December 2002

Science & Technology REVIEW

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

The Continuing National Security Mission

Also in this issue:

- Learning to Move Molecules
- Laser Communications at Gigabit Speeds

Lawrence Livermore
National Laboratory

*Making History
Making a Difference*

1952-2002

About the Cover

In this issue, we conclude the series of highlights that commemorate the 50th anniversary of Lawrence Livermore National Laboratory. The final highlight, which begins on p. 4, describes the evolution of Livermore's science and engineering expertise from weapons research and development to stockpile stewardship applications. The images on the cover are of Livermore's continuing work to safeguard the nation. At left is the W87 warhead designed at Livermore and now, under the Stockpile Stewardship Program, being refurbished to extend its lifetime. In the center is an experiment being prepared at the Contained Firing Facility at Livermore's Site 300 high-explosives research facility. At right, the Minuteman III missile, another Livermore design, blasts off.

Cover design: Kitty Tinsley

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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Lawrence
Livermore
National
Laboratory

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Sequencing frog and bacteria genomes

At the Joint Genome Institute (JGI) operated by the Lawrence Livermore, Lawrence Berkeley, and Los Alamos national laboratories, researchers have been decoding the DNA of one organism after another. They recently sequenced the fugu, a tasty but potentially toxic Japanese pufferfish whose compact genome is similar in many respects to the human genome. (See *S&TR*, October 2002, p. 3.) They then went on to map the DNA of a diminutive, fast-growing African frog, *Xenopus tropicalis*.

Frogs are of interest to biologists because their growth from eggs to tadpoles to mature organisms provides information about the development of cells and organs. The *X. tropicalis* has a genetic structure that is smaller and easier to decode than that of other frog species. Says Robert Grainger, a leading *Xenopus* researcher from the University of Virginia, "Studies on frogs have long been instrumental in understanding such fundamental processes as cell division and how cells in the embryo communicate with one another. Because these are the processes that go awry when birth defects occur or cancer strikes, we must seek a better understanding of them. This genome project will provide a major step in that direction."

JGI researchers have also been analyzing the DNA of various lactic acid bacteria—that is, bacteria that ferment sugars into lactic acid—to help food scientists enhance the preservation and safety of fermented foods. Not only are these probiotic, or good, bacteria important in food production, but they can also contribute to the health and balance of the intestinal tract and to fighting illness and disease. The JGI has sequenced the genomes of 11 lactic acid bacteria targeted by the Lactic Acid Bacteria Genome Consortium, a group of molecular scientists from a dozen U.S. universities.

In early October, scientists from around the nation gathered at JGI to examine the genomes of nine of these economically and scientifically important microbes. David Mills, a food microbiologist and assistant professor of viticulture and enology at the University of California at Davis, said that looking at these bacteria would help food producers use their genetic traits to make better products as well as to retard or prevent food spoilage. Furthermore, he said, "To our knowledge, no one has ever sequenced such a large number of genetically related microbes before. This gives us an unprecedented opportunity to learn about genome evolution within a defined, related group."

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Migrating water holds clues about climate change

Climate scientists from the Laboratory are making progress toward reconstructing past climate from the chemistry of water moving through the vadose zone, the region between the land surface and groundwater aquifers. In their initial studies, the researchers needed to confirm a long-held assumption that water migrating to deep water tables may be 10,000 to 100,000 years old. Then they needed to determine how large an effect changes in surface temperature and rainfall amounts—that is, climate—might have on water chemistry.

To resolve these issues, they used supercomputers to simulate the chemical interaction of water with the rocks through which it migrates. The changing type and abundance of minerals in rocks affect the chemical composition of the water as it flows through. Scientists can determine the chemistry changes along the path of the water flow as a function of flow rate. In arid environments where water tables are hundreds of meters deep, scientists have assumed that it would take tens of thousands of years for surface water to reach the water table. The simulations confirmed that and also showed that climate changes had a measurable effect on water chemistry, even after thousands of years and after migrating hundreds of meters through the vadose zone.

"What this implies in principle is that one could use a combination of water temperature, water chemistry, abundance of water, and isotopic signatures to reconstruct past climate conditions on a regional scale on most continents. This is one of the things needed to test and verify global climate change models," says William Glassley, leader of the research team.

To go forward in interpreting the climate record, the researchers need to conduct highly detailed computer simulations using a vast amount of rock property data that are not usually measured. They also need to obtain some as yet unestablished property data, such as how much surface area of a mineral a migrating water would travel through. But their progress indicates that they soon will be able to reconstruct a 100,000-year-old climate record.

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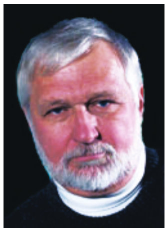


Doing It All: Sustaining Our Working Solutions, Rising to New Challenges

IN this issue, *Science & Technology Review* concludes its look back at the Laboratory's 50th anniversary with a highlight, beginning on p. 4, that reviews Livermore's work for the nation's Stockpile Stewardship Program and discusses opportunities and challenges for the future.

During the Cold War, the U.S. relied on its science and technology infrastructure to provide military advantages for national defense. In the process, the U.S. government created both the doctrine and the reality of nuclear deterrence, which in effect forced the nation's most prominent adversary, the Soviet Union, with its much larger but conventional military forces, to refrain from invading Western Europe or initiating a first strike on the U.S. Outstanding science and technology capabilities allowed the U.S. to gain leverage against an opponent with asymmetric advantages. Having a focused enemy also provided comfortable benchmarks of U.S. military strength and defense investments.

Research and development to support national security is even more crucial in the 21st century. Today, the U.S. maintains a smaller nuclear deterrent and relies on the national laboratories to ensure the reliability of that stockpile in the absence of new weapon development or nuclear testing. Although the nation has an overwhelming advantage in conventional weapons, it faces potential adversaries that are smaller and much more difficult to find. As the events of September 11, 2001, made all too clear, the oceans no longer provide a shield around the continental U.S., and protecting the U.S. homeland poses significant challenges.

The nation's decision makers are finding that, in countering terrorism, "the event defines the organization chart." That is, reporting structures must change quickly and efficiently, depending on the response needed. In addition, timely action may not conform to established approval processes for acquisitions, requirements, and funding. National security in the 21st century requires that government agencies and other organizations—whether at the federal, state, or local level—cooperate quickly and efficiently across organizational boundaries.

At Livermore, we, too, are evaluating our roles and responsibilities to ensure that we have the people, resources, and processes needed both to maintain working solutions and to rise to new challenges. As the Laboratory celebrated its 50th anniversary, the Center for Global Security Research sponsored a series of workshops to assess the future environment of science and technology and their roles in national security. In chairing this project, I was as concerned with defining the attributes of successful research organizations as with the specifics of future research and development to solve new national security problems.

Lawrence Livermore has many of the resources and attributes needed to succeed in and contribute to this emerging world. For example, using our expertise in stockpile stewardship and weapon simulations, we can model other countries' or even terrorists' inferred weapon designs, determine whether they are credible, and if necessary, devise ways to render them harmless. We also are developing tools for nuclear forensics, which will allow scientists to work backwards to determine the source and type of an explosion by examining its debris—technology that could become an essential component of deterrence in the 21st century. The deployment of biological detectors at the 2002 Olympics in Salt Lake City and other efforts after September 11 provided good tests of the multiorganizational world required for national security.

The successful laboratory of the future must be agile—in how it uses its people, in how it develops its processes, and in how it reacts to changing scenarios. Our staff will need not only technological excellence but also interpersonal and operational excellence, especially in understanding the needs and styles of other organizations.

The more we interact with others, the better we will perform against these standards. Successful laboratories may indeed have to "do it all" in the national security arena, but as the past 50 years have shown, Lawrence Livermore has the people, tools, and experience to meet these challenges.

■ Jay Davis joined the Laboratory in 1971. From 1998 to 2001, he served as founding director of the Department of Defense's Defense Threat Reduction Agency in Washington, D.C. He returned to Livermore in 2001 as the first National Security Fellow for the Center for Global Security Research.

Emerging from the Cold War

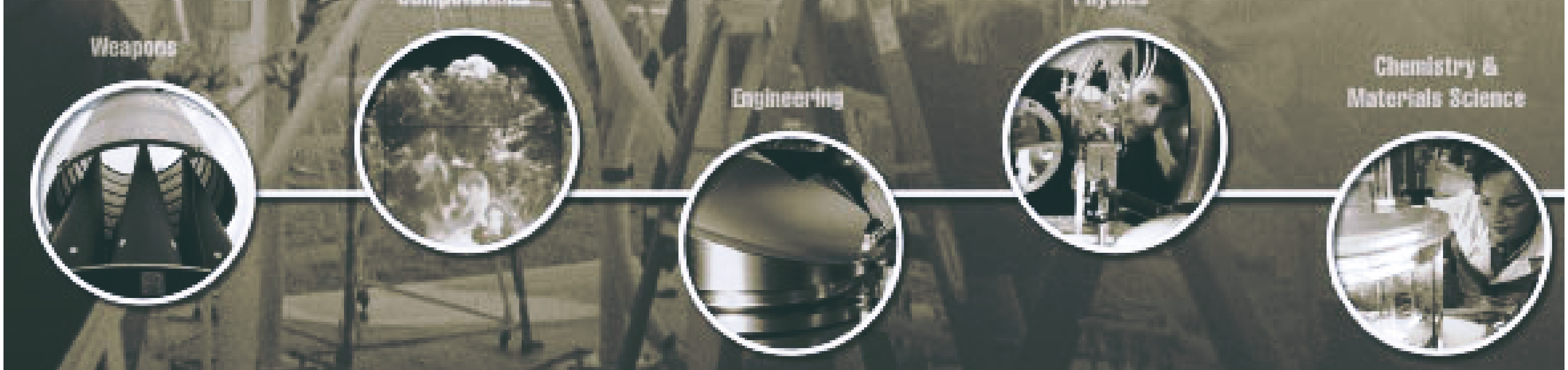
Stockpile Stewardship and Beyond

HISTORIES of the 20th century often celebrate the American spirit that united the country in 1941 after the bombing of Pearl Harbor. The heroism and sacrifice of U.S. citizens, whether fighting on the front lines, building equipment for the military, or rationing supplies at home, marked a great era for this country.

World War II was also a watershed for science and technology research in the United States. Before that war, most scientific research was funded privately. In the 1930s, Ernest O. Lawrence, who later cofounded Lawrence Livermore, built the Crocker Laboratory for housing his fourth cyclotron with contributions from several foundations and individuals, including $75,000 from William Crocker, chairman of the University of California's Board of Regents. But in 1942, the U.S. government found its military ill-equipped for the kind of war it was entering. To bring the military up to date, the government funded an extensive science and technology effort, including the Manhattan Project—a top-secret project in Los Alamos, New Mexico, to build the world's first atom bomb.

"The science of today is the technology of tomorrow."

—Edward Teller



Reviewing the successes from the war-related research and development effort, President Franklin Roosevelt wrote in a letter to Vannevar Bush, director of the Office of Scientific Research and Development, that the lessons learned by the teams conducting this research could be applied after the war "for the improvement of the national health, the creation of new enterprises bringing new jobs, and the betterment of the national living standard." President Roosevelt asked Bush to recommend a new model for research and development that built on the achievements of the war effort.

In July 1945, Bush presented his recommendations to Roosevelt's successor, President Harry Truman, in a report titled *Science: The Endless Frontier*. The ideas presented in the Bush report shaped research and development activities for the remainder of the 20th century. In particular, government funding for research in support of national security increased dramatically, and improved designs for nuclear weapons continued to be developed at Los Alamos.

After the Soviet Union successfully tested its first atom bomb, the government responded by expanding nuclear weapons research. On September 2, 1952, a branch of the University of California Radiation Laboratory was opened at the deactivated Naval Air Station in Livermore, California.

"The founding of our Laboratory was a realization of the Vannevar Bush model," says physicist Kimberly Budil, who is the current scientific editor for *Science & Technology Review*. "Bush's report recommended that military research continue after the war, so the country would never again have to struggle to catch up technologically in a time of crisis. Also, to support industrial research plus help the economy and improve the American standard of living, the federal government was encouraged to fund basic research and provide educational opportunities—especially to returning soldiers—so the U.S. could renew its talent pool for future science and technology efforts."

The focus of the Laboratory in its early history was on meeting national needs for nuclear expertise. Experts in chemistry, physics, and engineering were encouraged to explore innovative solutions to the problems they faced in developing new weapon designs. Over time, not only did Lawrence Livermore achieve notable successes in its national security mission, but it also became one of the world's premier scientific centers—using its knowledge of nuclear science and engineering to break new ground in magnetic and laser fusion energy, nonnuclear energy, biomedicine, and environmental science.

Budil says that reviewing Livermore's history has given her a new appreciation for its founders. "In 1952, many of the first scientists who joined the Laboratory were young, especially to be taking on this kind of challenge. Herbert York was only 32 years old when he became the first director. The relative youth of our founders, along with their enthusiasm for a new challenge, drove the innovative spirit that we see throughout the Laboratory's history."

Innovative Solutions to Complex Problems

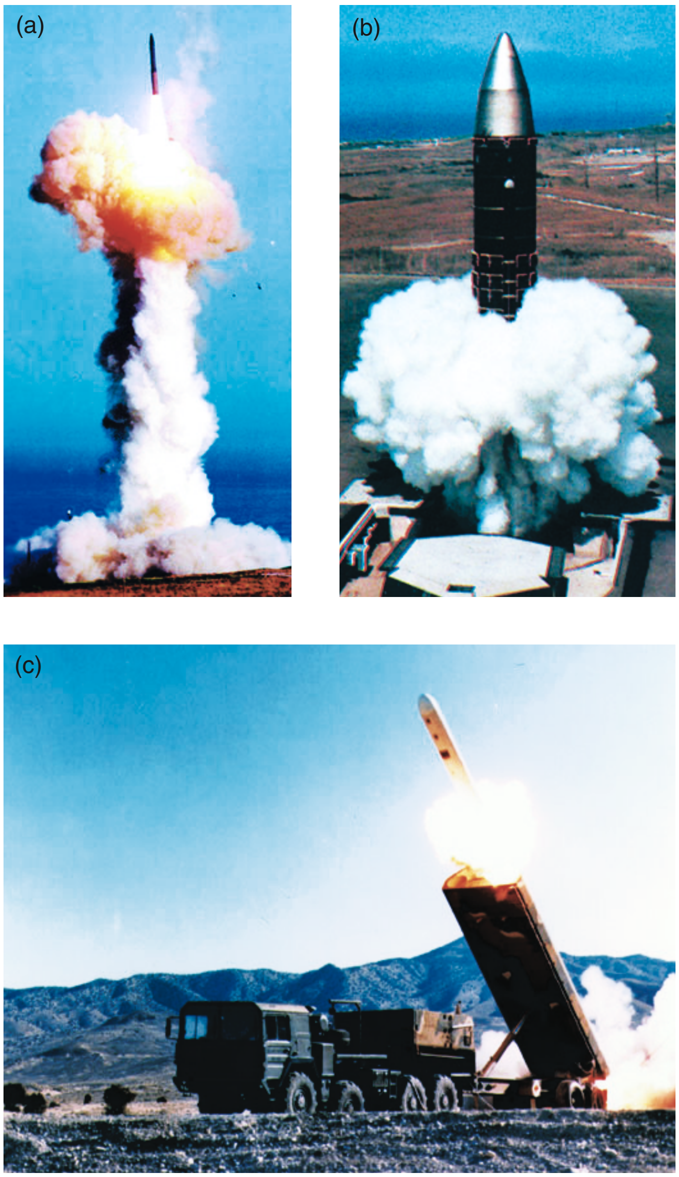
Innovation has been an integral part of Livermore's success. The military requirements for high-yield, low-weight weapons often led researchers to explore new design approaches. For example, in a 1950s project to design a warhead for the Navy's Polaris missile, the Laboratory's goal was to develop a small, efficient thermonuclear weapon that could be carried by submarine. Researchers came up with novel designs for the primary and secondary stages of the weapon to minimize the overall mass of the warhead.

These design improvements had far-reaching effects on future weapon designs. In Edward Teller's autobiography, *Memoirs: A Twentieth-Century Journey in Science and Politics*, he says that the warheads for Polaris greatly improved the nation's ability to deter attack. "That a portion of our retaliatory force would survive a surprise attack guaranteed that the Soviets would never find it advantageous to attempt a first strike."

The success of Polaris also set the tone for research at the Laboratory. Says Budil, "Part of our culture at the Laboratory is a willingness to explore creative solutions so we can find the best approach to the complex issues we need to resolve. That philosophy comes with enormous risk, both for the institution and for individual scientists, but it also offers the potential for enormous gain. Our history is filled with examples

of scientists putting their credibility on the line, risking failure in search of the best solution."

Livermore's multidisciplinary approach to problem-solving was bolstered by the work of scientists and engineers on progressively more complex weapon designs. Because designing a nuclear weapon is an iterative process, weapon



Test launches of three missiles with Livermore-designed warheads. (a) The Minuteman III intercontinental ballistic missile (ICBM) is equipped to carry the W62 warhead, and (b) the Peacekeeper ICBM is equipped to carry the W87 warhead. (c) The W84 warhead, now inactive, was designed for the ground-launched cruise missile.

researchers often found they had to understand concepts and processes outside their assigned disciplines or areas of expertise.

For example, at the beginning of a weapons project, computer simulations were often used to evaluate design options. Then, once a new design was built, it had to be tested to ensure it worked as predicted. To acquire data on weapon performance, Laboratory engineers developed diagnostic equipment and techniques that would operate in the highly volatile environment of nuclear tests. These diagnostics had to record data in a fraction of a second, before the detonation vaporized the detectors, test apparatus, and cables.

In developing the elaborate setup for underground nuclear experiments, everyone involved in a test—engineers, physicists, code developers—had to understand the requirements of the other disciplines. According to Laboratory Director Michael Anastasio, this working relationship fostered an integral program of testing, simulation, and fundamental science. "Our work groups had those same permeable boundaries," he says, "where scientists from computation, design, and experimental science all contributed to achieving the goal of delivering a new device."

This multidisciplinary approach to research has provided added benefits to the nation's science and technology base—an advantage Vannevar Bush might have predicted. "To solve the problems encountered in designing nuclear weapons," says Budil, "Laboratory scientists often find themselves at the forefront of new technology. As a result, Livermore has an amazing history of technological firsts as well as spinoff applications that have benefits outside our national security mission."

For example, Livermore developed increasingly powerful lasers—Janus in 1975, Shiva in 1977, and Nova in 1984—so scientists could study thermonuclear physics in a laboratory setting. Data from laser experiments improved computer modeling capabilities for weapons research and were a valuable supplement to underground nuclear tests. But the benefits of laser science and technology extend well past the nuclear weapon community. Programs in inertial confinement fusion and laser isotope separation were begun as efforts to enhance the nation's energy supplies. Other laser research activities set the stage for improving medical treatments and studying the solar system.

"Such advances in scientific understanding and technology development do not happen merely by chance," says Budil. "They require strong capabilities for basic and applied scientific research. Livermore has stable funding, excellent research facilities, and outstanding researchers—factors that are essential to the success of big multidisciplinary science projects. They've contributed to the Laboratory's success both in weapons research and in other programs such as biotechnology and environmental restoration."

A New Course for Weapons Research

Nearly four decades after Lawrence Livermore was founded, the Berlin Wall was torn down, and the Soviet Union collapsed—the Cold War had been won. Today, the U.S. maintains a much smaller stockpile of weapons, but nuclear deterrence remains an integral part of its national security policy.

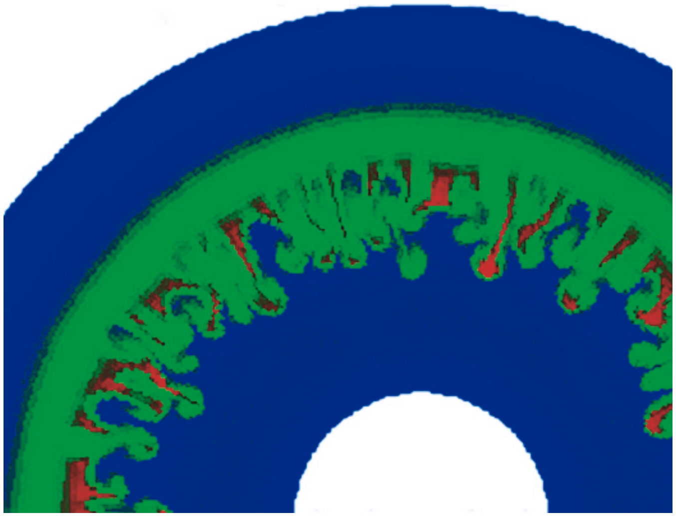
In 1992, President George H. W. Bush declared a moratorium on nuclear testing, and new weapons development ceased. The ending of the nuclear arms race dramatically affected the nation's three weapon laboratories—Livermore, Los Alamos, and Sandia—but their central missions still focused on national security science and technology.

In 1995, President Bill Clinton announced a new program called Stockpile Stewardship—an ambitious effort to improve the science and technology for assessing an aging nuclear weapons stockpile without relying on nuclear testing. For stockpile stewardship to succeed, all aspects of weapons must be understood in sufficient detail so experts can evaluate weapon performance with confidence and make informed decisions about refurbishing, remanufacturing, or replacing weapons as the needs arise.

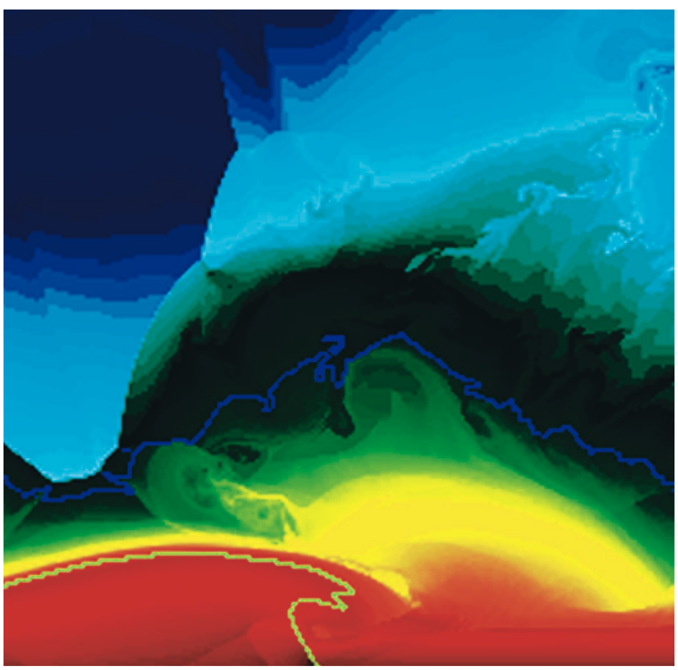
An Annual Assessment Review is conducted on the status of the stockpile. In this process, the secretaries of Defense and Energy receive formal evaluations of the stockpile from the three laboratory directors, the commander-in-chief of the U.S. Strategic Command, and the Nuclear Weapons Council. From those evaluations, the president makes a determination whether the weapons would perform as designed, should they ever be needed, or if nuclear testing is required again to certify performance. (See *S&TR*, July/August 2001, pp. 4–10.)

A view inside the target chamber for the National Ignition Facility (NIF), which is under construction at Livermore. Experiments with NIF will allow scientists to replicate various physical processes at the energy densities and temperatures approaching those in a weapon detonation. The first experiments are planned for 2003.

Aboveground diagnostic setup for an underground experiment at the Nevada Test Site. Data signals from a test explosion moved from the device, 300 meters downhole, up to the surface through cables, and the cables fanned out along the surface to trailers that housed instruments for reading the signals.



Simulation from a Laboratory-developed code run on ASCI Blue Pacific, one of the Advanced Simulation and Computing program's supercomputers at Lawrence Livermore. In this simulation, an arbitrary Lagrangian–Eulerian hydrodynamics code is used to model fluid motion as a function of increasing temperature, pressure, and density (or a Richtmyer–Meshkov instability) in an imploding inertial confinement fusion capsule.



Snapshot of a simulation run on ASCI Blue Pacific. This calculation modeled the density field of an x-ray burst on the surface of a neutron star. The yellow curve is the detonation front, racing across the stellar surface. The blue curve shows how the initial surface of the accreted atmosphere deforms.

Maintaining a safe and reliable stockpile without underground testing required a culture shift for the weapons program. "It changed the fundamental nature of our work," says Anastasio. "In the past, we asked ourselves whether a design would work. Now, with stockpile stewardship, we want to know when weapons fail. To certify reliability in this broader area, we must survey the state of a weapon periodically throughout its life cycle and try to predict when we'll lose confidence in its performance."

Stockpile stewardship was a radical departure for the weapons program in concept, but not in day-to-day activities. "Stockpile stewardship is an extension of how we were already doing business," Anastasio says. "Originally, in designing a weapon, Laboratory scientists would conduct tens of tests to put a weapon in the stockpile. But by 1980, we knew enough about how weapons worked that we could just test them at their performance margins. So we only conducted one to three nuclear tests before certifying a weapon. We also were developing simulation tools to answer questions that had been asked for decades. In effect, we were early pioneers of stockpile stewardship, even though such a program didn't officially exist at that time."

Keys for Successful Stewardship

The basic concepts for the Stockpile Stewardship Program were developed in the mid-1990s under the direction of Vic Reis, the assistant secretary for the Department of Energy's Defense Programs, with input from the Navigators Committee, a small committee of experts from the weapon laboratories. "We knew that certifying weapon performance without underground testing would be a hugely complicated task," says physicist George H. Miller, who represented Livermore on the Navigators Committee. "We'd need a much better understanding of the fundamental physics involved in a nuclear detonation if we were to determine when a weapon would fail."

According to Miller, the committee focused on defining the key features for a successful program of stockpile stewardship. "Experimental capabilities would be crucial. We'd need laboratories where scientists could scale nonnuclear experiments to closely match weapon physics conditions so they could examine properties at the microstructural level. We'd also need to dramatically improve the fidelity of our computer modeling capabilities, so we could more accurately simulate these complex interactions. And perhaps most important, we'd need a new methodology for certifying the judgment and credibility of future stockpile stewards."

From the Navigators Committee meetings and additional workshops led by Reis, DOE created a program that builds on the talent, resources, and capabilities available at the three weapon laboratories. Now administered by the National Nuclear Security Administration (NNSA), the Stockpile Stewardship Program integrates data from past nuclear tests with past and present nonnuclear tests, fundamental science and component-level experiments, surveillance of actual weapons withdrawn from the stockpile, and advanced simulations.

Previous highlights on the Laboratory's 50th anniversary have discussed the new facilities being built at Livermore in support of the Stockpile Stewardship Program. For example, the National Ignition Facility (NIF), a 192-beam laser designed to produce 1.8 megajoules of energy and 500 terawatts of power, will allow scientists to replicate various physical processes at the energy densities and temperatures approaching those that occur in a weapon detonation. (See *S&TR*, September 2002, pp. 20–29.) Miller, who is now associate director for NIF Programs, says, "In effect, NIF will allow us to break apart the physics of a weapon and examine the processes in isolation."

Experimental facilities alone would not provide a robust stockpile stewardship effort. To analyze the new data, scientists also needed vastly improved computer modeling capabilities so they could simulate a weapon in three dimensions from start to finish.

"Just to simulate the physical interactions that we understood," says Miller, "we estimated it would take computing speeds of 100 teraops," or 100 trillion operations per second—nearly 100 times the computer industry's top speed in 1994. "To develop that capability within one decade, we'd need to outstrip Moore's law." That is, Stockpile Stewardship could not wait for computer speed to double every 18 to 24 months—a computer industry standard first predicted in the 1970s by Intel Corporation's cofounder Gordon Moore.

To provide the necessary computing resources, DOE developed the Accelerated Strategic Computing Initiative (ASCI), a multilaboratory effort with strong partnerships in the computer industry designed to push computational power to the 100-teraops level. Now called the Advanced Simulation and Computing program and administered by NNSA, ASCI is producing remarkable results.

"We're seeing unexpected benefits from ASCI all over the scientific community," says Miller. "It's almost a new field—developing three-dimensional codes to run on the big computers, like the ASCI White machine here at Livermore. It's improving our scientific understanding in biology, chemistry, basic physics—every area of science." (See *S&TR*, June 2000, pp. 4–14.)

Miller believes NIF experiments, which are planned to begin in 2003, will also enhance scientific capabilities in many research areas besides weapon physics. For example, NIF will give astrophysicists their first laboratory setting for studying astronomy and should greatly improve their understanding of space physics. (See *S&TR*, May 2001, pp. 21–23.) "It's breathtaking science," Miller says. "Once again, we're reminded that when the federal government invests in high technology, there are surprising spinoffs that benefit the nation in many ways."

Training the Next Generation

As with Laboratory projects over the last 50 years, Livermore's stockpile stewardship work is a multidisciplinary effort, involving researchers from many directorates, including Defense and Nuclear Technologies, Engineering, NIF Programs, Chemistry and Materials Science, Computation, and Physics and Advanced Technologies. (See *S&TR*, March 2001, pp. 23–25;

Livermore's largest two-stage gas gun, which is 20 meters long. The gun's projectile flies down the barrel at speeds up to 8 kilometers per second and, upon impact, produces a shock wave millions of times the pressure of air at Earth's surface. Gas-gun experiments such as this one, which is being set up by technicians Leon Roper (left) and Keith Stickles, allow scientists to improve their understanding of the physics of shocked fluids and condensed matter—an important part of the nation's Stockpile Stewardship Program.

May 2001, pp. 24–26; July/August 2001, pp. 18–20.) Not only does the Stockpile Stewardship Program help the nation maintain its nuclear deterrent, but it is also helping Lawrence Livermore maintain its capability base to respond to future national needs. In particular, the program provides the technological challenges that scientists need to hone their problem-solving skills and build the scientific credibility that is a hallmark of the nation's weapon laboratories.

According to Anastasio, training the next generation of weapon scientists is imperative when the nation's nuclear deterrent is maintained in the absence of nuclear testing. "The test moratorium is 10 years old," he says, "and many of today's stockpile stewards have no experience designing a weapon or fielding a test. NNSA's Stockpile Stewardship Program is designed to help this generation of scientists gain the kinds of experience that we used to get with underground testing."

Multidisciplinary research is especially important for the program to succeed. By building new research facilities and computing capabilities, NNSA is combining experimental laboratories with computational laboratories so that physicists, code developers, engineers, and technicians can work in teams to solve stockpile-related problems. For example, ASCI code designers are working closely with physicists, chemists, material scientists, engineers, and others from the weapons program to validate the new codes used to model weapon physics. "We're working together to model real physics and to validate the codes against experimental data from our underground experiments," Budil explains.

NIF will provide the same cooperative research opportunities on the experimental end of stockpile stewardship. The power of NIF will allow scientists to perform weapon-relevant experiments in an aboveground nonnuclear environment. Nevertheless, setting up experiments and diagnostics will be an immense challenge, similar in many ways to preparing for a test at the Nevada Test Site.

"In the past, a designer's career record in the test program gave him or her credibility," says Budil. "For example, George Miller's opinions about nuclear weapons and how they work have the weight and credibility of his extensive experience. Without a test program, how does the Laboratory maintain its expertise and the public's confidence?"

To develop this experience and credibility, says Anastasio, Laboratory managers must allow scientists to once again follow the bold ideas that lead to innovation. "Livermore cannot become a risk-adverse institution if we are to maintain our creativity and flexibility in responding to the technical demands of national security. We must give scientists a chance to fail. We must let talented people put their technical reputations on the line—let them experience a few sleepless nights and confront the reality that an experiment might not work—so we can certify their credibility at making such critical decisions."

According to Miller, this need to challenge and test a scientist's judgment is one reason the nation has benefited from having competition between Lawrence Livermore and Los Alamos national laboratories. "When someone is diagnosed with a serious disease—a disease that, even with the best medical science, is still understood imperfectly—the patient wants to get more than one opinion." For the past 50 years, the nation has used this same approach with nuclear weapons. By having two independent weapon laboratories, the federal government has two sources of independent advice. And, Miller says, "Should the experts disagree—whether we're talking about medicine or

The U1a complex at the Nevada Test Site. The complex consists of several buildings and instrumentation trailers from which scientists can monitor experiments conducted underground. Today, the complex is used for subcritical experiments, which provide data to complement those from past underground nuclear tests.

weapon physics—it's possible that something is being missed." By building research facilities and new technology capabilities to be used by researchers at more than one laboratory, the Stockpile Stewardship Program ensures that the nation continues to have independent sources of expertise, each with credible histories in weapons research and the necessary research tools.

The Future of the Laboratory

Anastasio says that the future for Lawrence Livermore is both exciting and sobering. "September 11 reemphasized our mission. The nation is facing unprecedented security challenges. At Livermore, we must use our science and technology to build capabilities that serve the national interest."

As with the activities for stockpile stewardship, the Laboratory's role in research and development for homeland security is emerging from its ongoing work in nonproliferation and counterterrorism. "The scope of homeland security is daunting," says Anastasio. "The nation needs tools and technologies to prevent attacks, reduce threats, and manage the aftermath, areas we have long been working in to develop the relevant technical capabilities. Unfortunately, there's no silver bullet—no single technological widget—to solve this extraordinarily complex problem, and a layered, system-level approach is required."

An important part of this effort will be assessing the risks and balancing competing priorities while implementing solutions. In developing the nation's nuclear deterrent and maintaining the stockpile, researchers at Livermore have demonstrated the capability to work problems from end to end, and they build on this approach to problem-solving in projects for homeland security. "To focus our research in the right areas," says Anastasio, "we must understand not only what threats are facing the nation, but also what is needed to counter them." Researchers no longer focus solely on military applications for new technologies but rather are developing tools that can be used in various venues—from airports, hospitals, and post offices to theaters and sports arenas.

"We are developing real products that we can put in the hands of the end users," Anastasio says. "Once new technologies are developed, we'll transfer them to U.S. industry and then train the end users so these new tools can be deployed effectively."

Such activities are not new to the Laboratory. Many of Livermore's mission responsibilities and programs are relevant to homeland security and provide the Laboratory's scientists with an excellent overall perspective of the threats, technical opportunities, and user needs. "Homeland security will be an enduring national security mission for the Laboratory," says Anastasio, "With our successful track record of scientific innovation and technology development, we can provide effective solutions for this long-term endeavor."

Science and Technology in the 21st Century

Part of Livermore's 50th anniversary celebration has been to look at the future of science and technology in the context of national security and opportunities for the Laboratory. To foster this discussion, the Center for Global Security Research (CGSR) sponsored a 2002 Futures Project called "Science and Technology for National Security: The Next 50 Years—Pioneering the Endless Frontier," a series of workshops designed to examine the interactions and conflicts of science and technology, national security, and globalization. The CGSR workshops did not focus on predicting future technologies or national needs. Instead, participants were encouraged to identify the trends that intersect these three spheres of influence because the difficult challenges of the future will most likely involve issues at this interface.

Eileen Vergino, CGSR deputy director and cochair of the Futures Project, said, "Through these workshops, we not only wanted to examine the science and technology requirements imposed by national security. We also wanted to evaluate the inherent challenges and constraints to security that may be caused by science and technology breakthroughs and by globalization in the next 50 years."

One important goal of the Futures Project was to facilitate discussions between communities that rarely interact. Workshops included science advisors at federal agencies, fellows from the American Association for the Advancement of Science, other social scientists and experts in policy and national security, undergraduate honors students at Pennsylvania State University, and some of the younger scientists at Livermore, who may lead the Laboratory in the future. "We wanted to bring a lot of bright minds together and get them talking to each other," says Jay Davis, CGSR's first National Security Fellow and the other project cochair. "We asked a lot of questions and then gave the participants time to discuss the issues we brought up so they could examine problems and opportunities from multiple viewpoints."

Vergino notes that the terrorist attacks of September 11 serve as a cogent example of the interplay between the forces of globalization, national security, and science and technology. "Because of recent advances in communication technology, such as cell phones and the Internet, we can quickly correspond with people around the world," she says. "These new tools can also empower small, geographically dispersed groups, who can become a threat to national security merely by exploiting existing technology."

As a result, the U.S. can no longer focus its national security policy primarily on threats from one superpower or nation–state, as it did during the Cold War. Instead, it must plan for a complex world of competing smaller-scale threats, many of which can quickly inflict disastrous, long-term consequences.

"A serious concern where science and technology threaten security is bioterrorism or even an outbreak of a naturally occurring disease," Budil says. "And this threat is not only to the United States, but to the global community. With the ease of international travel we have today, a disease outbreak in one country can quickly spread across the world."

Workshop participant Robin Newmark adds, "Many aspects of our lives have changed since September 11, and as a nation, we're trying to sort out the conflicts that arise between implementing an effective homeland security policy and protecting the personal freedoms that we hold dear. In a very short time, we've learned to accept that we might be searched before we enter a sports arena or board a plane to visit our grandmother."

Newmark, who leads Livermore's Geosciences and Environmental Technologies Division, says research laboratories such as Livermore have an important role to play in addressing these new security issues. "For the short term, we can modify our current tools and apply them to the security problems. But we also need to find better technologies for addressing these issues. By asking difficult, open-ended questions, the facilitators at the CGSR workshops are helping us consider these problems from many viewpoints."

Finding solutions to technically challenging problems requires devoted attention over the long term, and for that, researchers must have stable funding. Vannevar Bush's model for government funding of basic science research has been used effectively since World War II. But Newmark asks, "What would happen to research institutions like Livermore if our funding sources change in the next 50 years? What if universities must rely on corporate sponsorships? We also must consider how these changes might alter the focus of our research and what opportunities they might bring."

Of course, advances in any science can have unexpected social costs, and participants in the CGSR workshops were asked to consider the ramifications of future research and development efforts. For example, says Davis, "If we were to cure cancer or cardiac disease, what effect might that have on retirement plans

Example trends that intersect the three spheres of influence—national security, globalization, and science and technology—as identified by workshop participants in the Center for Global Security Research's Futures Project. The difficult challenges of the future will most likely involve issues that intersect the three spheres.

and health-care programs? Can we envision a way to protect our economy? Furthermore, in an increasingly globalized world, do our efforts to stop research in a particular area, such as stem-cell research, serve to simply move that research to another country where we can no longer benefit from it or provide ethical guidance on its application?"

Budil adds that this kind of brainstorming, where participants not only contribute ideas but also evaluate the consequences of each choice, allows scientists to exercise their skills at making connections across disciplines—a skill that often leads to innovative uses of old technologies. "One of the great innovations to come from the Laboratory's weapons program is PEREGRINE," she says. (See *S&TR*, June 2001, pp. 24–25.) "Who would have guessed 20 years ago that we could spin off a tool for planning cancer radiation treatments by combining our expertise in Monte Carlo modeling and radiation transport? But those are the connections that scientists can make in a multidisciplinary environment such as this Laboratory, and the CGSR workshops encourage the discussions that lead to such connections."

The final workshop was held in September 2002, in conjunction with Livermore's 50th anniversary celebration, and a report on the Futures Project will be issued in the next fiscal year. Says Vergino, "It's clear from the discussions we've had that U.S. national security depends on maintaining our lead in science and technology. The nation must continue to support a strong, flexible capabilities base, as it has since World War II. To respond quickly in times of crisis, our government needs talented scientists and engineers—people who can understand complex problems, rapidly analyze scenarios, and then integrate systems to implement strategic solutions, whatever that might be." (For more information on CGSR, see *S&TR*, June 1998, pp. 10–16, and September 2001, pp. 11–18.)

According to Lee Younker, associate deputy director for science and technology, the greatest success of the Futures Project is that it stimulated the thinking of the participants. The project also helped Livermore's senior managers to refine their ideas for how the Laboratory's role might evolve over the next 50 years. "The defining events for the United States affect national priorities," says Younker, "and they often refocus the nation's attention on its science and technology infrastructure. National laboratories must be prepared to respond quickly in critical times by devoting people and resources to the research areas where they can have an immediate effect on problems of national importance."

Innovative Science Is a Moving Target

In its 50th anniversary year, Lawrence Livermore faces new challenges. Nuclear weapons remain part of the nation's security policy, but the number of weapons in the stockpile has declined dramatically. The nature of national security is evolving, and the Laboratory must follow that evolution to maintain its vitality. Thus, Livermore's senior managers must determine how the Laboratory can best contribute to its evolving security mission and which capabilities will complement other national needs.

Younker says that part of Livermore's success stems from the stable funding it has received for weapons research. "We're a superb laboratory when we have resources to do what we do best." In today's economy, few industries can afford to work on large-scale basic science research or technology development because they need a quicker return on their investment as determined by market forces. Federal funding of science and technology projects, such as nuclear weapons research or the space program, typically has a much longer-term horizon and thus has provided a tremendous benefit for the country. But Livermore's senior managers know the Laboratory must continue to evolve, as it has under the Stockpile Stewardship Program, so the institution and its capabilities base can remain a vibrant national resource for the next 50 years.

"We can predict the future all we want and be wrong," Miller says. "What's important is for the nation to have a system that provides capabilities and flexibility so the country can respond to whatever threatens us. We can't sit back and wait—our enemies will find a way to attack us if we remain static. Instead, we must use periods of relative peace, as we've had more or less for the last 50 years, to try to push our knowledge and technology in a positive direction and prepare for times of crisis."

"In one sense," says Anastasio, "the future of Lawrence Livermore is to be the thing we've always been, and that is a laboratory of outstanding people who can get work done—who are flexible, responsive, and make great contributions to our country."

—Carolin Middleton

Key Words: Center for Global Security Research (CGSR) Futures Project, nuclear test moratorium, post–Cold War science and technology, stockpile stewardship, underground nuclear testing, Vannevar Bush.

For more information on the Center for Global Security Research:

www.llnl.gov/nai/cgsrjd/cgsr.html

For Vannevar Bush's complete report,* Science: The Endless Frontier*:

www.nsf.gov/od/lpa/nsf50/vbush1945.htm

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

www.llnl.gov/50th_anniv/

Chemist Andrew Vance working in his laboratory.

Machines from Interlocking Molecules

IMAGINE a mechanical device created from a handful of molecules. Such a device could be a sensor that can detect infinitesimal traces of chemicals or biological agents, or it could be an on–off switch, a miniature building block for creating molecular computers. These ideas are moving closer to reality because of recent work on mechanically interlocking molecules at Livermore.

Unlike molecules that are joined by covalent bonds (by sharing pairs of electrons), mechanically interlocking molecules are physically joined, in the same way as the links in a chain or the rings in the Olympic Games symbol. Mechanically interlocking molecules are of growing interest to synthetic chemists, such as Livermore's Andrew Vance, who view them as potential building blocks for future molecular-scale devices—motors, sensors, and machines on the nanometer scale.

Vance heads up an effort originally funded through Laboratory Directed Research and Development to find new mechanically interlocking molecules that will consistently attach in a single layer on a gold surface. The team, which includes Vance, physicists Anthony Van Buuren and Art Nelson, and University of California at Davis physics graduate student Trevor Willey, is focusing on molecules known as catenanes and rotaxanes. A catenane has two or more interlocking rings. A rotaxane consists of a long, straight molecule—an "axle"—ringed by a doughnut-shaped molecule. Molecular "caps" at both ends of the rotaxane's axle keep the ring from sliding off. No chemical bond holds ring to ring or ring to axle.

Vance notes, "Interlocking molecules in solution are well understood, but not much is known about them on surfaces. Questions such as which molecules attach best, what's the best way to determine how well they're attached, and how to make the attachments stable are virtually unexplored."

Looping the Loop

The team started by exploring what kind of molecules worked best for forming a loop on a gold surface. Forming loops is the first step toward creating a monolayer of catenanes, in which each attached loop would thread a ring. Vance explains, “We started at the most fundamental level, looking at how different molecules attached to the surface and how well they attached.” The challenge was to come up with a molecule that would consistently attach at not just one but both ends.

The team first tried a linear dithiol monomer. (A thiol is a molecule that has an atom of sulfur bound to an atom of hydrogen. This particular monomer had a thiol at each end; hence, it is a dithiol.) The monomer was, according to Vance, “a floppy molecule.” The researchers reasoned that when the sulfur atom at one end attached to the gold surface, the molecule would flop over and the sulfur at the other end would also attach, forming a loop. But measurements taken with x-ray absorption (XAS) and x-ray photoemission spectroscopy (XPS) at the Laboratory and at Stanford’s Synchrotron Radiation Laboratory revealed that only about 50 percent of the sulfur atoms had bonded to gold. (See the box, below right.) “In other words, most of the monomers had one unattached sulfur,” says Van Buuren.

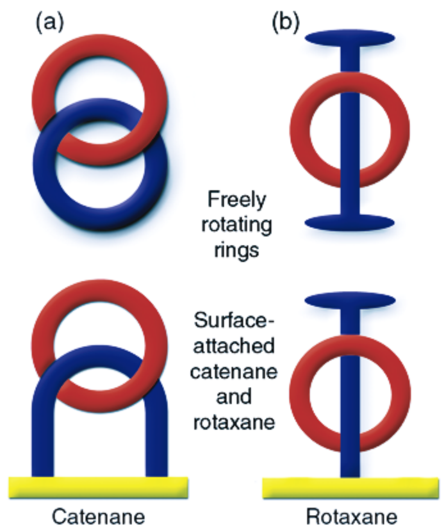
Other measurements indicated that these monolayers were disordered and had molecules that, on average, were tilted slightly more than 55 degrees from the surface. “All these data indicated that most monomers were essentially standing on end on the surface,” notes Van Buuren. Because the concentration of monomers was quite high, the suspicion is that the monomers packed the surface, leaving little room for them to flop over and make a loop.

Another set of experiments used a polymer containing disulfide components. (A disulfide is two atoms of sulfur bound to each other.) In this case, the scientists expected the disulfide bonds to cleave, the sulfurs to bind to gold atoms, and the polymer to form a loop. XPS measurements showed that the resulting monolayer contained over 90 percent of bound sulfurs, evidence that nearly all the molecules had successfully formed surface-attached loops.

“The presence of a disulfide made it more likely that both sulfurs would attach to the surface,” says Vance. “All this pointed out the importance of designing molecules that will bind to surfaces in a predictable manner to form monolayers. In the case of surface-attached loops, simply preparing compounds with end components that bind well to the surface doesn’t guarantee loop formation. Other factors come into play, including the solution concentration and the shape of the molecule. Following these initial results, we also looked at molecules with built-in turns that encourage loop formation over single attachment.”

Of Axles and Rings

Next, team members turned their attention to attaching rotaxanes to gold. As in the previous experiments, the team took two different approaches. One involved an electron-deficient, positively charged T-shaped thiol (which had the characteristic sulfur–hydrogen bond at one end and an anthracene stopper at the other) and an electron-rich crown ether ring. In solution, the two molecules are drawn to each other. The thiol threads the crown ether to form a pseudorotaxane with only one stopper. “Our question was whether the pseudorotaxane would then attach to the gold, or would the crown ether ring slip off, leaving only a thiol to attach to the surface,” explains Vance. Vance also synthesized a [3]rotaxane composed of three molecules: two crown ether rings threaded by an antracene-capped thiol with a disulfide bond in the middle. “From our work with loops, we felt



(a) Catenanes are formed from two or more molecular rings interlocked like links in a chain.
(b) Rotaxanes are formed from a ring molecule threaded on an “axle” molecule capped by two molecular stoppers.

X-Ray Vision

To “see” what was happening with the synthesized molecules and the gold surface, the physicists in Andrew Vance’s team used two techniques—x-ray absorption spectroscopy (XAS) and x-ray photoemission spectroscopy (XPS). Both techniques use x rays from the soft end of the spectrum (with wavelengths between those of ultraviolet light and harder, medical x rays). For the photoemission measurements, the team used the soft x rays created by a beamline at the Stanford Synchrotron Radiation Laboratory as well as a newly acquired Physical Electronics Quantum 2000 scanning XPS system here at Livermore.

The two techniques enable scientists to obtain detailed and specific information about the monolayers under scrutiny. According to physicist Trevor Willey, XPS measurements reveal the chemical composition of what’s on the surface as well as the nature of chemical bonds between the surface and the material. “We used XPS to determine whether the sulfur atom of the thiol was bound to gold or whether the thiol was just lying on the surface, essentially unattached,” he explains. Measurements with XAS revealed the orientation of the molecule. “With XAS, we could tell whether the thiol molecules were standing up, lying down, or leaning in some direction relative to the gold surface,” Willey says. “This also gave us information on how well ordered the layer was—that is, whether the attached molecules were packed together in ordered domains or leaning randomly every which way.”

confident that when the disulfide bonds cleaved, we'd get surface-attached rotaxanes," says Vance.

The team's physicists took spectra of powder samples of the crown ether rings, anthracene caps, and [3]rotaxane for reference as well as a spectrum of thiol attached to gold. When the experimental results were compared to these control spectra, the spectra from the [3]rotaxane experiments did indeed show surface-attached rotaxanes. However, the spectra from experiments with the pseudorotaxane precursor were identical to that of simple thiol on gold.

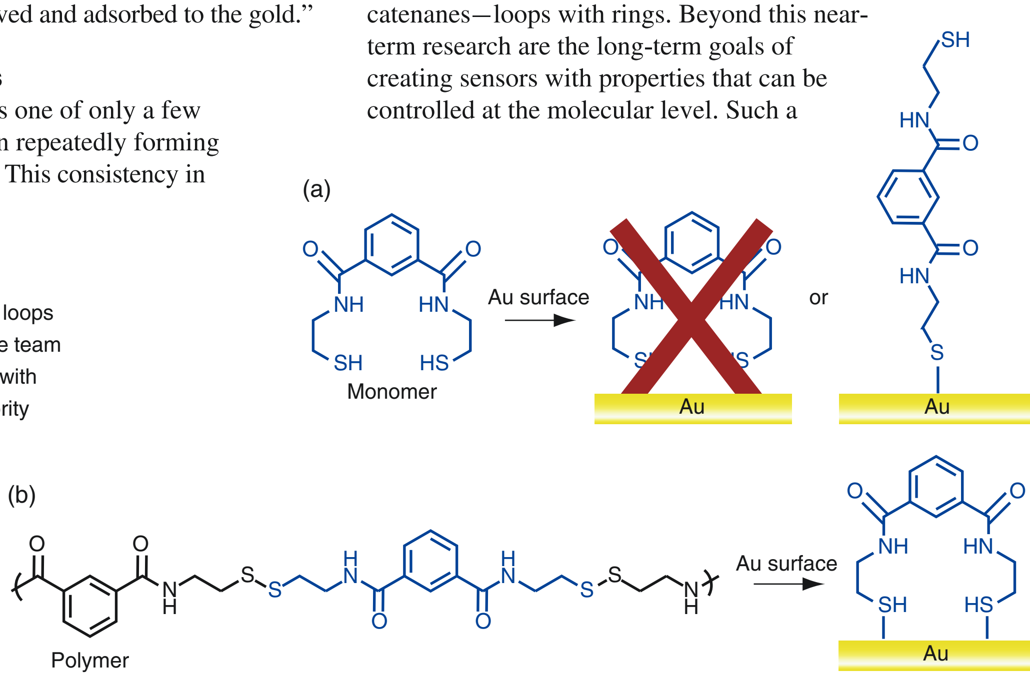
"The results confirmed that even though we'd set up a process for the thiol to thread the rings in solution, the rings came off before the sulfur could attach to the gold," says Vance. "For the [3]rotaxane, the rings were locked into place by the endcaps right up until the two sulfur atoms cleaved and adsorbed to the gold."

Links to Future Possibilities

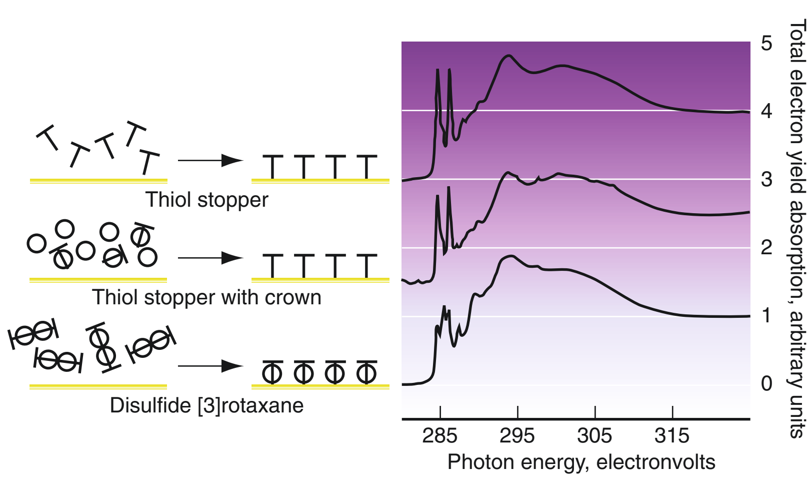
To date, the Livermore team is one of only a few groups that has been successful in repeatedly forming rotaxane monolayers on surfaces. This consistency in results is important if such surface-attached molecules are to become molecular machines of the future.

The success of Vance and his colleagues has led to a collaboration with a group from the University of California at Los Angeles (UCLA) led by chemistry professor and researcher Fraser Stoddart, one of the world's foremost experts in the synthesis of rotaxanes and catenanes. Vance's team has been taking interlocking molecules created by the UCLA group, attaching them to surfaces, and using XAS and XPS to examine the results.

In addition, the team continues its fundamental studies of surface attachment and is beginning to explore attaching molecules to other surfaces, including silicon. Furthermore, they are working on ways to create surface-attached catenanes—loops with rings. Beyond this near-term research are the long-term goals of creating sensors with properties that can be controlled at the molecular level. Such a



The team experimented with creating loops from different molecules. (a) When the team tried to attach monomers terminating with sulfur–hydrogen bonds, the vast majority attached at just one end instead of forming the hoped-for loop on gold. (b) A polymer with disulfide linkages was far more successful in attaching its sulfurs to the gold surface.



Results of surface-attached rotaxane research. Researchers started with thiols in solution (T-shaped molecules), attached them to gold, and used the resulting spectrum from x-ray absorption spectroscopy as a reference. Beginning with crown ether rings and anthracene-capped thiols in solution, researchers attempted to create pseudorotaxanes (single rings on axles capped at one end) and attach them to gold. The resulting spectrum was nearly identical to the reference, indicating that almost all the rings slipped off before the thiols attached. But using disulfide [3]rotaxane—two rings threaded on a thiol and restrained by anthracene endcaps—was effective in creating a surface-attached rotaxane. The resulting spectrum shows peaks similar to the reference spectrum for rotaxane powder.

sensor might have arrays of surface-attached catenanes with rotating rings that have tunable properties.

"By controlling the rotation of the ring, for instance, we can create an on–off switch," Vance explains. "Suppose you could create a ring that has a small hydrophobic component. In the presence of a water molecule, it would spin one way; without water present, it would spin the other way. You could also create rings that are electrochemically or optically reactive and turn them on or off by changing the charge at the surface or by the presence or absence of light. Developing these switchable features is on our list of plans for the future."

Vance believes the combination of synthetic chemistry and spectroscopy, chemists and physicists is a critical element in making this research possible. "What we're doing now," he continues, "is fundamental science that has intriguing possibilities. In the future, these surface-attached interlocking molecules could be used in molecular machines, sensors, and electronics in ways we've yet to even imagine." It all comes down to being able to understand and control these small structures on the molecular and atomic level. And it's a combination of chemistry and physics that, in the end, will make this possible.

—Ann Parker

Key Words: catananes, molecular machines, rotaxanes, Stanford Synchrotron Radiation Laboratory, surface-attached mechanically interlocking molecules, x-ray absorption spectroscopy (XAS), x-ray photoemission spectroscopy (XPS).

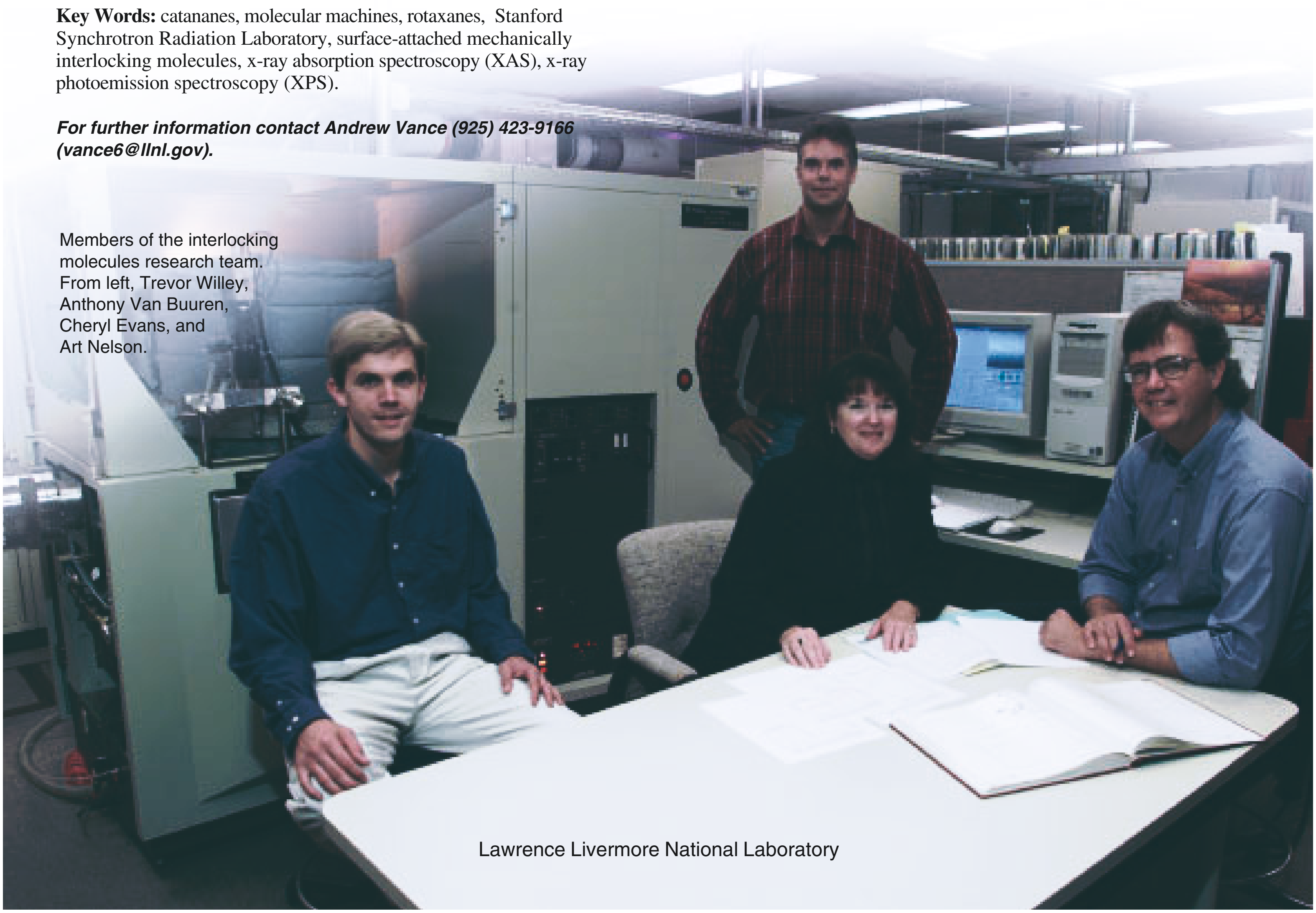
For further information contact Andrew Vance (925) 423-9166 (vance6@llnl.gov).

An Idea Whose Time Has Come

Nearly a century ago, Richard Martin Willstätter, a German chemist destined to win a Nobel Prize in chemistry for synthesizing complex organic molecules, raised the possibility of interlocked molecular rings. It took until the early 1960s for synthetic chemists to invent procedures for forming such molecules in the laboratory.

One such method invoked brute statistics. Mix a huge number of ring-shaped molecules with U-shaped molecules inclined to form rings in solution, and by sheer statistical chance, the linear molecule will thread the circular molecule before forming a ring. The first catenane resulted from such a threading process.

Nowadays, synthetic chemists such as Livermore's Andrew Vance use a method called template synthesis, which offers far more control over the synthesis of these structures. Template synthesis techniques use metal ions or noncovalent interactions such as hydrogen bonding, which force the stringlike molecules to thread the rings, providing a less hit-or-miss way to create catenanes and rotoxanes.



Members of the interlocking molecules research team. From left, Trevor Willey, Anthony Van Buuren, Cheryl Evans, and Art Nelson.

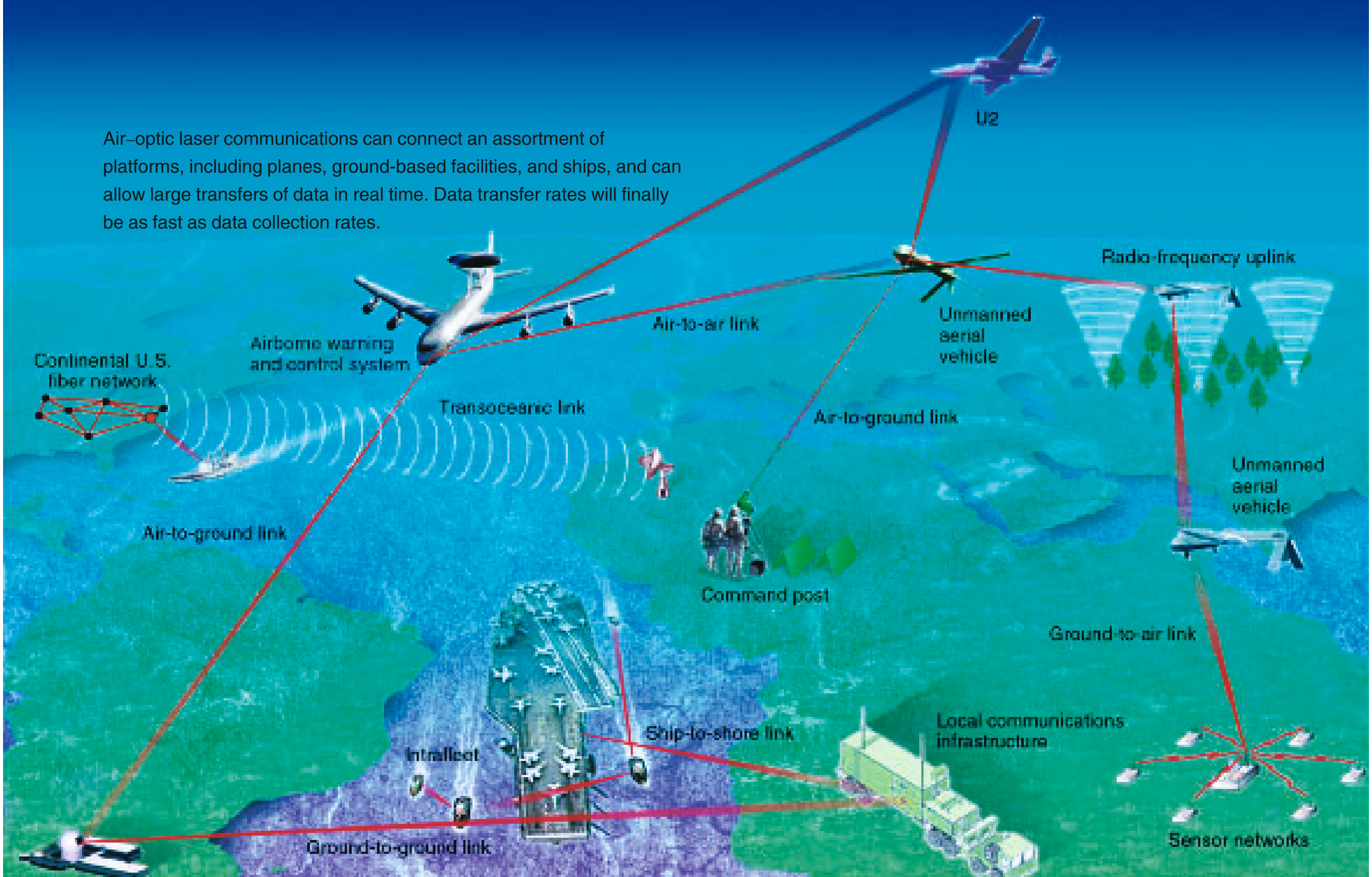
Laser Zaps Communication Bottleneck

BACK in February, the first laser communication link between Lawrence Livermore and the top of the 915-meter-high Mount Diablo, 28 kilometers away, transmitted data at 2.5 gigabits per second on a single laser channel, a rate comparable to 1,600 conventional T1 (local area network) data lines, 400 channels of television, or 40,000 simultaneous phone calls. "That event was one of the longest terrestrial high-capacity air–optics links ever," says Tony Ruggiero, principal investigator for the project.

Even though there's the ever-present beeping of cell phones, buzzing of pagers, and notices popping up that you've got mail, users still demand better, faster communications. The demand is especially high from the military, whose highly sensitive, remote, sensor-based intelligence, surveillance, and reconnaissance (ISR) systems collect massive quantities of data.

Tremendous improvements have been made on data collection capabilities. Now the challenge is delivering data for timely evaluation and action. "Advanced sensors can collect data at rates of up to a gigabit per second," notes Ruggiero. "But the fastest that the data can be transmitted is currently 270 megabits per second using state-of-the-art radio frequency links." For most ISR applications, data from several types of sensors must be aggregated to be useful, driving the total data collection rate into the tens of gigabits per second and creating a massive bottleneck.

Since the February test, Ruggiero's project, the Secure Air–Optic Transport and Routing Network (SATRN), has closed the link between the Laboratory and Mount Diablo at 10 gigabits per second using four 2.5-gigabit-per-second channels running at slightly different wavelengths. The team



Air–optic laser communications can connect an assortment of platforms, including planes, ground-based facilities, and ships, and can allow large transfers of data in real time. Data transfer rates will finally be as fast as data collection rates.

collected extensive performance data under a variety of atmospheric and weather conditions. Soon, Ruggiero expects to be delivering data via a laser beam at the rate of 100 gigabits per second.

The success of the SATRN project may finally give the U.S. military the means to eliminate the bottlenecks that have hindered information transfers to date. Data will also be able to move quickly and securely among various kinds of platforms—between a moving plane and ship, for example, or from a plane to a ground-based facility.

Reducing the Response Timeline

"The bad guys feed off latency—the delay between gathering intelligence and being able to use it," says Ken Israel, former director of the Defense Airborne Reconnaissance Office.

Latency is a challenge when, for example, ISR sensors onboard an unmanned aerial vehicle (UAV) detect enemy activity. As shown in the figure below, the chain of events that follows the detection is to reorient sensors to gain additional information and then use high-resolution imagery to verify the activity, target it, and finally destroy it. Reducing this sensor-to-shooter timeline is a primary goal of the SATRN project.

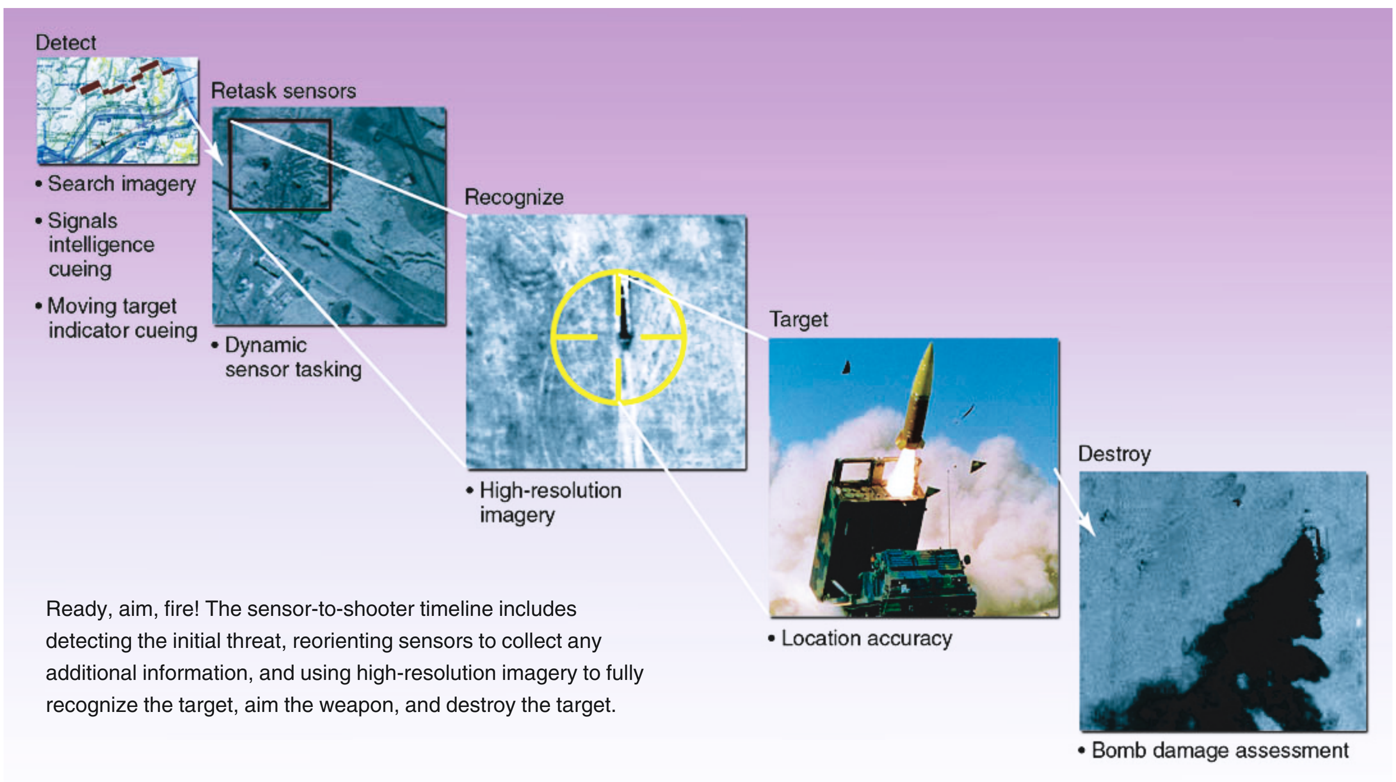
Today, about 30 minutes of image data from the UAV would take 83 days to transmit over a 56-kilobit ISDN (digital phone) line, 3 days over a T1 line, or 15 minutes over the best transfer technology available. With a 1-gigabit-per-second laser communication line, data transfer would occur in real time. Verification, targeting, and destruction would follow almost immediately.

"With data transfers at 40 to 100 gigabits per second, multiple sensors could be combined in a single platform," says Ruggiero. "A UAV could carry synthetic aperture radar, signal intelligence, and video, and all of them could be transmitting information at once to the decision makers in command."

New Technologies Make It Work

Laser communication is already in use but only to transmit information very short distances, typically from 100 to 500 meters and usually between buildings. Extending laser communication over longer distances and between mobile platforms has been hampered by the effects of the atmosphere on the laser beam.

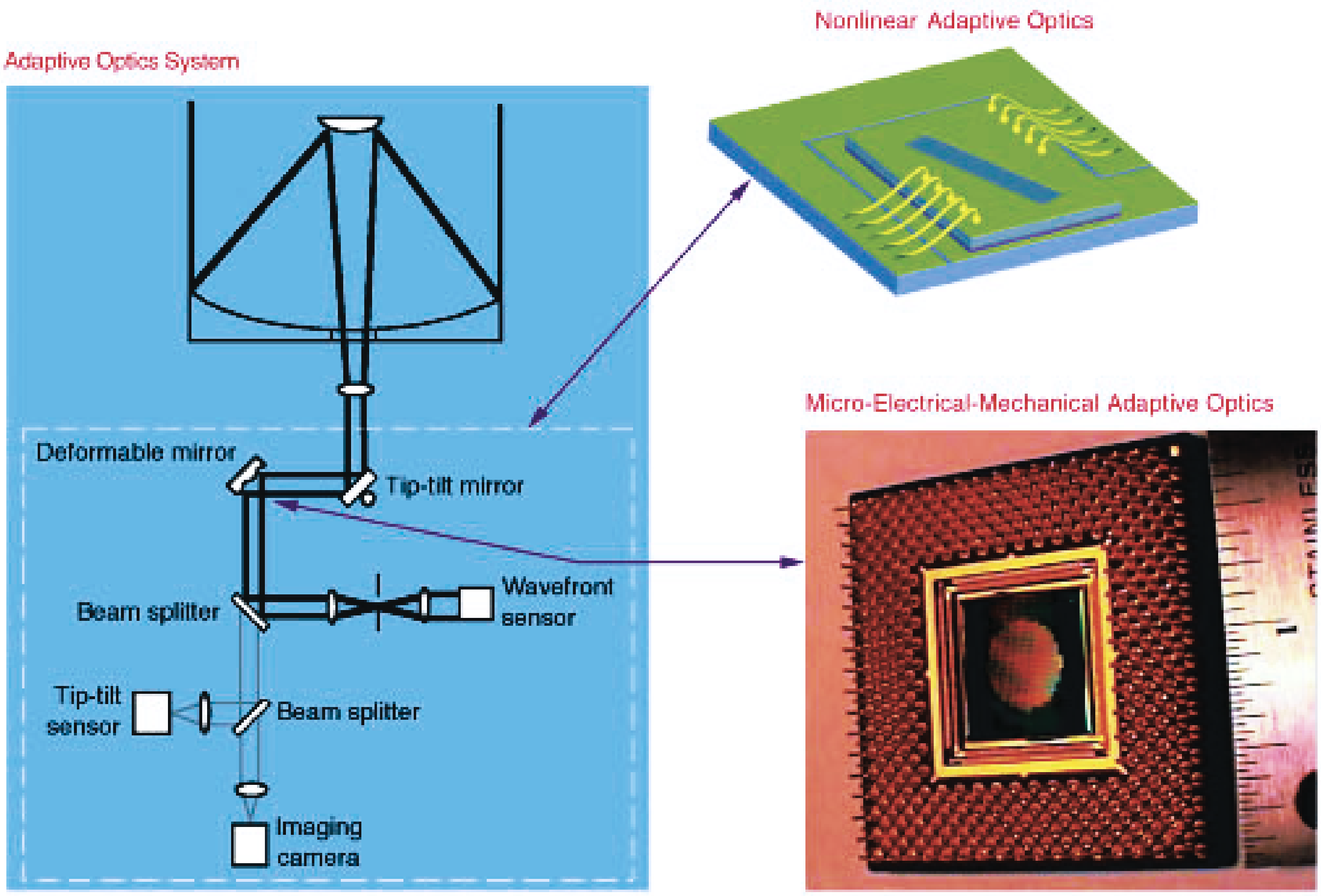
The atmosphere is composed of random pockets of slightly varying temperature that destroy the spatial properties of an



Ready, aim, fire! The sensor-to-shooter timeline includes detecting the initial threat, reorienting sensors to collect any additional information, and using high-resolution imagery to fully recognize the target, aim the weapon, and destroy the target.

electromagnetic beam and cause the beam's intensity to fluctuate at the receiver. This is a much greater problem for the shorter wavelengths used in laser links than it is for radio and microwaves. Atmospheric attenuation—the interaction of the laser beam with gases and particulate matter in the air—is another problem that causes an overall reduction in the detected power level of the beam. At the same time, atmospheric turbulence causes the beam to break up, spread, and wander, so that its power fluctuates. Livermore's SATRN team is developing several innovative technologies to cut through the atmosphere, minimize beam fading, and amplify the power of the beam.

Cutting through the atmosphere to maximize transmitter and receiver beam coupling can be done most efficiently with adaptive optics. Livermore-developed adaptive optics systems have already proved their mettle in astronomical observatories, where they mitigate the atmospheric disturbances that prevent astronomers from having a clear view of stars. (See *S&TR*, July/August 1999, pp. 12–19, and June 2002, pp. 12–19.) For SATRN, the team is producing two versions of adaptive optics to enhance laser communications. One is based on micro-electrical-mechanical systems and builds on adaptive optics technology that Livermore has been working on for almost a decade. The other is an entirely new methodology based on nonlinear optics in fibers and semiconductor systems. Still in the research and development phase, these approaches show promise of exceeding the performance of current adaptive optics receiver systems.



Adaptive optics systems in use today in astronomical observatories have deformable mirrors that move extremely quickly to compensate for atmospheric disturbances. Nonlinear adaptive optics, a revolutionary new technology, uses fiber optics and semiconductor chip technology to make real-time corrections to the spatial profile of a laser beam.

Minimizing beam fading caused by beam wander and obscurations such as birds in the laser path requires a process known as forward error correction. Conventional error correction methods do not work for laser communications because of the high data rate and relatively long duration of the atmospheric fades. The SATRN team is collaborating with industry to develop new error correction techniques specifically for air–optic communications.

Lastly, to overcome path losses due to poor air quality and fog, new high-power fiber amplifier technologies are based on photonic crystal fiber technologies. For this work, Livermore is collaborating with researchers at the University of Bath in the United Kingdom, where photonic crystal fibers were invented. The new technology may provide 10 times the power of current commercial amplifiers that are designed for use in wavelength-division-multiplexed communication systems.

Crucial to all of this work is modeling the laser beam both as it propagates normally through the atmosphere and as it propagates with various new technologies. Modeling is helping the team to optimize the design of the optical system and predicting the performance of open-air links under specified atmospheric conditions and ranges. "We will soon integrate the codes to provide an unprecedented capability at Livermore for simulating terrestrial laser communications," notes Ruggiero.

Beaming Up to the Future

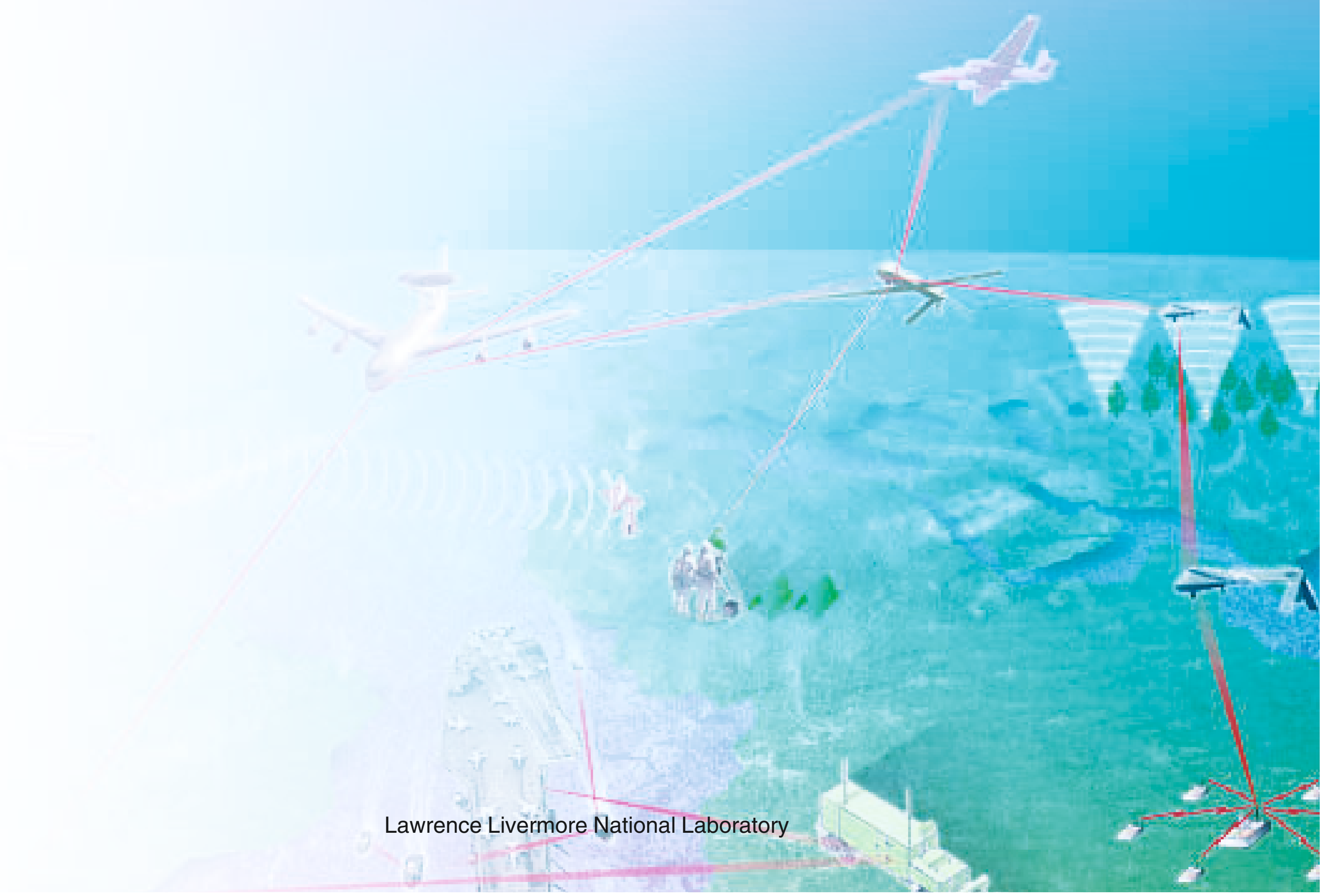
The next major experiment for SATRN will be to create a link to airplanes and UAVs in collaboration with the U.S. Navy's Third Fleet and the Naval Postgraduate School in Monterey, California. That effort will take place in 2003.

Work to date on SATRN has been internally funded by Laboratory Directed Research and Development. Beginning next year, the Department of Defense and other government sponsors will fund further development and experimental deployments. SATRN technologies will be integrated into the Tera-Hertz Operational Reachback (THOR) program of the Defense Advanced Research Projects Agency, the primary research and development organization for the Department of Defense. The goal of THOR is to develop high-bandwidth air-to-air, air-to-ground, ground-to-air, and air-to-sea optical links to the tactical warfighter. SATRN will fit right in.

—Katie Walter

Key Words: laser communications link, Secure Air–Optic Transport and Routing Network (SATRN).

For further information contact Tony Ruggiero (925) 423-1020 (ruggiero1@llnl.gov).



Patents and Awards

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

Thick Adherent Dielectric Films on Plastic Substrates and Method for Depositing Same

Paul Wickboldt, Albert R. Ellingboe, Steven D. Theiss, Patrick M. Smith
U.S. Patent 6,436,739 B1
August 20, 2002
Thick adherent dielectric films are deposited on plastic substrates as a thermal barrier layer to protect the substrates from high temperatures that occur during laser annealing of layers subsequently deposited on the dielectric films. The barrier layer needs to be 1 micrometer or more thick, adhere to a plastic substrate, not lift off when its temperature increases and decreases, have few or no cracks, not crack when bent, resist lift off when submersed in fluids, insulate electrically, and preferably be transparent. The thick barrier layer may be composed of a variety of dielectrics and certain metal oxides and may be deposited on a variety of plastic substrates by various known deposition techniques. The key to the method of forming the thick barrier layer on the plastic substrate is to keep the substrate cool during the deposition process. Cooling may be accomplished by the use of a cooling chuck on which the plastic substrate is positioned and by directing a cooling gas such as helium, argon, or nitrogen between the plastic substrate and the cooling chuck. Adherent dielectric films up to about 5 micrometers thick have been deposited on plastic substrates so the substrates can withstand laser processing temperatures applied to materials deposited on the dielectric films.

Hyperbaric Hydrothermal Atomic Force Microscope

Kevin G. Knauss, Carl O. Boro, Steven R. Higgins, Carrick M. Eggleston
U.S. Patent 6,437,328 B1
August 20, 2002
A hyperbaric hydrothermal atomic force microscope for imaging solid surfaces in fluids, either liquid or gas, at pressures greater than normal atmospheric pressure. The sample can be heated and its surface imaged in aqueous solution at temperatures greater than 100°C, with less than 1-nanometer vertical resolution. A gas- pressurized microscope base chamber houses the stepper motor and piezoelectric scanner. A chemically inert, flexible membrane separates this base chamber from the sample cell environment and constrains a high-temperature pressurized liquid or gas in the sample cell while allowing movement of the scanner. The sample cell is designed for continuous flow of liquid or gas through the sample environment.

Charge Amplifier with Bias Compensation

Gary W. Johnson
U.S. Patent 6,437,342 B2
August 20, 2002
An ion beam uniformity monitor for low beam currents using a high-sensitivity charge amplifier with bias compensation. The ion beam monitor is used to assess the uniformity of a raster-scanned ion beam, such as that used in an ion implanter, and uses four Faraday cups placed in the geometric corners of the target area. Current from each cup is integrated with respect to time, thus measuring accumulated dose, or change, in coulombs. By comparing the dose at each corner, a qualitative assessment of ion beam uniformity is made possible. With knowledge of the relative area of the Faraday cups, the ion flux and area dose can also be obtained.

Awards

In a ceremony held in October, the Council of Energy Resource Tribes (CERT) presented this year's **American Indian Spirit Award** to Laboratory Executive Officer **Ron Cochran** and the **Laboratory** for their "continued dedication and commitment to Native American education and leadership." The award was presented by Chairman Alvin Windy Boy of the Chippewa Cree Tribe.

CERT is an organization that promotes tribal energy efforts and increased educational opportunities for American Indian youth. Said Cochran, "This award is a very special honor, and I accepted it on behalf of the Laboratory, UC, and DOE. The Laboratory's American Indian Program has worked hard to partner with the Indian communities through CERT."

Laboratory physicist **Kennedy Reed**, a researcher in the Physics and Advanced Technologies Directorate, is the 2003 recipient of the American Physical Society's **John Wheatley Award**. This award is given to a physicist who has made an outstanding contribution to physics research and education in a developing country. It is given every two years and includes a prize of $2,000 and a certificate citing the recipient's contributions.

Reed is cited for "multifaceted contributions to the promotion of physics research and education in Africa, for developing agreements for exchange of faculty and students between U.S.A. and African institutions, for organizing and conducting international workshops and conferences on physics in Africa, and for advocating increased U.S.A. and international involvement with physics in Africa."

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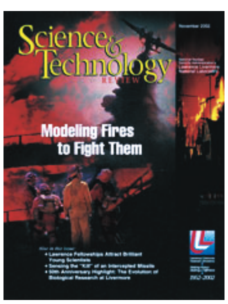

November 2002

December 2002

Coming Next Month

Re-creating One of the Earliest Forms of Matter

Scientists are attempting to create quark–gluon plasma, a state of matter that has not existed since the first moments following the big bang.

Also in January/February

- *Forty-five years after atmospheric nuclear testing ceased, Livermore environmental scientists continue to develop ways to assess and limit radiation exposure to assist in resettling the Marshall Islands.*

- *Chemists and biologists simulate the workings of complex biological systems to understand life more comprehensively.*

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