision in a ladderlike frame of silicon runners. The microlenses are preloaded and glued into the silicon runners to form a structure of 10 lenses. The entire 10-lens assembly is then attached to the SiMM package in a single step. The microlens array serves to collimate the radiation of the laser diode bars from its original 30-degree divergence angle down to a beam with a divergence angle of only about 0.5 degrees. Finally, a glass block seals off the base of the microchannels and serves as a manifold for the cooling water as it flows in and out of the package.

Benefits Abound

Two other approaches compete with the new SiMM cooling technology. The first one relies on stacking single diode bar array packages, a process known as rack and stack. The individual packages are fabricated of copper and use larger macrochannels to flow cooling water. The other technology relies on mounting the laser diode bars on thermally conductive bar mounts and attaching them to a backplane cooler through which water flows.

The primary improvements of the SiMM package over these technologies are in its integration of high-performance heat removal within the high-density, multibar package and the use of low-cost fabrication methods. First, the thermal engineering of the SiMM package allows it to produce an average exitance (irradiance in the emitted laser beam) that is 2.6 times greater than that of its nearest competitor. Second, the use of a monolithic cooler is unique to SiMM. By attaching 10 individual laser diode bars to each SiMM cooler, rather than one bar per cooler as in the rack-and-stack method, the cost of the cooler package is spread over 10 bars. Finally, the majority of the cost of diode-pumped solid-state lasers is in the diode arrays that serve as their pump excitation sources. These lasers thus benefit tremendously from the low-cost fabrication methods in SiMM. SiMM's cost per watt is less than one-third that of its nearest competitor.





At left is a 41-kilowatt laser diode array constructed from 28 individual packages of silicon monolithic microchannels (SiMMs). In a SiMM package below, next to a quarter for scale, 10 diode bars placed in V-shaped grooves are combined with 10 microlenses glued into silicon runners.

Let's Get Together

The innovative SiMM is already being incorporated into new military defense systems. In the near future, a 1-megawatt version will become a key element in the award-winning laser described on p. 8. That laser, the most powerful solid-state laser system in the world, is currently pumped using flash lamps but will soon incorporate the smaller SiMM diode-pump array. An award winner meets an award winner.

—Katie Walter

Key Words: R&D 100 Award, silicon monolithic microchannel (SiMM) laser diode array, solid-state laser diodes.

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World's Most Powerful Solid-State Laser

START with a 6-second shot of laser light. End up with a 1-centimeter hole in a 2-centimeter-thick slice of steel.

In the past, this sort of fire power was only available from large gas or chemical laser systems. But thanks to a new technology developed at Livermore, this feat was accomplished by a refrigerator-size laser system using about 30 cents worth of electrical current from a wall socket. Dubbed the solid-state heat-capacity laser (SSHCL), this system garnered one of 100 awards presented annually by *R&D Magazine* to honor the most technically innovative products for the year. The SSHCL can produce up to 13,000 watts in a single, high-quality beam with output-pulse energies of more than 600 joules, making it the most powerful solid-state laser in the world.

The system's solid-state heat-capacity design paves the way for a laser, now under development, that will produce 100,000 watts in a single beam and opens up a range of applications for industrial materials processing and military defense. (See *S&TR*, April 2002, pp. 19–21.)

New Operation Mode Means More Power

According to Brent Dane, who led the SSHCL team in Livermore's Laser Science and Technology program, the breakthrough that made this laser possible involves a revolutionary, yet seemingly straightforward solution to dealing with the high temperature gradients that occur while operating a solid-state laser system.

Before the SSHCL, solid-state lasers operating with high-energy pulses have been limited to power outputs of less than 1,000 watts. The stumbling block to increasing the power involved the heat generated during laser operations. "Any laser creates waste heat in the system," explains Dane. "For a solid-state laser, this heat is deposited inside the optics—the glass or crystal—that provide the gain for lasing. If not removed, the heat can damage the optics."

Most solid-state laser systems are continuously cooled while operating to avoid such damage. Waste heat is conducted from inside the glass to the surface where it can be carried away by coolant, such as water. This cooling process occurs at the same time as the lasing, creating a large difference in temperature between the optical material's relatively cool surface and its heated interior. These large temperature gradients lead to mechanical stress, physical deformation, optical distortion, and ultimately, to the fracture of the optic.

Dane and his team have demonstrated a different operating mode, in which the laser's cooling cycle is completely separate from its high power bursts. During a burst, the waste heat accumulates evenly throughout the glass or crystal material of the optic. At the end of the burst—which typically lasts 10 to 20 seconds—the laser is shut off, and the optical material is aggressively cooled over a period of from 30 seconds to several minutes. Operating the system in this pulsed manner—separating lasing cycles from cooling cycles—means that there are no significant thermal stresses on the optical material during lasing. The average power emitted by the laser is now limited only by the power capacity of the laser pump source, which for the SSHCL is flashlamps or another Livermore-developed technology, the high-average-power diode array (see the article on diode arrays, p. 6). "This pulsed operation means that the average power cap is removed for solid-state lasers, allowing us to scale up the output to hundreds of thousands of watts," says Dane.

Members of the solid-state heat-capacity laser development team are, from left, Balbir Bhachu, William Manning, Scott Fochs, Bruce Roy, James Wintemute, Steve Sutton, Georg Albrecht, Brent Dane, and Mark Rotter.

Many Advantages to SSHCL

This unique pulsed operating mode makes the SSHCL the most powerful solid-state laser around. When compared with other pulsed-format solid-state lasers, the average power of the SSHCL during a burst is better than that of the competition by more than tenfold. And when compared with the most powerful nonpulsed solid-state lasers, the SSHCL exceeds their average power by up to two times.

But what about other lasers that are not solid-state based? According to Dane, the realm of truly high-average-power laser systems has been historically dominated by chemical and gas lasers. Because these lasers, by their very nature, can flush out the waste heat from their systems along with the expended (and often toxic and corrosive) combustion products, it has been possible to scale their output powers to the highest values ever obtained for any laser system. However, says Dane, the SSHCL is now prepared to scale up to and challenge the highest powers obtained from these lasers as well. SSHCL has other advantages over these giants of the laser power world, including the ability to operate at a shorter wavelength of laser light. A shorter wavelength allows a laser beam to propagate longer distances through the atmosphere with less beam spread. (The greater the beam spread, the lower the power density—that is, watts per unit area—delivered to the target.) For example, given the same size beam, the smallest theoretically achievable beam area spread for the powerful deuterium fluoride chemical laser is 12 times greater than the beam spread for the SSHCL, and for the carbon dioxide laser, it is 100 times greater.

The SSCHL also has the advantage when it comes to operational logistics. It can be installed and operated on a mobile vehicle the size of a jeep and powered by electrical generating equipment that consumes conventional fuels such as diesel or gasoline. In practice, says Dane, advanced versions of the SSHCL will also be able to use high-storage-capacity, rechargeable batteries that are part of a vehicle. A subscale prototype SSHCL amplifier, capable of 15,000 watts of output power using advanced lithium-ion batteries, is being constructed and will be demonstrated at Livermore next year.

Bright Future Foreseen

From military to industry, organizations and companies foresee a bright future for the world’s most powerful solid-state laser system.

One interesting possibility, notes Dane, is using the large pulse energies of the SSHCL to clear orbital space debris from the paths of satellites and manned shuttle flights. Precisely targeted laser pulses could cause the orbits of space trash to decay, allowing the trash to harmlessly burn up during reentry into the atmosphere. Other more down-to-earth applications for the future include heat treatment of metals and thick-section metal cutting and drilling.

Laser technician Balbir Bhachu monitors the performance of the 13,000-watt solid-state heat-capacity laser during a low-power test. The prototype uses an electrical source to power flashlamps, which in turn pump nine neodymium-doped glass laser disks that release energy in pulses of laser light.

Because the project is sponsored by the U.S. Army Space and Missile Defense Command, the first application is a military one: to defend against rockets, artillery, mortars, and other tactical threats at close range (1 to 10 kilometers). There is, Dane notes, currently no effective protection against these weapons in the battlefield. Michael W. Booen, vice president of Directed Energy Systems for Raytheon Electronic Systems, said, “Tests of this laser to melt metals and damage other materials are convincing many audiences that the era of tactical, solid-state weapons may be fairly close at hand.”

The Livermore team and its industrial partners (including Raytheon, General Atomics, PEI Electronics, Northrop Grumman, Goodrich Corporation, Armstrong Laser Technology, and SAFT America) are already working on a version of the SSHCL capable of being transported and powered on the modern version of the Humvee military jeep. This final laboratory demonstration version of the SSHCL, which will have an output power of 100,000 watts under burst mode for up to 10 seconds, could be ready to demonstrate to the Army by 2007.

—Ann Parker

Key Words: R&D 100 Award, solid-state heat-capacity laser (SSHCL), tactical laser weapon, U.S. Army Space and Missile Defense Command.

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Stepping Up to Extreme Lithography

A revolutionary microprocessor technology developed by Lawrence Livermore and Veeco Instruments Inc. could increase the speed of personal computers by 10- to 20-fold and their memory capacity by 100- to 1,000-fold. The Production-Scale Thin-Film Coating Tool is a highly precise deposition system that opens the door to advanced, high-volume manufacturing of the next generation of microprocessors. It is one of this year's R&D 100 Award winners.

With the new technology, powerful desktop computers could be made that realize a wealth of exciting applications, including real-time multilanguage voice recognition, translation, and human interfaces. "Applications such as these are impossible on today's 1-gigahertz PCs," says Regina Soufli, Livermore physicist and leader of the team that developed the coating tool. "Technology enabled by the tool will allow tomorrow's PCs to approach the computing power of today's multimillion-dollar mainframe systems that presently only exist in laboratories."

Down the Optical Road

The semiconductor industry relies on optical lithography to manufacture computer chips. In the most advanced optical lithography in use today, light of 193-nanometer wavelength is projected through masks patterned with intricate circuit diagrams. The transmitted pattern is reduced by being relayed through a series of refractive lenses. In steppers (industry jargon for systems that repeat manufacturing steps over and over), the patterned image is reproduced onto thousands of silicon wafers, which are processed and developed into integrated circuits.

Presently, optical lithography can reduce circuit patterns to have features as small as 130 nanometers (the diameter of a human hair is 100,000 nanometers). This is approaching the limit of resolution, as dictated by the physics of light diffraction for the wavelengths used in current technology. But to increase the speed and power of computers, the semiconductor industry will need circuit patterns as small as 30 nanometers for computers operating at 10 gigahertz or faster. Thus, the industry has initiated a quest to find the next-generation lithographic technique that can further reduce feature size.

Extreme ultraviolet lithography (EUVL) has been recognized as the most feasible next step. It uses light of 13-nanometer wavelength, which is 15 times shorter than the wavelengths used by today's technologies. Adopting EUVL, however, represents a giant challenge.

Going Extreme

Radiation at the extreme ultraviolet wavelengths is strongly absorbed by matter such as air or the lens material. For this reason, the entire EUVL system has to be maintained under a vacuum, and the light that produces the circuit image must be reflected from mirrors rather than refracted through lenses. Furthermore, the mirrors must consist of precisely figured glass substrates that have been coated with alternating layers of molybdenum and silicon to a thickness of 280 nanometers.

Shown against a backdrop of the projection optics for the coating deposition system they co-developed with private industry, members of the Livermore team are, from left, Jim Folta, Rick Levesque, Claude Montcalm, Swie-In Tan, Mark Schmidt, Regina Soufli, Fred Grabner, Chris Walton, and Eberhard Spiller. Missing from the photo is Steve Vernon.

This thickness can only vary by less than 0.05 averaged over the entire optical surface; such a variance is equivalent to one-quarter the diameter of a silicon atom.

If this stringent specification is not met, the printed circuits will be blurred and will fail. The challenge of making precision-coated optics and doing so in a reproducible manner is daunting and thus an obstacle to implementing EUVL lithographic steppers. "There were doubts that such thickness precision could be achieved repeatably," says Soufli.

A daunting task to be sure, but Soufli and her team are receiving accolades for accomplishing it. Built on the basis of Livermore's expertise in thin-film technology, the coating tool can deliver commercial-quality multilayer coatings on the optics used in the camera and illuminator of EUVL semiconductor steppers. The tool has achieved the 0.05-nanometer-thickness precision required on camera optics. As a demonstration of success, the same optics have also been used to print integrated circuit patterns as small as 39 nanometers. This is the best imaging resolution ever achieved with optical lithography and foreshadows the ability to print circuits at the 30-nanometer resolution required for next-generation microprocessors.

The Way It Works

The new coating tool is based on the magnetron sputtering method widely used for thin-film deposition. The coating takes place inside a chamber where molybdenum and silicon sputter sources have been placed 180 degrees apart. The sources, called magnetrons, have a magnetic field attached to the back of their surface. With the chamber maintained under vacuum, the magnetrons are ignited, and a small amount of argon gas is introduced into the system. Argon ions, excited by the electromagnetic field, impinge on the sources and sputter atoms off the two materials. The atoms land on the optical substrate that sits atop a rotating deposition platter. The rotating platter passes alternately under the magnetrons, resulting in alternating layers of the two materials being deposited onto the optical surface. The platter is rotated under the sources at speeds of about 1 rotation per minute, while the individual substrates are simultaneously spinning fast around their centers at several hundred rotations per minute, thereby equalizing the spatial variations of the sources.

The tool's ability to control film thickness is based on a simple concept: The speed at which the optic passes under a sputtering source determines how much of that sputter material is deposited on the optical surface. Platter speed is modulated as the substrate passes under the silicon and molybdenum targets, depending on what thickness profile is desired.

The most critical step of the entire process is determining the right coating recipe for a given optic, and this is done with the help of computer simulation. First, using the substrate shape and desired coating thickness profile as input, a custom-designed computer model simulates the deposition process. The algorithm calculates the platter velocities and angles that should be applied and proposes a coating recipe that is tested on a surrogate optic. The resulting coating thickness on the surrogate optic is measured, compared with the desired profile, and fed back to the algorithm to adjust the recipe. The final recipe is arrived at after four or five iterations of simulation and adjustment. When put into use, the recipe must be calibrated only once for each set of optics and is stable enough to be repeatedly used for over a year.

Process engineer Mark Schmidt places an optical substrate in the coating deposition chamber.

The new coating deposition system can produce multiple sets of optics in a high-volume production mode with precisely identical thickness profile. This way of controlling coating thickness is accurate, quick, and inexpensive.

Riding the Wave of the Future

The coating tool represents a breakthrough in semiconductor equipment manufacturing. It enables the commercialization of EUVL. Beyond EUVL, the tool's capabilities can be applied in other areas where thin films with precision thickness control are needed, such as astrophysics, magnetics, and biological x-ray imaging.

"We achieved commercial-level thickness control for the first time ever on large multilayer optics," says Soufli. "By implementing a versatile design and a unique deposition algorithm, the tool has enabled commercialization of EUVL as the next-generation technology for highly advanced computers of the future." The first EUVL-fabricated computer chips are scheduled to be developed in 2007. Expect to be able to buy your very own "supercomputer" shortly thereafter.

—Whitney Lacy

Key Words: extreme ultraviolet lithography (EUVL), magnetron sputtering deposition, production-scale thin-film coating tool, R&D 100 Award, semiconductor computer chips.

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Relief for Acute and Chronic Pain

EACH year, over 50 million Americans are treated for pain resulting from wounds or surgery, joint and muscle injuries, or arthritis. As America's baby boomers age and begin to suffer from chronic illnesses, they will be seeking better ways to effectively manage pain.

One management method, ancient and well-established but not commonly used, is transcutaneous electrical nerve stimulation, or TENS. In this method, low-level electrical pulses are delivered through the skin to inhibit or interfere with the transmission of pain signals to the brain.

The problem with the method is that it has been too expensive and difficult to use. But that's about to change, because a team of Livermore, private-industry, and Russian scientists has developed a device that turns TENS into a viable treatment process. For their work, the team has been awarded an R&D 100 Award.

About TENS

In 1965, Canadian psychologist Ronald Melzack and British physiologist Patrick Wall performed an in-depth study of pain transmission and published a now-famous theory that spawned the development of TENS devices. Their study and those of others revealed that in 25 years of use, TENS had caused no serious side effects or injuries. In fact, these studies and the sustained sales of TENS devices during the study period validated TENS as an effective and safe pain-relieving alternative.

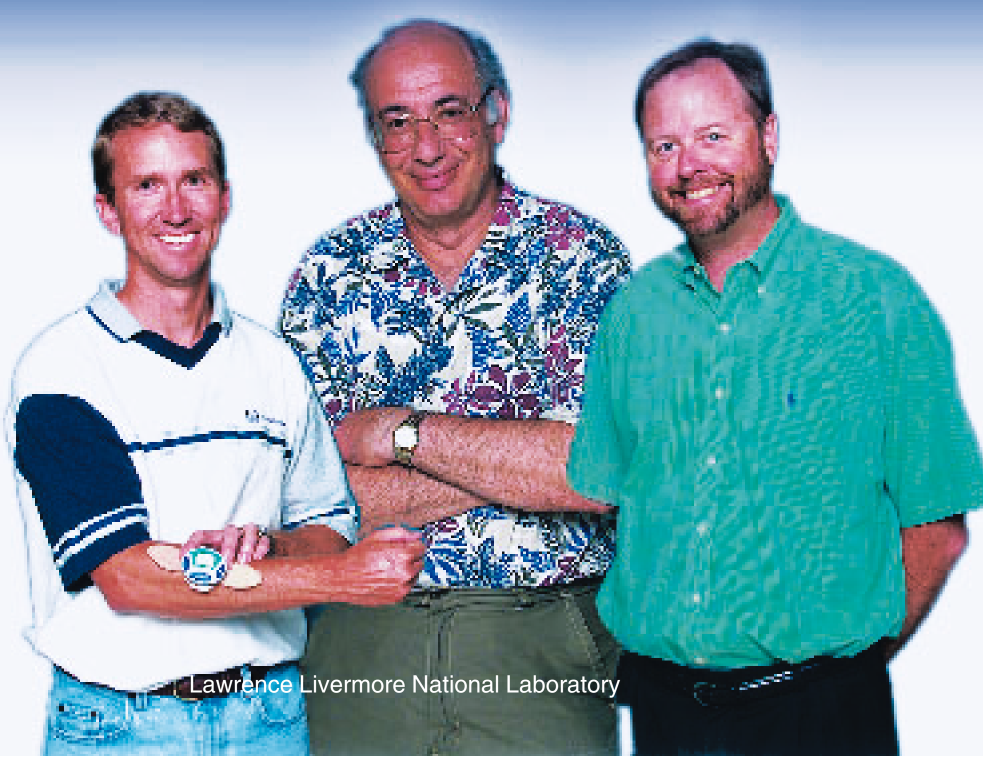
Traditionally, TENS devices have been prescribed for managing intense, intractable chronic pain. They are also routinely used in conjunction with other therapies during physical rehabilitation to maximize pain relief and increase patient tolerance for exercise and movement.

But standard TENS devices have been largely inappropriate for short-term, acute pain management because they have been large, complex, and expensive and have required operation by a licensed therapist or physician. If TENS were easier to use and less expensive, it could supplant narcotics and other common medical prescriptions for pain.

Wireless and Portable

That has now happened. Lawrence Livermore, Cyclotec Advanced Medical Technologies (Cyclotec), Inc., and the Biophysical Laboratory (Biofil) Ltd. of Sarov, Russia, working under the Department of Energy Initiatives for Proliferation Prevention Program, have formed a joint cooperative research agreement to develop an advanced, easy-to-use TENS technology, currently known as STIM-2002 TENS.

Jeffrey S. Mannheimer and Stephen A. Michaelson of Cyclotec developed the initial concept and clinical methodologies for the product based on commercial market needs. Livermore scientists Bill W. Colston, Jr., Kenneth J. Michlitsch, Luiz B. Da Silva, Alexander Rubenchik, Ted Saito, and John E. Marion partnered with Cyclotec and Biofil to develop and miniaturize a smart controller for the improved TENS device.



Some Livermore members of the team that developed STIM-2002 TENS. From left, Bill Colston (demonstrating one way of applying the STIM-2002 TENS device), Alexander Rubenchik, and John Marion. Not pictured are Kenneth Michlitsch, Luiz Da Silva, and Ted Saito.

Russian scientists from Biofil, working with Cyclotec, completed the mechanical and electrical packaging and construction of the device.

The STIM-2002 TENS device consists of two miniature electronic modules. One is a remote-controlled, preprogrammed transmitter that can be kept in the user's pocket or worn like a pendant around the neck. The other is a stimulator–receiver that is positioned on top of a conductive adhesive electrode that attaches the device to the patient. The transmitter sends the stimulation paradigm to the receiver, which produces the pain-relieving pulses where the module has been applied. Because the receiver is integrated with and mounted on the electrode, lead wires—which encumber other commercial pulse stimulators—are unnecessary.

To use the device, a patient simply puts it on like a bandage. The electrodes can be easily reconfigured for different body applications (to the arm, wrist, knee, back, neck, or a small wound). Using the three buttons on the transmitter, a patient can select one of six stimulation treatment modes (depending on the pain and the desired therapy), different intensities of stimulation, and different cycling protocols (that is, cycling through selected stimulation modes for a desired treatment). The fingertip programming that the user performs is similar to changing the settings on a digital wristwatch and is much simpler than programming a VCR. In fact, the operation of this TENS is intuitive; it can be used safely and effectively without professional guidance.

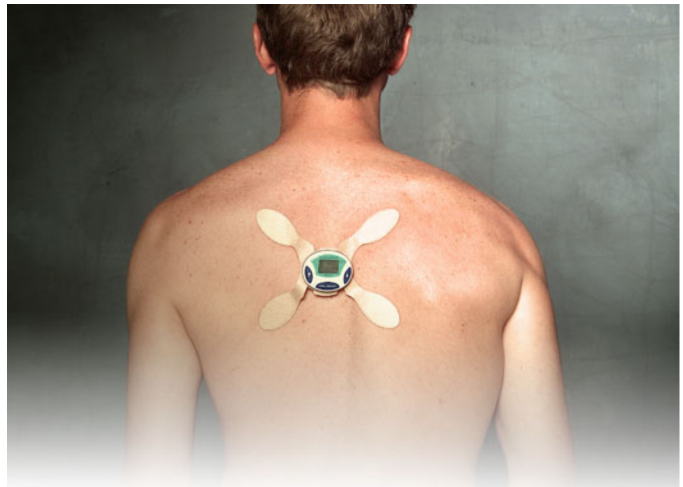
The device provides patients with feedback on operational status by continuously displaying current mode, elapsed time, and intensity. It also collects usage data that physicians can download if they so desire.

With its small size (as much as five times smaller than other TENS), wirelessness, ease of use, and cost effectiveness, the STIM-2002 TENS certainly gives patients greater flexibility, comfort, and rapid pain relief.

A Significant Breakthrough

Physicians, psychiatrists, and physical therapists believe STIM-2002 TENS to be a significant breakthrough because it allows TENS to be used outside the doctor's office. The U.S. National Institute on Drug Abuse, which supported the development of STIM-2002 TENS through grants to Cyclotec, recommends this TENS medical instrument because it offers pain sufferers with a "viable alternative to drugs for pain relief" and allows them to avoid drug side effects, abuse, or dependency.

In a range of uses—from treatment of minor cuts, burns, scratches, and wounds where regular bandages are applied, to alleviating the pain of minor surgical procedures such as suturing, to providing relief after arthroscopic surgery—TENS offers faster, more precisely directed relief than oral and even some injected drugs. It has not caused any serious side effects and does not have anesthetic, narcotic, or addictive effects. Furthermore, TENS treatment can be stopped instantaneously, without waiting for the body to eliminate accumulated drugs.



The wireless STIM-2002 TENS receiver–stimulator can be applied to different parts of a patient's body. It is remote-controlled by a palm-sized transmitter.

The Next Improvements

In the future, the technology development team sees STIM-2002 TENS products configured as dynamic splints, braces, supports, and straps. They envision remote-controlled TENS transmitters in wristwatch form. They are completing an even smaller electronic "Band-Aid" that can protect open wounds, control pain, and enhance circulation to promote healing.

Clearly, the STIM-2002 TENS device will significantly improve the quality of life for millions of Americans. Users will have greater control and management of their pain so that their work and activities will not be affected or interrupted. And health professionals—including physical therapists, physical rehabilitation physicians, chiropractors, occupational therapists, and medical clinicians—will find that this device significantly augments and benefits their work.

—*Sharon Emery*

Key Words: electronic adhesive bandage, medical device, pain management, R&D 100 Award, transcutaneous electrical nerve stimulation (TENS).

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Energy and Environment
Understanding Our World

THE country's focus on energy—its availability and its costs, both monetary and environmental—has waxed and waned over the half-century of the Laboratory's existence. Similarly, the nation's rate of investment in the environment has fluctuated. When energy and environmental concerns have been at the forefront of national attention, Lawrence Livermore has stepped up its research activities to alleviate those concerns. In quiet times, the Laboratory has continued research in the energy and environmental arenas that are related to its national security mission. Many of these efforts can draw lines of inheritance back to the initial nuclear weapons work that forms the Laboratory's historical foundation.

The first 20 years at Livermore saw the beginnings of efforts to harness fusion as a source of cheap, inexhaustible power by using enormous magnets and, later, powerful lasers. Energy research at the Laboratory burgeoned in the 1970s and early 1980s during the energy crisis, when finding ways to enhance the nation's energy supply became a national priority. At the time, Livermore was already in the energy business through Project Plowshare, which explored the peaceful uses of nuclear explosions for recovering oil and gas and for other applications. In the 1970s, the Laboratory also became active in researching how to safely dispose of radioactive waste from nuclear power plants, an activity that continues to this day. And when the country's attention turned toward alternative energy supplies, Lawrence Livermore's scientists and engineers researched energy sources such as coal, oil shale, geothermal energy, solar power, advanced batteries, flywheels, and more.

Analyzing the environmental effects of nuclear weapons tests led naturally to examining other environmental issues—from the atmospheric to the subterranean. As a result of assessing fallout from atmospheric tests, capabilities such as the National Atmospheric Release Advisory Center and projects such as the Marshall Islands Dose Assessment and Radioecology program were born. Over the years, there was a further branching out of such research into other environmental concerns. Livermore scientists have, for example, analyzed the effects of accidental spills of liquefied natural gas; designed innovative methods for tracking, cleaning up, and modeling contaminants in groundwater; calculated how structures respond to earthquakes; and developed seismic prediction models.

> ***Available energy is the main object at stake in the struggle for existence and the evolution of the world.***
>
> *Ludwig Boltzmann (1844–1906)*
> *Austrian mathematician and physicist*

Harnessing the Power of Stars

The drive to find new ways to produce energy was present from the Laboratory's genesis. Herbert York, who Ernest O. Lawrence put in charge of organizing the Livermore branch of the University of California Radiation Laboratory, viewed work on controlled thermonuclear reactions as a natural adjunct to Livermore's nuclear weapons research. In such reactions, two lightweight nuclei combine and release energy, which is the same process that powers the stars and thermonuclear weapons. The idea of using fusion for power production came to the fore in the early 1950s.

Initial efforts focused on using strong magnetic fields to trap a plasma fuel long enough to achieve fusion. This was the work of the Controlled Thermonuclear Reactions (CTR) program, classified until 1958. The goal of the first CTR group was not

to get a reaction going, but, according to York's prospectus for the Livermore site, ". . . to reach some sort of halfway point, say, setting up a plasma with a temperature of 100 electronvolts and then investigating various points of interest such as particle mobility across and along field lines, heat conductivity, plasma oscillations, etc."

Physicist Dick Post, reminiscing in 1982 about those first efforts, said, "In 1952, hardly anyone understood even the simplest aspects of the confinement of plasma by magnetic mirrors; there just wasn't any prior work to go on." Diagnostics for this kind of work were also in a similar state. "An understanding of the basic physics of magnetic confinement was not the only thing we were lacking back in 1952–1953," Post added. "While we were trying to gain understanding through experiments, we also had to feel our way along by inventing our own diagnostic techniques to measure the plasma properties."

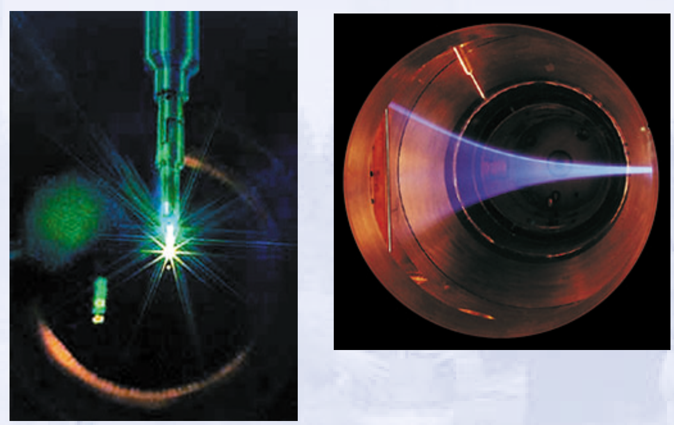
By summer 1954, the Table Top Reactor was completed and tested. It provided a clear demonstration of the magnitude of the magnetic forces involved when the magnet's coil windings were crushed by the sheer strength of the magnetic fields. In 1961, Livermore achieved the first definite fusion reactions. In 1977, Livermore began the Tandem Mirror Experiment, exploring an approach in which the reactor vessel holds a long solenoid magnet in its middle, where the plasma fuel is held. Large quantities of electric current traveling through huge magnet coils surrounding the solenoid magnet produce the immensely strong magnetic fields needed to confine the plasma. Magnetic mirrors at the ends of the reactor vessel keep the plasma from leaking out.

The Tandem Mirror Experiment and its upgrade, completed in 1981, demonstrated a marked improvement over the Laboratory's previous systems in terms of plasma confinement. These magnetic confinement machines used large electric current traveling through huge magnet coils to produce the immensely strong magnetic fields needed. The magnetic system for the Magnetic Fusion Test Facility-B, initiated in 1981, was the largest superconducting system ever built in the world.

In 1986, the Department of Energy decided to focus its magnetic fusion energy research on a different technology, the tokamak. The Laboratory contributed to the International Thermonuclear Experimental Reactor project for designing and building the world's first full-scale magnetic fusion reactor based on the tokamak design. In a tokamak, magnetic fields are generated by large, external magnetic coils surrounding a doughnut-shaped reactor. Livermore continues to provide leadership in computational fusion energy science and to explore alternative approaches to fusion energy.

Recently, Livermore began to revisit the spheromak concept. (A spheromak takes the hole out of the doughnut-shaped reactor.) In the spheromak configuration, the plasma fuel produces some of its own confining magnetic fields, requiring only an external set of coils and making for a much more compact machine capable of producing a higher-temperature and higher-density plasma. (See *S&TR*, December 1999, pp. 18–20.)

The Laboratoy also has explored using laser light as a method of creating fusion energy and providing a virtually inexhaustible, low-cost, safe, and environmentally attractive energy source. Laboratory researchers envisioned doing this through inertial confinement fusion (ICF), in which small targets of fuel are imploded by laser beams until the fuel



Since its inception, the Laboratory has explored the prospects of creating fusion as an energy source through (a) using the energy of laser light to generate laboratory fusion and (b) using enormous superconducting magnets to confine plasmas.

reaches temperatures that induce fusion. Beginning in 1972, the Laboratory pursued this vision in a series of increasingly powerful laser systems. (See *S&TR*, September 2002 pp. 20–29.) The latest—the National Ignition Facility—will be a key component of the National Nuclear Security Administration's Stockpile Stewardship Program and will, in addition, provide the most powerful system yet for exploring the ICF energy production process.

Plowshare's Energy Legacy

In 1957, the Atomic Energy Commission (the predecessor to DOE) officially established Project Plowshare to explore the use of nuclear explosives for peaceful purposes, including using these explosives to stimulate natural gas reservoirs and process underground oil shale into oil. Even though Plowshare was terminated in 1977, its legacy lived on through these and other energy projects.

From 1974 through 1988, the Laboratory developed an underground coal gasification process that converted coal beds into gas without mining. This method had two benefits. First, it reached coal that was not economically feasible to mine with the usual techniques. Second, the method produced a combustible gas that was easy to clean—easier, in fact, than removing the pollutants from stack gas at coal-fired power plants.

This project and others included large-scale demonstrations to prove or disprove the commercial viability of a given technology. "Large-scale demonstrations were the Laboratory's forte because of our experience in nuclear testing," notes retired physicist Bob Schock, who spent more than two decades managing one aspect or another of the Laboratory's energy efforts beginning in the 1970s. "The Laboratory did some large experiments in Wyoming in the late 1970s to early 1980s to gasify coal seams in place. We started by using high explosives—we'd foregone nuclear explosives by then—and came up with a technique that gasified the coal without explosives." The technique used the natural fractures in coal and controlled the burn zone through a movable oxygen injector.

"In situ coal gasification is still a good idea," says Schock. "If the technology is ever implemented, it could double or triple the accessible U.S. coal reserves and has the advantage that the carbon dioxide produced by the process can be separated out and captured."

In another Plowshare offshoot, the Laboratory investigated the feasibility of using nuclear explosives—and later, high explosives—to fracture oil shale. Oil shale can be converted to

On December 10, 1967, a 29-kiloton nuclear device was exploded in a sandstone formation 1,200 meters deep in the San Juan basin of New Mexico. The experiment, called Gasbuggy, was the first of three Project Plowshare experiments exploring the use of nuclear explosives to stimulate natural gas production in rock too impermeable for production by conventional means.

In the 1980s and early 1990s, Livermore developed an oil-shale retort technology to help unlock the vast oil-shale reserves in the western U.S. Such reserves could provide an important alternative source of liquid fuel.

oil by subjecting it to high temperatures and high pressures—in other words, by speeding up the geologic clock. Laboratory researchers envisioned using explosives to fracture the vast oil-shale reserves in the western U.S. so that the oil could be processed in place, thus providing an important alternative to imported oil. That effort evolved in the early 1980s into a surface oil-shale retorting process that used hot oil-shale particles as the heat carrier. The research also produced a model of how oil is formed. Today, this model aids the exploration efforts of every major oil company in the world.

Work supporting fossil fuel research and exploration still continues at Livermore. For instance, in 1997, Laboratory researchers developed a much-improved version of a tiltmeter to help oil explorers determine the orientation of fractures in deep oil wells. (See *S&TR*, October 1997, pp. 14–15.) Livermore is also part of the DeepLook consortium, an oil industry collaboration formed to find breakthrough technologies for detecting, predicting, and monitoring hydrocarbons, particularly in reservoirs deep below the surface. Livermore is developing computational modeling techniques to produce three-dimensional images of such reservoirs, computational neural networks to evaluate strategies that will help maximize gas and oil production, and nuclear magnetic resonance techniques to look for oil. (See *S&TR*, November 2001, pp. 12–19.)

Closing the Nuclear Fuel Cycle

With nuclear fission power still an important source of energy in the United States and throughout the world, a way must be found to satisfactorily close the fuel cycle—that is, to safely dispose of the radioactive waste produced by nuclear power plants. Beginning in 1977, the Laboratory participated in studies of candidate sites for a U.S. high-level waste repository that culminated in the recent choice of the Yucca Mountain site in Nevada.

In 1987, Congress directed DOE to study the Yucca Mountain site for its feasibility as a permanent repository for high-level nuclear waste. The Laboratory was given responsibility for designing the waste package and barrier system for the proposed repository. As part of this work, Livermore scientists designed a computer code that would run on the world's most powerful computers and show how buried nuclear wastes would affect the Yucca Mountain geology. (See *S&TR*, March 2000, pp. 13–20.)

From 1980 to 1984, Livermore scientists and engineers also designed, built, and operated at the Climax Mine in Nevada an

Livermore's involvement in the Yucca Mountain project dates from 1977. The current focus for Laboratory researchers is on developing a system of engineered barriers surrounded by natural barriers to contain highly radioactive waste. Little is known about how modern materials, placed in a geologic site and subjected to initially high temperatures and radiation, will behave during time periods of thousands of years. So, much of Livermore's development work is based on predictive models and accelerated age testing of materials and systems.

In the 1970s, the Laboratory explored the feasibility of using shallow ponds to store solar energy to produce domestic heat and run chemical processes.

underground repository to test the storage and retrieval of commercial spent-fuel and to monitor the environment. At the time, Climax was the first place in the world where high-level radioactive waste from fission reactors was stored underground for any lengthy period. The successful demonstration of this concept paved the way for future work on repositories.

Small Projects, Innovative Ideas

Although the Laboratory had many large demonstration projects during the energy heyday of the 1970s and 1980s, small innovative energy projects also flourished, such as research into solar energy. Some of these projects continue to this day.

For instance, battery research at the Laboratory, which started with aluminum–air batteries in the 1970s, has transformed into today's fuel cell research. Fuel cells, which convert the chemical energy of a fuel directly to usable energy without combustion, are widely viewed as the technology of the future for replacing internal combustion engines in vehicles.

Livermore scientists are working on several fuel cell approaches. The refuelable zinc–air fuel cell—an alternative to the standard lead–acid batteries now powering most electric cars and other vehicles—promises trouble-free, nearly 24-hour-a-day operation for numerous kinds of electric vehicles, from forklifts to delivery vans and maybe even personal automobiles. (See *S&TR*, October 1995, pp. 6–13.) Other possibilities include a fuel cell based on a proton exchange membrane and the solid-oxide fuel cell that uses hydrogen or other combustible gas as fuel. (See *S&TR*, September 2002, pp. 17–19; December 1998, pp. 4–12.) Another concept, the carbon-conversion fuel cell, uses an electrochemical process to convert carbon particles from fossil fuels directly into electricity. (See *S&TR*, June 2001, pp. 4–12.)

Interest in developing high-technology flywheels—rotating wheels to store kinetic energy, as in a potter's wheel—also grew in the 1970s. The Laboratory's flywheel research started when Dick Post envisioned flywheels made of composite materials for storing energy in electric vehicles and improving power quality. When the energy crisis hit in the mid-1970s, the Laboratory began serious research into flywheels and the necessary composite materials. Funding disappeared in the mid-1980s when the nation's focus shifted away from energy research. Flywheel research resumed in the 1990s when affordable graphite composite materials of very high strength became widely available and the U.S. Council for Automotive Research—a consortium of the Big Three U.S. automakers—developed hybrid vehicle components. (See *S&TR*, April 1996, pp. 12–19.) Livermore's flywheel technology was licensed to a commercial company in 1994. Today, flywheel researchers are working on using better carbon-composite materials and developing passive magnetic bearings to replace present-day mechanical bearings.

Environment: The Air Above

From the Laboratory's earliest days, large computers were used to simulate three classes of fluid dynamics problems: weapons explosions, the plasmas contained in magnetic fusion energy machines, and stellar physics. A natural extension was another area of fluid dynamics—the weather. In the late 1950s, with the encouragement of Livermore cofounder Edward Teller, Chuck Leith constructed the first global general circulation model. It simulated the growth, movement, and decay of large weather systems from the fundamental laws of physics. This model was the first in a series in which the Laboratory's computational capabilities were used to study atmospheric processes. (See box on p. 19.)

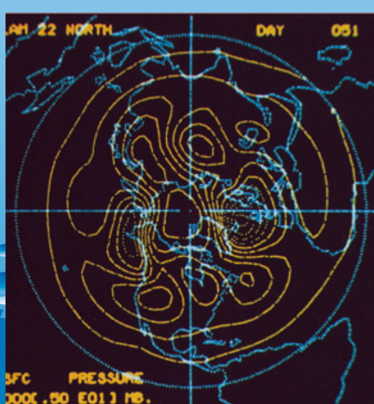
At about the same time, activities for Project Plowshare required assurance that radioactive fallout would not reach harmful levels in populated areas. A small group of scientists began developing computational models of the atmospheric transport and diffusion of radionuclides. They quickly became involved in forecasting the weather when they needed to factor wind speeds into their estimates of the amount of material released, how far the material would disperse, and what the radionuclide dose would be along the trajectory of the nuclear cloud.

Global Climate Modeling

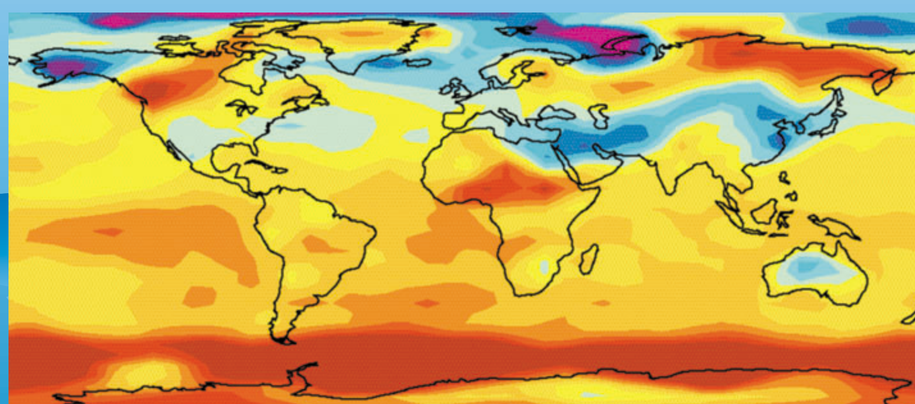
Global climate research—which has been a part of Livermore's work for nearly 35 years—had its origins in the Laboratory's nuclear weapons development and testing programs. Livermore's climate modeling researchers applied computation expertise originally developed to simulate nuclear explosions to the task of modeling the climate. The atmospheric science expertise they drew upon originated from efforts to model fallout from nuclear explosion testing.

Early on, researchers focused on global warming and its possible causes, including increased levels of atmospheric carbon dioxide, introduction of trace gases as a result of industrial and agricultural practices, aerosols from volcanic eruptions, and even variations in solar radiation. (See *S&TR*, October 1996, pp. 6–13.) This research into global warming and its causes continues. Livermore scientists have used sophisticated climate models to separate the effects of recent major volcanic eruptions and El Niños from other causes of climate change. Results indicate that cooling caused by major eruptions in 1982 and 1991 has masked some of the warming brought about by human activities, such as the conversion of forests to farm land. (See *S&TR*, July/August 2002, pp. 4–12.)

As more complex global climate models were developed, the disagreements among models and between models and observations remained significant and poorly understood. So Livermore established the Program for Climate Model Diagnosis and Intercomparison (PCMDI) in 1989 to develop improved methods and tools for evaluating global climate models. The program does not make new models but, rather, sets a standard to which all climate models can adhere and thus gain validity. The ultimate goals are to develop improved methods and tools for the diagnosis, validation, and intercomparison of global climate models and to conduct research into problems in climate modeling and analysis. In one project, for instance, some 30 international modeling groups simulated the climate of the decade 1979 to 1988, and PCMDI evaluated the results.



In the late 1950s, researchers applied numerical methods used for weapon physics to develop the first global general circulation model, which was able to simulate the behavior of large weather systems.



Temperature variability for an ensemble of 20 different simulations, showing mean surface temperatures for December through February. This comparison was conducted in the mid-1990s by Livermore's Program for Climate Model Diagnosis and Intercomparison on behalf of the International World Climate Research Programme.

In the late 1960s and early 1970s, the Laboratory became more involved in the study of the regional and global effects of pollutants. At the same time, researchers came up with a plan for estimating in real time the consequences of an accidental radionuclide release. This idea evolved into the Atmospheric Release Advisory Capability (ARAC). The original intent was to establish an emergency response service for the federal government. With the accident at the Three Mile Island nuclear power plant in March 1979, ARAC, which had just begun a limited pilot service to three Atomic Energy Commission facilities, opened ahead of schedule and operated around the clock for a month, providing information to on-scene emergency response managers and others.

Since that time, ARAC has become the National Atmospheric Release Advisory Center (NARAC), which has responded to more than 70 alerts, accidents, and disasters and has supported more than 800 exercises. Besides accidental radiological releases, NARAC has assessed volcanic ash clouds, earthquake-induced hazardous spills, the Kuwaiti oil fires, several toxic chemical accidents, and more. (See *S&TR*, June 1999, pp. 4–11.) In the aftermath of September 11, NARAC has been called upon to help local communities better plan for and respond to releases of chemical or biological agents. The program, called the Local Integration of NARAC with Cities (LINC), will provide local agencies with capabilities to predict the dispersion of chemical and biological agents, which is useful—indeed necessary—for emergency planning and response.

At Bikini Atoll, Livermore scientists experimented with a two-part remediation technique for cleaning up coral islands for resettlement. First, they used potassium fertilizer in agricultural areas to reduce the uptake of radionuclides into locally grown foods. They found that the fertilizer reduced this uptake by nearly 90 percent and also increased plant productivity. Second, they replaced contaminated soil with crushed coral in housing and village areas. This eliminated most of the radionuclide dose resulting from ingestion and inhalation of soil particles.

The Ground beneath Our Feet

Environmental research at the ground level also began at Livermore in the late 1950s and early 1960s. Some of the first research concerned fallout from atmospheric tests at the Nevada Test Site to better understand the dynamics of radionuclides and human and animal metabolism. The Plowshare tests, which created radionuclides that nobody had worked with before, such as isotopes of tungsten, raised further questions. To address them, the Laboratory acquired a small dairy herd to study the metabolism of radionuclides in cattle, a project that lasted into the 1970s.

This research into the interaction of radionuclides in the environment broadened in the 1970s, when the Laboratory became involved in environmental evaluations in the Pacific and in California. One effort, which continues to this day, concerns the effect of the radionuclides released to the environment by the nuclear tests conducted at the Bikini and Enewetak atolls in the Marshall Islands. The islanders were relocated from Bikini Atoll in 1946 and from Enewetak in 1947 before U.S. nuclear testing began. In 1962, both groups of islanders began asking to return to their ancestral homes. U.S. officials decided that more knowledge of the conditions at the atolls was needed before resettlement could begin. Laboratory scientists conducted large-scale environmental surveys of the radionuclide distribution on the islands to determine what long-term radioactive exposures would result, for instance, from eating locally grown crops, drinking the water, or eating fish caught in the lagoons.

They performed 30 years of scientific investigations on the levels and distributions of fallout radionuclides at the atolls and developed remediation techniques for cleaning up the coral islands for resettlement. One technique, developed in large-scale field experiments conducted on Bikini by Livermore environmental scientist Bill Robison (now retired) and others involves using common plant fertilizer to reduce the uptake of radionuclides into locally grown foods and replacing contaminated soil in the housing and village areas. Portions of Enewetak were resettled in 1980, and a cleanup and rehabilitation program on neighboring Rongelap Atoll is under way.

Livermore supports the Marshall Islands resettlement in many ways, including monitoring the health of resettlers by using advanced accelerator-based measurement technologies to analyze urine samples at Livermore's Center for Accelerator Mass Spectrometry. (See the box on p. 22.) Researchers also continue the work started in the 1950s—characterizing the radiological conditions at the various atolls;

determining the transport, uptake, and cycling of radionuclides in the ecosystem; and estimating the potential radiological doses and risk.

Other ground-level research started with looking at the environmental effects of different energy sources and evolved from there. For instance, in 1984, DOE was looking into the pros and cons of liquefied natural gas (LNG) as a possible energy source. Through 1988, DOE and Livermore conducted a series of large-scale spill tests at the Nevada Test Site to obtain more information about various aspects of LNG safety and about chemical spills in general. The spill test site now holds the Remote Sensor Test Range, which is the proving ground for nascent remote-sensing technologies developed by DOE's national laboratories. At the range, sensor developers can submit their technologies to full-scale testing consisting of releases of chemicals and mixtures. (See *S&TR*, April 2000, pp. 19–21.)

Into the Underground

Another environmental realm extends far below the ground—a world of groundwater, fractures, and tectonic plates. Livermore environmental scientists and geologist have spent many years seeking to shed light on this underworld.

In the late 1970s and early 1980s, people became aware that the contaminants put into the ground—either deliberately or as accidental spills—didn't necessarily stay in one place, but could migrate. In 1983, in conjunction with a seismic evaluation at the Livermore site, groundwater samples were analyzed for natural mineral content and for solvents. The Laboratory found that the groundwater beneath the Livermore site was contaminated by volatile organic chemicals.

Extensive record checking revealed that many—if not most—of the solvents causing the groundwater contamination resulted from the operations of the Livermore Naval Air Station, which was located at the Lawrence Livermore site during World War II. Tests on the nearest domestic well revealed 400 parts per billion of perchlorethylene (PCE), a volatile organic compound once used extensively for cleaning metal airplane parts—far exceeding the drinking water standard of 5 parts per billion.

Since the discovery of the contaminated groundwater plumes, Livermore has drilled hundreds of wells for sampling groundwater, measured the extent and concentration of PCE and other chemicals, and evaluated the complex geology of the affected subsurface. Cleanup of the groundwater by the pump-and-treat method started in 1989 at the Livermore site and in the early 1990s at Site 300, Livermore's remote experimental test facility. Livermore researchers continue to develop innovative technologies for cleaning up groundwater and soil. Examples include soil-vapor extraction, in which solvents are sucked out of the soil above the groundwater; dynamic underground stripping, in which the subsurface is heated and the solvents extracted; and microbial treatments, in which bacteria are injected into the subsurface to break the contaminants in situ. (See *S&TR*, May 1994, pp. 11–21; July/August 1997, pp. 21–22).

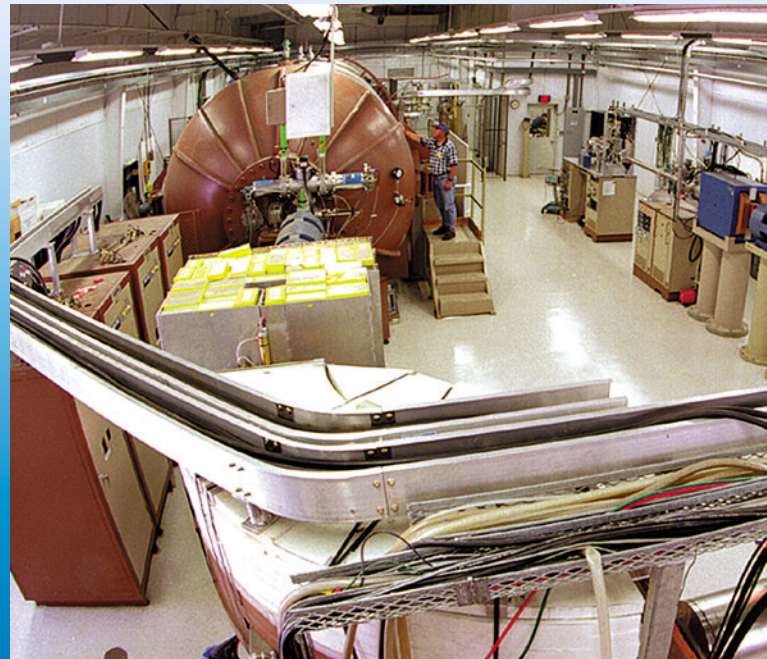
Joy Hirabayashi (left) and Tina Carlsen collect surface water samples as part of the Laboratory's ongoing environmental monitoring program.

Research to understand the complex underground environment has broadened to include other studies as well. For instance, some scientists are looking at how groundwater moves through rock fractures underground, studying in particular the relationship between the rate of fluid flow and the rate of mineral dissolution in a fracture. Underground fluid flow is of particular interest to nuclear waste isolation research at the Laboratory. Advances in numerical methods and computational power is helping researchers to gain a better understanding of cracks and fractures, which play a major role in the mechanical behavior of rock at all scales. Accurate predictions of the strength and mechanical behavior of large rock masses are important in many applications in civil, environmental, and mining engineering. Seismic codes developed by Livermore researchers, such as computer scientist–geophysicist Shawn Larsen, simulate the rupturing of an earthquake fault. Researchers such as engineer David McCallen then feed predictions of ground motion into a code that he codeveloped to simulate how bridges and buildings respond to earthquakes. (See *S&TR*, December 1998, pp. 18–20.) Livermore seismologists also have developed ways to use seismic

One Part in a Quadrillion

Established in 1989, Livermore's Center for Accelerator Mass Spectrometry (CAMS) was created to help Laboratory researchers diagnose the fission products of atomic tests and track the spread of nuclear weapons to other countries by detecting radioisotopes in air, water, and soil samples. In addition, the technique is now used to study environmental quality, climate change, seismology, archaeology, and biomedical science.

Accelerator mass spectrometry is a sensitive technique for measuring concentrations of specific isotopes in very small samples. It can be used, for example, to seek out one carbon-14 isotope out of a quadrillion other carbon atoms. Today, the center's scientists participate in about 70 collaborative research projects with universities worldwide. Examples of research using CAMS capabilities are described in *S&TR*, June 2001, "Environmental Research in California and Beyond," pp. 13–21; July/August 2000, "Biomedical Research Benefits from Counting Small," pp. 12–19; January/February 1997, "The B-Factory and the Big Bang," pp. 4–13, and "Assessing Exposure to Radiation," pp. 14–21.



measurements to detect clandestine underground explosions, and they have built a worldwide network of seismic stations to help in this effort. (See *S&TR*, July/August 2002, pp. 24–30.)

A Linked World

Coal, fusion energy, nuclear power, solar energy, rock mechanics, metabolism of radionuclides, global warming—these are only a sample of the dizzying spectrum of energy and environmental topics Livermore's researchers have explored over the past half-century. In many instances, notes Associate Director for Energy and Environment C. K. Chou, these efforts have overlapped, revealing how inexorably connected our world is. "Now that these efforts are in a single organization at the Laboratory," he says, "researchers can more easily link environmental factors to technologies related to energy production and use." As an example, he points to research in three interrelated issues: energy technologies (which may release carbon dioxide), management of human-caused carbon dioxide (which may reduce carbon dioxide's effects on climate), and global climate–carbon cycle modeling. Understanding the complex interactions between the earth system and human activities in the biosphere requires that all three issues be considered as an integrated package.

The Laboratory has always risen to the occasion when addressing environmental and energy issues of national concern. Chou stresses that Lawrence Livermore does not make policy. Rather, the Laboratory provides the scientific understanding that enables policy makers to make informed decisions. It is through this integrated approach that the Laboratory can help those who do make policy to address the complex interrelated energy and environmental challenges that face the nation and the world today.

—Ann Parker

Key Words: atmospheric transport and dispersion, coal gasification, fossil fuel, fuel cells, global climate modeling, groundwater contamination, inertial confinement fusion, magnetic fusion, Marshall Islands, nuclear fuel cycle, nuclear waste repository, Project Plowshare, rock mechanics, Yucca Mountain.

For further information about the Energy and Environment Directorate, see:

en-env.llnl.gov/

For further information about the Laboratory's 50th anniversary celebrations, see:

www.llnl.gov/50th_anniv/

Each month in this space we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Optical Monitor for Real Time Thickness Change Measurements Via Lateral-Translation Induced Phase-Stepping Interferometry
Michael C. Rushford
U.S. Patent 6,411,389 B1
June 25, 2002
An optical instrument for monitoring etch depth and etch rate to control a wet-etching process. The instrument provides means for viewing through the back side of a thick optic onto a nearly index-matched interface. Optical baffling and the application of a photoresist mask minimize spurious reflections, which allows monitoring with extremely weak signals. A Wollaston prism enables linear translation for phase stepping.

High-Performance Parallel Processors Based on Star-Coupled Wavelength Division Multiplexing Optical Interconnects
Robert J. Deri, Anthony J. DeGroot, Ronald E. Haigh
U.S. Patent 6,411,418 B1
June 25, 2002
As the performance of individual elements within parallel processing systems increases, increased communication between distributed processor and memory elements is required. There is great interest in using fiber optics to improve interconnect communication beyond that attainable with electronic technology. Several groups have considered wavelength-division-multiplexing, star-coupled optical interconnects. The invention has a fiber-optic transceiver to provide low-latency, high-bandwidth channels for such interconnects using a robust, multimode fiber technology. Instruction-level simulation quantifies the bandwidth, latency, and concurrency required for such interconnects to scale to 256 nodes, each operating at 1-gigaops performance. Performance scales have been shown to approximate 100 gigaops for scientific application kernels using a small number of wavelengths (8 to 32), only one wavelength received per node, and achievable optoelectronic bandwidth and latency.

Method for Maintaining a Cutting Blade Centered in a Kerf
Kenneth L. Blaedel, Pete J. Davis, Charles S. Landram
U.S. Patent 6,412,377 B1
July 2, 2002
A saw having a self-pumped hydrodynamic blade guide or bearing for retaining the saw blade in a centered position in the saw kerf (width of cut made by the saw). The hydrodynamic blade guide or bearing uses pockets or grooves incorporated into the sides of the blade. The saw kerf in the workpiece provides the guide or bearing stator surface. Both sides of the blade entrain cutting fluid as the blade enters the kerf in the workpiece, and the trapped fluid provides pressure between the blade and the workpiece as an inverse function of the gap between the blade surface and the workpiece surface. If the blade wanders from the center of the kerf, then one gap will increase and one gap will decrease. The consequent pressure difference between the two sides of the blade will cause the blade to recenter itself in the kerf. Saws using the hydrodynamic blade guide or bearing have particular application in slicing slabs from boules of single-crystal materials, for example, as well as for cutting other difficult-to-saw materials such as ceramics, glass, and brittle composite materials.

Composition Analysis by Scanning Femtosecond Laser Ultraprobing (CASFLU)
Muriel Y. Ishikawa, Lowell L. Wood, E. Michael Campbell, Brent C. Stuart, Michael D. Perry
U.S. Patent 6,414,320 B1
July 2, 2002
The composition analysis by scanning femtosecond ultraprobing (CASFLU) technology scans a focused train of extremely short-duration, very intense laser pulses across a sample. The partially ionized plasma ablated by each pulse is spectrometrically analyzed in real time to determine the ablated material's composition. The steering of the scanned beam can then be computer-directed to either continue ablative material removal at the same site or to successively remove nearby material for the same type of composition analysis. This invention has utility in high-speed chemical-elemental, molecular-fragment, and isotopic analyses of the microstructure composition of complex objects, for example, the oxygen isotopic compositions of large populations of single osteons in bone.

Three-Dimensional Coil Inductor
Anthony F. Bernhardt, Vincent Malba
U.S. Patent 6,417,754 B1
July 9, 2002
A three-dimensional coil inductor, which includes a substrate, a set of lower electrically conductive traces positioned on the substrate, a core placed over the lower traces, a set of side electrically conductive traces laid on the core and the lower traces, and a set of upper electrically conductive traces attached to the side traces so as to form the inductor. Fabrication of the inductor includes the steps of forming a set of lower traces on a substrate, positioning a core over the lower traces, forming a set of side traces on the core, connecting the side traces to the lower traces, forming a set of upper traces on the core, and connecting the upper traces to the side traces so as to form a coil structure.

Light Diffusing Fiber Optic Chamber
Duncan J. Maitland
U.S. Patent 6,418,252 B1
July 9, 2002
A light-diffusion system for transmitting light to a target area. The light is transmitted in a direction from a proximal end to a distal end by an optical fiber. A diffusing chamber is operatively connected to the optical fiber for transmitting the light from the proximal end to the distal end and transmitting said light to said target area. A plug is operatively connected to the diffusing chamber for increasing the light that is transmitted to the target area.

Awards

Two Laboratory researchers were among 60 winners of the **Presidential Early Career Award for Scientists and Engineers** (PECASE), the nation's highest honor for professionals at the outset of their research careers. Laboratory physicist **Mark Hermann** and **Paul Ricker,** whose work at the University of Chicago is supported by the Advanced Simulation and Computing (ASCI) program, received their awards at a ceremony at the White House in mid-July. PECASE awardees are nominated by government departments that support science research. They must be directly employed by a national laboratory or have an association with one, and they must be in the first five years of their career.

Herrmann has been working with lasers, currently on projects dealing with inertial confinement fusion and inertial fusion energy. He received a B.S. in physics and two M.S. degrees—in applied science and mathematics—from Washington University in St. Louis, Missouri. His Ph.D. in astrophysical science is from Princeton University.

Ricker is a computational astrophysicist at the ASCI Flash Center at the University of Chicago. He has a B.S. in physics from Pennsylvania State University and an M.S. and Ph.D. in physics from the University of Chicago.

Willy Moss of the Geophysics and Global Security Division of the Energy and Environment Directorate has been elected **fellow** of the **Acoustical Society of America**. He was honored "for contributions to numerical modeling and single-bubble sonoluminescence." The presentation of his fellowship certificate will be made during the plenary session of the society's meeting in Cancun in early December.

Francois Heuze, also of the Geophysics and Global Security Division, has been elected **president** of the **American Rock Mechanics Association** for a 2-year term. Heuze is a member of the Laboratory team working on problems of hard and deeply buried targets and is representing the Laboratory on the Mining Review Board for the U1a underground complex at the Nevada Test Site. Heuze's career in rock engineering began in 1962. He has been at the Laboratory for 23 years.

Coming Next Month

Computer Models Join the Fight against Wildfires

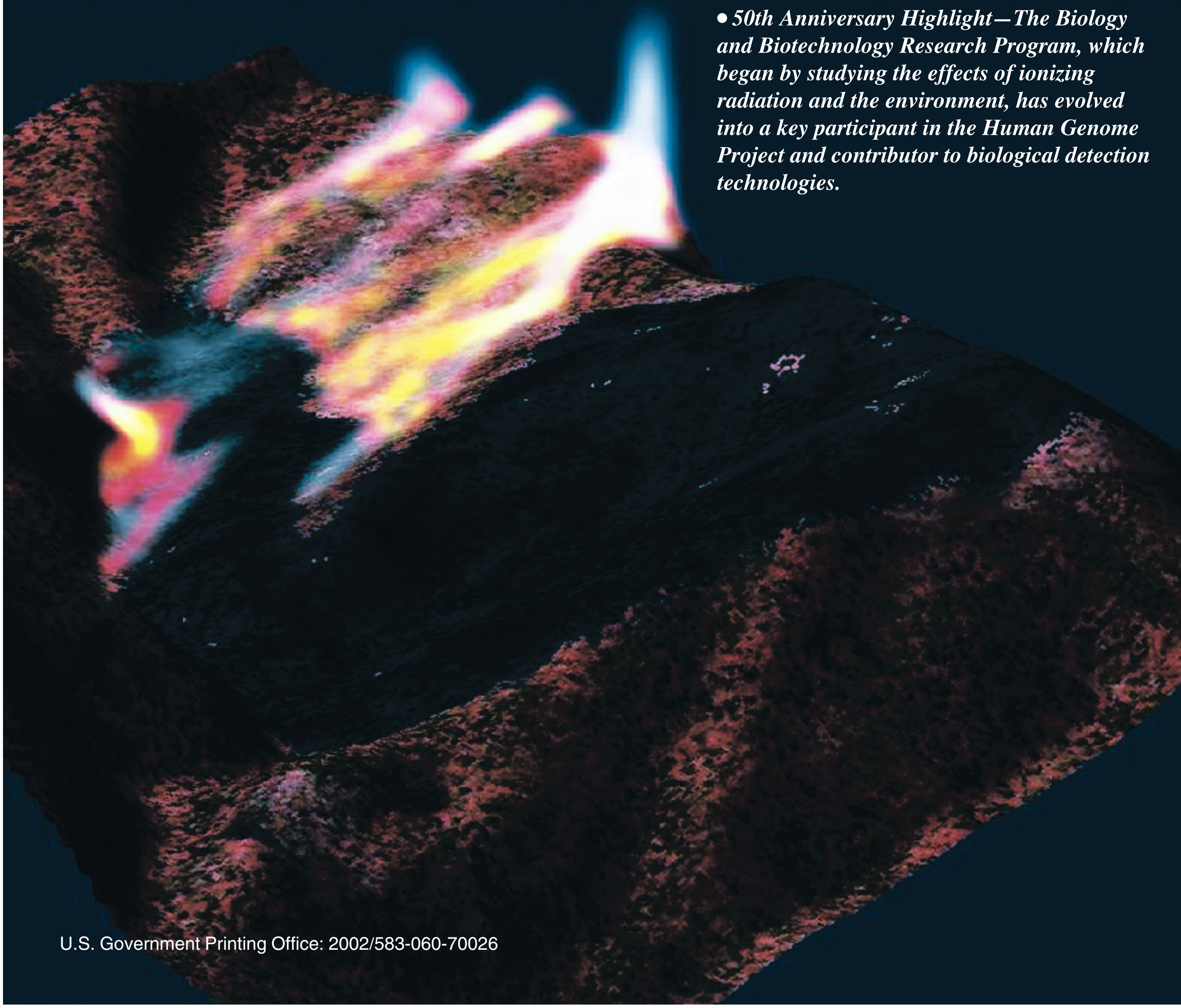
A new computer program simulates the physics of fire and weather patterns to help understand and combat wildfires.

Also in November

- ***The Lawrence Fellowship Program attracts the best and the brightest to pursue independent scientific research at Livermore.***

- ***Sensor systems and cameras collect spectral information and high-speed video to determine whether an interceptor missile has made a "kill."***

- ***50th Anniversary Highlight—The Biology and Biotechnology Research Program, which began by studying the effects of ionizing radiation and the environment, has evolved into a key participant in the Human Genome Project and contributor to biological detection technologies.***



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