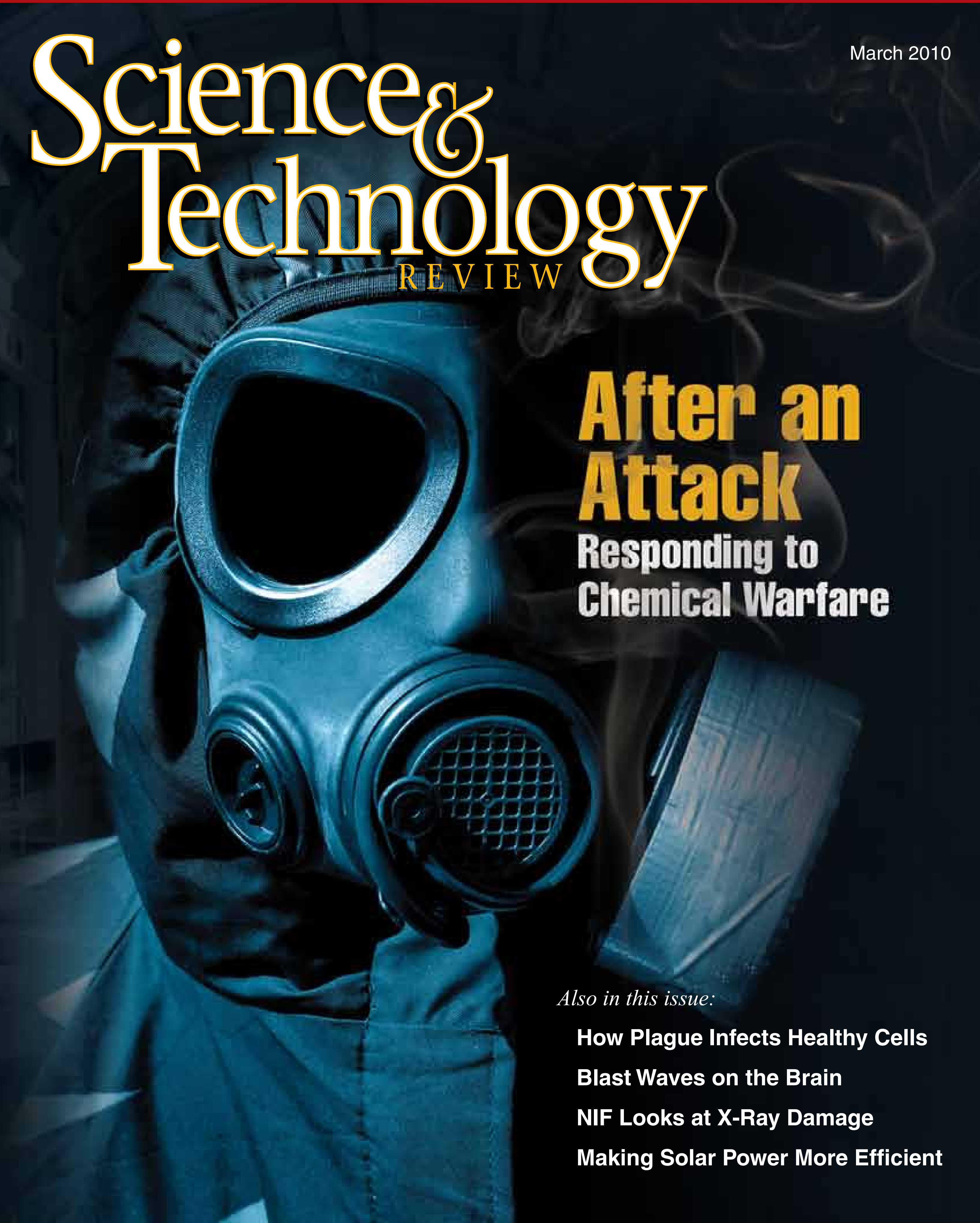
Lawrence Livermore National Laboratory

March 2010

Science & Technology REVIEW



After an Attack
Responding to Chemical Warfare

Also in this issue:

How Plague Infects Healthy Cells

Blast Waves on the Brain

NIF Looks at X-Ray Damage

Making Solar Power More Efficient

About the Cover

Chemical and biological weapons are an ever-present threat to national security. The article beginning on p. 4 describes some of the Laboratory's efforts to help counter or, if necessary, respond to the potential use of such weapons. For example, Livermore chemists are working on extremely sensitive methods to reliably and accurately analyze chemical warfare agents such as sarin and VX as well as their degradation products. In addition, environmental experts are helping to evaluate emergency procedures for rapidly restoring a contaminated facility, such as a major transportation center, to full operation. On the cover, an emergency responder dressed in full protective gear prepares to enter a contaminated area. The background image on the back cover shows passengers moving through an airport terminal.

Cover design: Amy Henke

About the Review

At Lawrence Livermore National Laboratory, we focus science and technology on ensuring 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 eight 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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NNSA National Nuclear Security Administration

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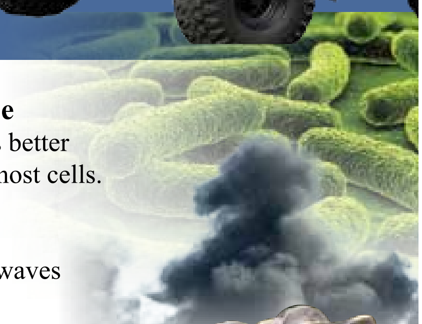

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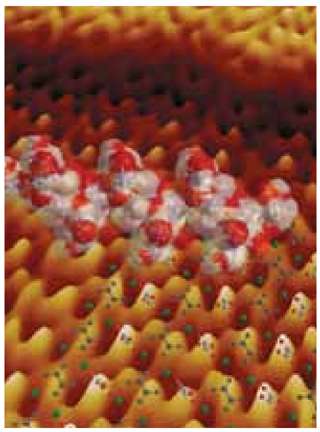
Images Reveal How Peptides Control Crystal Growth

Using high-resolution atomic force microscopy, researchers from Lawrence Livermore and Lawrence Berkeley national laboratories, the University of California at Davis, and the University of Alabama have for the first time imaged individual layers of a mineral interacting with small protein fragments, or peptides, as they fall on the mineral's surface. Such images (below) are helping scientists understand how biomolecules manipulate the shape of minerals by accelerating, switching, and inhibiting crystal growth.

Inorganic minerals play an important role in most biological organisms, forming structures such as bones, teeth, and shells through the process of biomineralization. Some minerals, however, negatively affect an organism. For example, aggregates of calcium oxalate minerals in the urinary track may cause kidney stones in humans and other mammals. To improve treatment strategies for such painful conditions, researchers want to determine how an organism limits the growth of these pathological minerals.



Images taken with an atomic force microscope captured the molecular structure of a crystal during the biomineralization process, allowing the research team to observe peptides adhering to the crystal's surface. The peptides appeared to temporarily slow down the growth process on one layer of the crystal and then "hop" to the next surface level. The images also revealed a mechanism that molecules can use to bind to surfaces that would normally repel them. In addition, researchers found that peptides will cluster together on crystal faces with the same electronic charge and, under varying conditions, can either slow down or speed up growth. Results from the team's research appeared in the January 5, 2010, issue of *Proceedings of the National Academy of Science*.

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A Catalyst Made of Nanoporous Gold

Livermore material scientist Juergen Biener and colleagues from the University of Bremen in Germany and Harvard University have found that nanoporous gold may be an ideal catalyst for various chemical reactions. The chemical industry is interested in using gold-based catalysts because they are nontoxic and can selectively promote reactions at low temperatures. However, gold particles must be deposited on oxide supports to prevent dissociation, a process that reduces the catalyst's long-term stability.

Nanoporous gold is a promising candidate because it does not require oxide supports. It can be easily prepared by leaching, or dealloying, silver from a gold–silver alloy. In fact, the team found that residual silver from the dealloying process regulates the availability of reactive oxygen on the surface and thus controls the selectivity and reactivity of the gold. The resulting material's large surface area and small pore size provide the reactive sites needed for efficient catalysis.

In this study, nanoporous gold served as a catalyst in the partial oxidation of methanol to produce methyl formate, a compound commonly used as a precursor agent and a solvent. The team successfully performed this reaction under continuous flow conditions at ambient pressures (100 kilopascals) and relatively low temperatures (below 100°C). Biener notes, however, that further research is needed to determine the economic viability of using nanoporous gold catalysts on a large scale. The team's research was published in the January 15, 2010, edition of *Science*.

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Diamond Research Looks at Planet Cores

Scientists at Lawrence Livermore, the University of California at Berkeley, and the University of Rochester have directly measured the melting temperature of diamond under extreme pressures and temperatures. The high-pressure, high-temperature behavior of diamond is an important area of astrophysical research. Diamond is a form of carbon—a primary element in the subsurface of giant planets such as Uranus and Neptune—and thus may dominate the cores of these planets. Better understanding how diamond behaves under the extreme conditions at a planet's core will help researchers predict the evolution and structure of giant planets.

Shock-compression experiments using the OMEGA laser at Rochester's Laboratory for Laser Energetics showed that at pressures of 6 to 11 gigapascals, diamond melts to a denser metallic fluid at temperatures between 8,000 and 10,000 kelvins. At even higher pressures—between 11 and 25 gigapascals—diamond melts to a complex fluid state as temperature increases above 50,000 kelvins.

"These measurements offer some intriguing possibilities for the inner structures of Neptune and Uranus if the planetary carbon gravitationally segregates near their cores," says Livermore physicist Jon Eggert, who led the research collaboration. "Our observations indicate that most of the cores of these planets experience conditions close to the melting line of diamond."

The experiments also show that pure carbon could be solid at all depths, although a hotter, deep interior may be isolated from the outermost atmosphere by a stably stratified, nonconvecting region within Uranus and Neptune. "In such warmer conditions, pure carbon could exist in the dense liquid metallic state, stably stratified from buoyant solid diamond, thus helping to sustain the anomalous planetary magnetic field," says Eggert. "In either case, the high sound velocity of a diamond-rich layer at intermediate depths could influence planetary normal modes that may be observable in the future." The team's research appeared in the January 2010 issue of *Nature Physics*.

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Commentary by Penrose (Parney) C. Albright

Countering the Growing Chem–Bio Threat

EVEN in small amounts, chemical and biological agents can be formidable weapons. History abounds with examples of their use, from ancient armies throwing diseased animals over castle walls to thousands of dead and maimed soldiers in World War I caused by exposure to mustard and chlorine gas. More recently, the Japanese cult Aum Shinrikyo released the nerve gas sarin in a Tokyo subway in 1995, hospitalizing nearly 1,000 and killing 12. The cult also unsuccessfully attempted to release botulin toxin and anthrax spores. A perpetrator in the U.S. was more successful in 2001, killing 5 people and infecting 17 with anthrax spores mailed to news media and U.S. senators.

Chemical and biological weapons remain a persistent—and growing—threat. Today, a small group or even a single determined individual armed with only a small amount of agent could cause catastrophic damage. Properly prepared and disseminated, one kilogram of anthrax could kill 300,000 people, and even a few milliliters of sarin could sicken or even kill thousands. Information on how to obtain and weaponize these and other agents is freely available on the Internet.

The article beginning on p. 4 discusses Lawrence Livermore's growing role in helping federal and state agencies strengthen their plans to effectively respond to an attack involving chemical agents such as sarin and VX. Much of our researchers' focus is on transportation centers such as international airports because of the thousands of people who frequent these facilities and the disruptions to the world's air transportation network that would stem from an attack. As the article relates, chemists from our Forensic Science Center have been sharing with Environmental Protection Agency laboratories advanced methods for detecting even the smallest amount of chemical agents. At the same time, Livermore scientists are strengthening scientific understanding of how chemical warfare agents interact with different building and office materials. Their findings are sure to help speed remediation efforts following an attack.

Helping agencies prepare to cope with a chemical or biological attack requires identifying the most efficient triage protocols, the health effects of an attack, effective countermeasures, the geographic spread of contamination, safe areas for public safety personnel, and robust remediation techniques as well as coordination of local, state, and federal agencies.

Orchestrating these—and additional—jobs must be done with an eye to minimizing casualties and returning a facility back to normal use as quickly as possible. Such a task requires a multidisciplinary approach, something at which Livermore excels. In this context, the Laboratory offers a unique mix of expertise in high-performance computing, systems analysis, biology, chemistry, environmental science, emergency management, and conduct of operations. Our experts are aided by world-class facilities such as the Center for Accelerator Mass Spectrometry, National Atmospheric Release Advisory Center, Forensic Science Center, and Biodefense Knowledge Center.

When advising the government, we don't try to "sell" a particular philosophy, methodology, or technology. Our unquestioned objectivity in determining the fastest, most effective, and easiest-to-use technologies and procedures for prevention, detection, and remediation of chemical and biological attacks is critical. In a time of unprecedented national security threats and strained budgets, we must provide the highest quality analytic products to our sponsors, on time and on budget. Anyone taking even a cursory look at the 192-beam National Ignition Facility at Livermore, easily the world's most powerful laser, will quickly recognize the extraordinary achievements that a multidisciplinary approach combined with top-flight project management and systems engineering can accomplish.

I know first-hand from my experience working in the federal government that national security roles and responsibilities are distributed among many agencies. The Department of Defense, Department of Homeland Security, Department of Energy, Environmental Protection Agency, Department of Justice, and the intelligence agencies all play important roles. In responding to national needs, Livermore researchers must be able to interact seamlessly with all of them. The dynamic and persistent threats to our nation's security demand the enduring focus of these agencies and of the capabilities here at Livermore that those agencies count on.

■ Penrose (Parney) C. Albright is principal associate director for Global Security.

Responding to a Terrorist Attack

Livermore scientists are helping federal, state, and local agencies prepare for the so-called poor-man's atomic bomb.

Involving Chemical Warfare Agents

BECAUSE of their availability and relative ease of dispersal, toxic and often lethal chemicals are potentially attractive weapons for terrorists. A chemical agent attack could result in high casualties, especially if the release occurs in an office building, indoor stadium, airport, or train station. The economic losses would be significant as well because of the time involved to remediate the area following such an attack. Federal and state agencies are thus working with major transportation centers to strengthen plans for responding to the possible use of chemical warfare agents. (See the box on pp. 6–7.)

Livermore researchers—environmental scientists, analytical chemists, and emergency response experts—have extensive experience helping federal agencies such as the Department of Energy and the Department of Homeland Security (DHS) prepare for a possible incident involving weapons of mass destruction, including chemicals, biological agents, and radiological devices. Over the past two decades, the Laboratory has made important contributions to homeland security with new kinds of miniaturized detectors, advanced chemical decontamination compounds, extremely sensitive analytical techniques, and more thorough decision-making processes required for quick and effective response to an incident.

At the Laboratory's Forensic Science Center (FSC), chemists have been working closely with chemical warfare agents since the early 1990s to support treaty verification and U.S. intelligence efforts. Founded in 1991, FSC supplies analytical expertise to counter terrorism, aid domestic law enforcement, and verify compliance with international treaties. FSC researchers analyze virtually every kind of chemical evidence, some of it no greater than a few billionths of a gram. In addition, the center is one of two U.S. laboratories internationally certified for identifying chemical warfare agents, sometimes referred to as the poor-man's atomic bomb.

Since 2008, Lawrence Livermore has been working closely with the Environmental Protection Agency (EPA) to prepare for incidents involving chemical weapons. FSC serves as EPA's environmental reference laboratory for developing and validating reliable, accurate, and extremely sensitive methods to analyze chemical warfare agents and their degradation products. Laboratory researchers have also characterized many toxic industrial compounds because the molecular structure and health effects of these substances are similar to those of known chemical warfare agents.

Livermore analytical chemist Carolyn Koester is principal investigator for the partnership with EPA. "We want to help EPA labs ensure that all public areas are safe after an incident involving chemical weapons," she says. Making sure the public can return to a facility following dispersal of a chemical warfare agent will probably require analyzing hundreds, perhaps thousands, of samples over the course of days or weeks as workers monitor the intense cleanup efforts after an attack.

Sensitive Detection Methods

The 1980 Comprehensive Environmental Response, Compensation, and Liability Act (also known as the Superfund Act) designated EPA as the primary federal agency responsible for the environmental remediation (cleanup) following acts of terrorism. In this capacity, EPA would take a lead role after an attack, providing expertise on effective decontamination approaches for indoor and outdoor areas.

If an incident involving chemical weapons were to occur on U.S. soil, a select group of EPA laboratories, part of the agency's Environmental Response Laboratory Network, would quickly become involved. The laboratories, using Livermore-developed techniques, would first determine the nature and extent of the contamination and would later help monitor decontamination and restoration activities. According to Koester, the EPA laboratories must be prepared for any kind of sample—liquid, solid, or vaporous and ranging from plants to clothing to carpeting.

FSC Director Dennis Reutter says that, before a facility can reopen, agencies must state with confidence that no harmful residue remains following decontamination. A major challenge is thus to develop techniques that can detect and identify extremely low concentrations of chemicals. He notes that Livermore's characteristic approach is to probe the lower limits of detection for many types of chemical and explosive compounds isolated during an investigation. For chemical weapons and their degradation products, he says, "We're pushing detection limits as low as 1 part per billion or even trillion."

At the same time, analysis methods must also be as fast as possible to give on-scene responders answers within hours instead of days. High-throughput methods will allow EPA laboratories to keep up with possibly thousands of samples. Reutter adds that Livermore could provide surge capacity to help EPA analyze a large number of samples.

For the past year, Livermore researchers have been training analysts from several EPA laboratories to use the new techniques

A Chemical Weapons Primer

Chemical warfare agents are nonexplosive compounds that can kill, injure, or incapacitate. The chemicals traditionally used to make these weapons are not widely available, but recipes for producing them are found on the Internet. Some have even been deployed in terrorist incidents.

The more toxic compounds (such as sarin, soman, cyclosarin, tabun, and VX) work by attacking the nervous system. Others may induce blistering (mustards and lewisite), choking (chlorine, phosgene, and diphosgene), or vomiting. In addition, some nonlethal compounds are designed to incapacitate an attacker or help disperse a crowd. The chemicals may be in solid, liquid, or gas form, but most liquids and solids can be made volatile for quick dispersal as aerosols and vapors over a large area.

Chemical warfare compounds can enter the body through the skin, eyes, and respiratory tract. Depending on the agent, its concentration, and the length of exposure, physical effects may be immediate or delayed.

An agent's persistence—how long it remains dangerous after dissemination—also varies widely. Gaseous agents such as chlorine, sarin, and some other nerve agents lose effectiveness after only a few minutes or hours, provided they are not trapped in porous materials. In contrast, persistent agents may linger in the environment for up to several weeks, which complicates decontamination efforts. Liquids such as blister agents and the oily VX nerve agent do not easily evaporate into a gas and therefore primarily pose a contact hazard.

A Long History in Warfare

Although chemical weapons may seem like a modern warfare technology, archeologists have discovered instances of toxic chemicals used in ancient conflicts. For example, in 256 A.D., Persian soldiers pumped lethal fumes from a brazier burning sulfur crystals and bitumen into tunnels, killing Roman soldiers hiding underground.

The horrifying capacity of these agents was evident during World War I. In 1915, the German military released 168 tons of chlorine gas in Belgium, killing an estimated 5,000 Allied troops. Sulfur mustard, the major cause of chemical casualties in that war, was used first by the Germans and later by Allied soldiers. Since then, chemical weapons have factored into other conflicts. For example, Iraq used chemical weapons, including mustard gas, against Iranian troops and Iraqi Kurds during the prolonged war in the 1980s.

Terrorists deployed chemical weapons against civilian populations for the first time in 1994, when the extremist Aum Shinrikyo cult released sarin gas in Matsumoto, Japan, leaving 7 dead and 280 injured. The following year, the cult released sarin vapor in the Tokyo subway system, killing 12 commuters and hospitalizing nearly 1,000. Because of the efficient decontamination effort, the subway was back in operation the following day.

Accidents involving toxic industrial chemicals, many of them close cousins to modern warfare agents, demonstrate the potential of chemical agents to kill and injure. For example, in 1984, an explosion at an industrial pesticide plant in Bhopal, India, released methyl isocyanate gas, killing more than 4,000 and sickening tens of thousands. Closer to home, two freight trains collided near Graniteville, South Carolina, in 2005, and a ruptured tank car released 70 tons of chlorine gas. Nine people died, at least 250 people were treated for chlorine exposure, and about 5,400 residents were forced to evacuate for nearly two weeks.

Outlawed by Chemical Weapons Convention

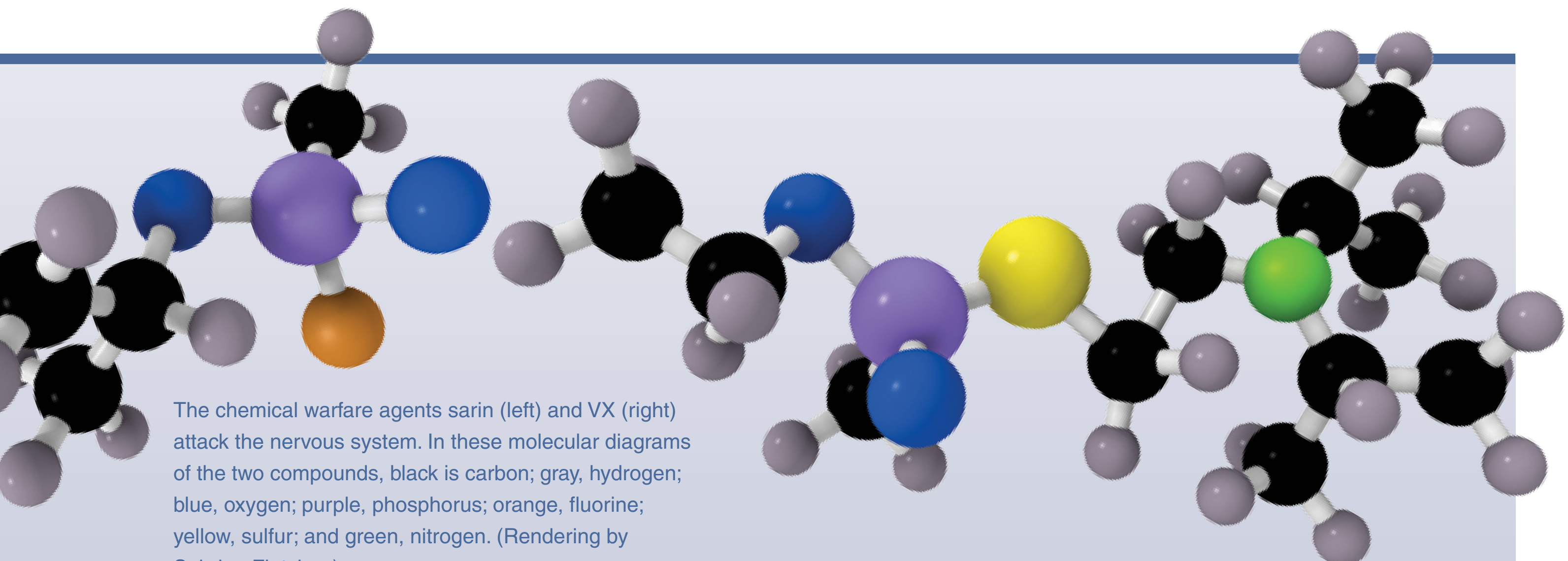
The United Nations classifies chemical warfare agents as weapons of mass destruction. The 1993 Chemical Weapons Convention (CWC), which has been ratified by 186 countries, including the U.S., bans the development, production, acquisition, and learn about procedures, including additional safety practices, required for working with chemical warfare agents. Analytical chemist Heather Mulcahy says, “The EPA labs have not previously worked with these compounds, but they are familiar with toxic materials and low-concentration samples. They also have considerable experience working with pesticides, whose characteristics are similar to those of some chemical warfare agents.”

The first set of developed techniques focused on the compounds that terrorists would most likely manufacture and deploy. Extremely small quantities of these agents were used to develop analytical methods. As the EPA personnel gain expertise with these techniques, Livermore scientists will add new ones for analyzing other agents. EPA laboratory analysts have also visited Livermore to work alongside experts in the field of chemical warfare detection. Personnel from additional EPA laboratories are expected to begin training this year.

To help in evaluating a laboratory’s readiness for a terrorist incident, Livermore chemists have synthesized minute amounts of chemical warfare agents and sent them to the EPA laboratories for identification. “In the first proficiency test,” says Koester, “the participating labs did very well in quantifying trace amounts of agents.”

Preparing LAX for Attack

Livermore scientists are also helping to strengthen management plans for responding to a chemical attack. One of the most exhaustive efforts is a multi-institutional collaboration to develop emergency response plans for airports, including Los Angeles International



The chemical warfare agents sarin (left) and VX (right) attack the nervous system. In these molecular diagrams of the two compounds, black is carbon; gray, hydrogen; blue, oxygen; purple, phosphorus; orange, fluorine; yellow, sulfur; and green, nitrogen. (Rendering by Sabrina Fletcher.)

stockpiling, and use of chemical weapons as well as the transfer of related technologies. CWC-monitored chemicals encompass thousands of compounds. In accordance with the convention, the U.S. Army Chemical Materials Agency has been destroying the nation’s stockpile of chemical weapons, which originally included more than 31,000 metric tons of nerve and mustard agents.

The Organization for the Prohibition of Chemical Weapons (OPCW), located in The Hague, Netherlands, is responsible for implementing the convention, which stipulates that all chemical warfare agent samples be analyzed by OPCW-certified laboratories. These laboratories test samples collected by OPCW inspectors to determine whether the samples contain chemical weapons agents, their precursor chemicals, or decomposition products. Federal legislation requires that samples taken from a U.S. facility be tested in a U.S. laboratory that is OPCW-certified.

In 2000, the U.S. State Department selected the Forensic Science Center (FSC) at Livermore as the nation’s second OPCW-certified laboratory. (The other facility is Edgewood Chemical Biological Center in Maryland.) FSC Director Dennis Reutter served in the 1990s as the Department of Defense representative to The Hague for negotiations on implementing the CWC. He also helped author the U.S. position for on-site inspections and sampling.

Lawrence Livermore has established a separate OPCW-certified laboratory within FSC for chemical weapons analysis. To date, no samples have been officially collected from any site or analyzed at any laboratory. However, to maintain its accreditation, FSC must analyze and identify test samples supplied by OPCW. Passing these annual tests is a challenging task because the samples may contain thousands of chemicals that are linked to chemical weapons production.

Analytical chemists (from left) Carolyn Koester and Heather Mulcahy work in an environmental reference laboratory at the Forensic Science Center to develop and validate sensitive methods for analyzing chemical warfare agents.

Airport (LAX), the world's sixth busiest, and San Francisco International Airport (SFO), the world's twenty-first busiest.

Ellen Raber, deputy program manager for chemical, biological, radiological, nuclear, and high-yield explosives countermeasures in Livermore's Global Security Principal Directorate, emphasizes the need to quickly restore a major airport facility after an attack. "A deliberate attack on an airport could have far-reaching impacts, not only in terms of public health but also in economics," Raber says. For example, if SFO were shut down, the lost revenue would top $85 million per day. The closure would also affect the national and international air transportation network and reduce public confidence in these facilities.

In 2006, Raber led an exercise in which Livermore researchers worked with SFO managers and state and local agencies showing how the airport could effectively respond to an attack involving biological agents such as anthrax. More recently, Laboratory scientists have applied their expertise and developed guidance documents and methods for

A chemical attack inside a terminal at an airport, such as Los Angeles International Airport, would be extremely costly, disrupt air traffic worldwide, and require decontamination and restoration. (Courtesy of Los Angeles World Airports.)

As part of a three-day demonstration exercise, California National Guard civil support personnel in full chemical protective gear demonstrate rapid-response operations. Personnel trained in chemical response procedures and technologies (left) drive by a portable personal decontamination facility and (right) sample air for chemical warfare agents.

response and recovery to a chemical warfare attack.

Livermore scientists participated in DHS's Chemical Restoration Operational Technology Demonstration Final Demonstration Event in October 2009. The three-day exercise, which took place at Ontario International Airport in southern California, capped three years of planning, studies, and experiments conducted by Lawrence Livermore, Sandia, Oak Ridge, and Pacific Northwest national laboratories. Funded by the DHS Chemical and Biological Science and Technology Division, the event focused on procedures, plans, and technologies to rapidly restore an airport or major transportation center to normal operations following a chemical attack. Raber says that EPA has also been a key contributor to strengthening response capabilities and has provided significant operational and technical requirements.

As part of the exercise, Laboratory scientists collaborated with personnel from LAX, DHS, and EPA as well as state emergency response groups, including the California National Guard. Livermore efforts focused on shortening the time required to decontaminate, restore, and reopen an LAX terminal under a hypothetical scenario.

The Livermore contribution also included strengthening emergency conduct-of-operations models, such as developing organizational structures with clear lines of responsibility. Much of this effort was led by the Laboratory's Environmental Protection Department because of its expertise in responding to environmental releases of health-endangering materials. Livermore scientist Sav Mancieri, who leads this effort, says, "In addition, we have a strong understanding of the environmental regulations that are key to effectively responding to such an event, and our researchers have worked closely with EPA's on-scene coordinators."

Recovery from a chemical agent release will present many challenges, caused in part by likely contamination to large open spaces, confined spaces, sensitive equipment (such as computers), and many types of materials. "The restoration of an airport is an extremely complex process, but it must be done quickly and effectively," Raber says. "Waiting for the agent to naturally dissipate will not be an option."

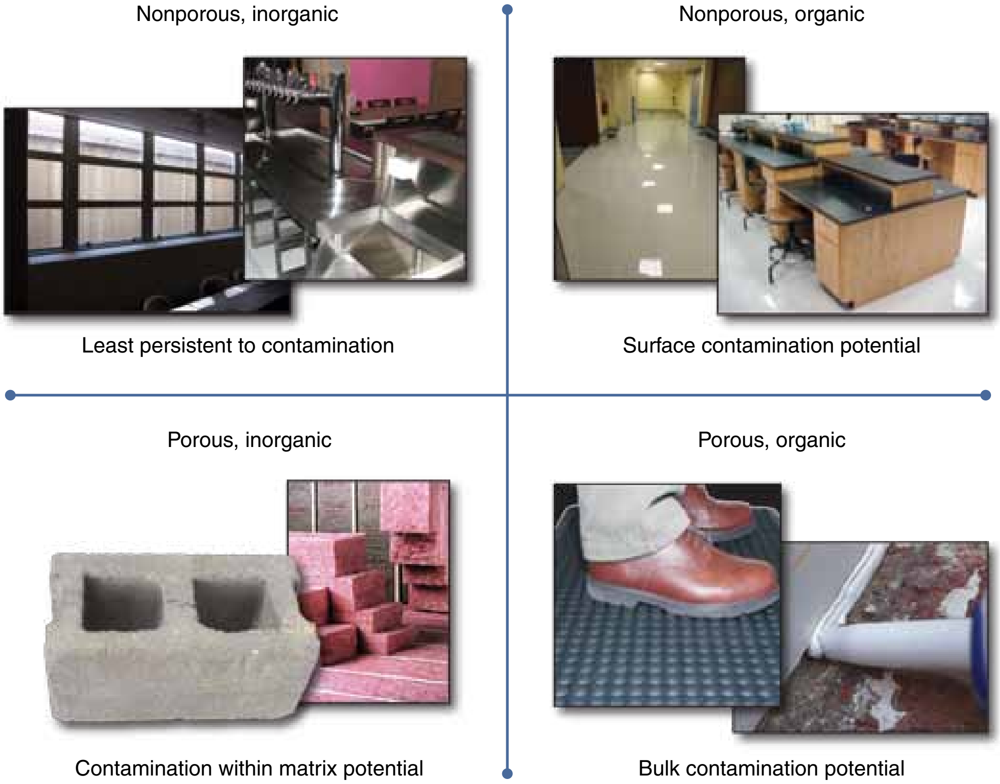
The demonstration featured a scenario in which an undetermined quantity of sarin was released in a busy LAX terminal. Sarin, a nerve agent, is one of the most toxic and rapidly acting compounds. Its vapor can spread easily by airflow typical of air-conditioned indoor environments. Demonstration participants reviewed every response step, from the first 911 calls and the arrival of LAX police, firefighters, and hazardous material personnel to the protracted course of decontamination, restoration, and reopening of the facility.

The final product from the demonstration, a suite of national-level guidance documents issued jointly by DHS and EPA, should prove helpful to any large transportation facility in the nation. Livermore environmental scientist Don MacQueen has been instrumental in coordinating and resolving comments in preparation for the documents' release and in determining the requirements for environmental sampling that would immediately follow a chemical release.

Strong Science Guides Remediation

Restoring a location to operation after a chemical attack will likely be a large and complex undertaking. The first step, identifying the chemical agent, will be performed by first responders such as the California National Guard civil support teams, who have air-sampling equipment to detect and identify a nerve agent such as sarin. Once the compound is identified, sampling would determine the extent of contamination and what areas require decontamination. According to Mancieri, on-scene managers will need to know how long agents remain on various surfaces and how best to decontaminate those surfaces.

To better understand how chemical warfare agents interact with typical indoor materials, a team led by former Livermore environmental scientist Adam Love tested a representative group of agents (sarin,



Tests on various indoor materials showed that vaporous chemical warfare agents can penetrate both organic and inorganic porous materials, making decontamination more difficult. New data on agent persistence are helping researchers to refine operational guidelines and make cleanup operations more rapid and less expensive.

mustard, VX, and cyclosarin). All of the chemicals were applied to a number of materials, including painted wallboard, glass, stainless steel, concrete, vinyl floor tile, heating and air-conditioning ducts, escalator handrails, caulking, and other common indoor objects.

"The military has done a lot of work on the effects of chemicals on outdoor environments and military surfaces," says Love. "But prior to our study, little research had been done on civilian materials." He notes that tests involving actual chemical warfare agents, rather than surrogates, provide more realistic data concerning surface interactions under different environmental conditions.

The experimenters discovered that in vapor form, chemical warfare agents can penetrate both organic and inorganic porous materials, making these materials more difficult to remediate. In effect, the agent becomes trapped inside the object, outgassing slowly. The new data on persistence are being used to refine operational guidelines and make possible more rapid and less expensive cleanup operations.

Love also headed a team that compared decontamination techniques, including bleach (the longtime standard), foams, and volumetric approaches in which hot (and sometimes humid) air is blown into an indoor facility to hasten dissipation of the agent. In spaces where surface deposits are at low concentration, volumetric techniques will clean all accessible surfaces simultaneously.

According to Love, every decontamination strategy is effective under some conditions, but no single approach is likely to be effective and efficient in restoring an entire facility. For example, with some porous materials, such as rubber handrails and vinyl tile, vaporous agent penetrates deeply, and bleach and foams are not effective. Stronger disinfectants are available, but would damage the objects, leaving removal a more efficient option. Another option is to apply a sealer over an object, in effect trapping the agent, but a Livermore study showed that some agent still manages to escape. Therefore, several strategies will probably be required, based on an understanding of agent–material interactions and the efficacy of the different decontamination approaches.

Clearly, planning is essential for efficient recovery from a chemical weapons release, to reduce the length of the remediation effort by days or weeks and to restore public confidence in a major facility. With EPA laboratories receiving the best training and major agencies adopting realistic and efficient remediation plans, Lawrence Livermore scientists are increasing the nation's ability to respond effectively to any incident involving chemical warfare agents and protect human health and the environment.

—Arnie Heller

Key Words: chemical warfare, Chemical Weapons Convention (CWC), decontamination, Forensic Science Center (FSC), Los Angeles International Airport (LAX), mustard, Organization for the Prohibition of Chemical Weapons (OPCW), San Francisco International Airport (SFO), sarin, VX.

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Revealing the Secrets of a Deadly Disease

PLAGUE is a notorious infectious disease, unrivaled throughout history in its scale of death and devastation. Caused by the enterobacterium *Yersinia pestis*, the disease is carried primarily by rodents (most notably rats) and spreads to humans via fleas. Plague is well known for wreaking havoc on society, such as in the Middle Ages when it was called the Black Death. Yet, even today, plague is endemic in some parts of the world. For example, in 1994, massive flooding from monsoon rains and clogged sewers led to an epidemic in Surat, India, which resulted in 52 deaths.

Not only does *Y. pestis* exist in nature, but it also might be dispersed as a biological weapon. Diagnosing an outbreak of plague could be delayed because the initial symptoms of the disease—headache, weakness, and coughing with hemoptysis (vomiting blood)—are similar to those of other respiratory illnesses. Antibiotics are effective against plague, but without diagnosis and treatment, the infection can be fatal in one to six days.

Researchers do not fully understand how *Y. pestis* infects healthy host cells. To better study its pathogenesis, a team of Livermore scientists in the Physics and Life Sciences Directorate has developed a device that examines these pathogen–host interactions one cell at a time. The system uses nanometer-scale optoelectronic tweezers (OET) to place *Y. pestis* bacteria in contact with susceptible host cells. A miniature camera mounted to a microscope then records the interactions between the pathogen and host as they occur.

Developed with funding from Livermore's Laboratory Directed Research and Development Program, the new OET system is designed to overcome some limitations of what biomedical scientist Brett Chromy refers to as the "mix-and-hope" method of studying pathogen–host interactions. With that method, researchers grow significant quantities of pathogen cells, mix them with host cells, and look at the combination under a microscope, hoping to observe an interaction. However, because both types of cells are so complex and the specific mechanisms of a pathogen invading a host have yet to be defined, researchers often spend a substantial amount of time scanning for pathogen–host interactions with little success.

According to Chromy, the odds of witnessing one interaction are extremely low, and thousands of bulk measurements are required for a statistically relevant study. The *Y. pestis* cells

Livermore scientist Peter Pauzauskie (above) holds a set of optoelectronic tweezers (OET), a device he helped develop while at the University of California at Berkeley. Below him are the plague bacteria, *Yersinia pestis*, and a common rat—the most notorious carrier for this disease.

measure 1 micrometer in diameter, and the host cells are 20 micrometers in diameter. "At such a small scale, it's difficult to perform single-cell studies with the mix-and-hope method," says Chromy, who leads the research team. "So far, no one has been able to zoom in and find a pathogen–host interaction occurring from start to finish. By the time we locate an interaction, we've likely missed the first 5 to 10 seconds, which is a critical time for elucidating pathogenesis and the host's response. With the new OET system, we can observe in real time how the *Y. pestis* cell invades the host cell from the beginning."

A Terrestrial Tractor Beam

The nanoscale OET is a low-powered, noninvasive device developed in 2005 by Ming Wu's electrical engineering group at the University of California (UC) at Berkeley. With this tool, researchers can trap, transport, and sort multiple cells, microparticles, and nanoparticles by projecting optical images onto a glass slide coated with photoconductive materials. OET's single light-emitting diode can confine more than 10,000 microparticles at one time.

Team member and biophysicist Ted Laurence compares OET to the tractor-beam device in the television show *Star Trek*. "Just as the tractor beam on the Starship Enterprise could trap smaller ships and move them to a different location without direct physical contact," says Laurence, "OET allows us to transport a *Y. pestis* cell to the location of a host cell."

One advantage of UC Berkeley's OET device is its low power requirements. Other cell-manipulation methods, such as optical tweezers, use high-powered lasers. However, the tight focusing requirements of laser beams limit the number of cells that can be moved at one time. OET has an optical power density 100,000 times less than that of optical tweezers, so it can create optical manipulation patterns over large areas in real time.

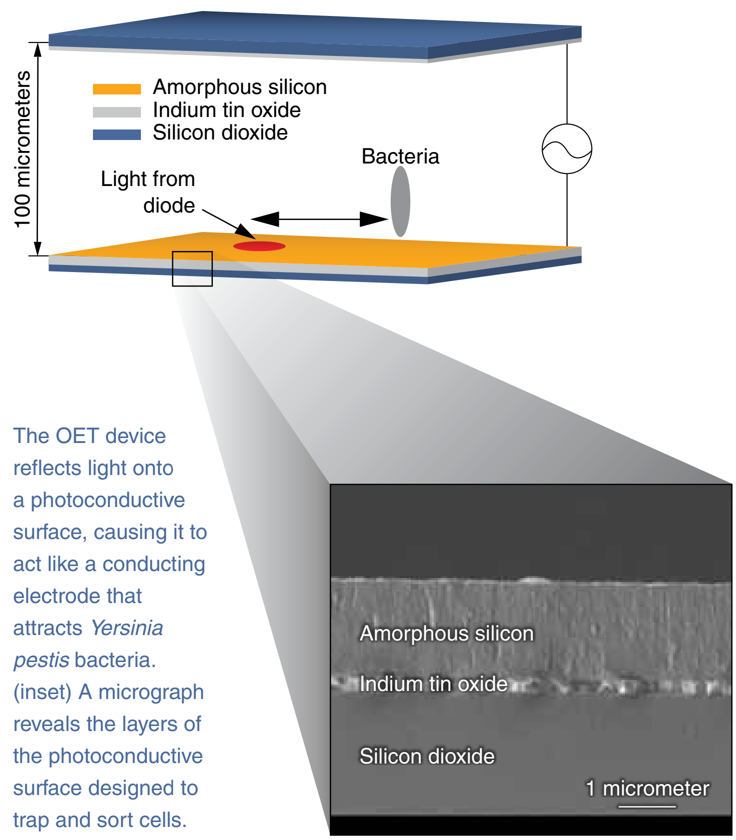
Another approach for cell manipulation is to create electric fields that either repel or attract particles. Dielectrophoresis, for instance, can move a greater number of particles, but it lacks the resolution and flexibility of optical tweezers. The UC Berkeley team adapted the OET device so that it can also use these dielectrophoretic forces and manipulate numerous cells simultaneously.

A photoconductive surface made with layers of amorphous or crystalline silicon transforms optical energy into electrical forces. Wherever light hits the photosensitive surface, the material behaves like a conducting electrode, while areas not exposed to light behave like a nonconducting insulator. Once a light source is removed, the material returns to its normal (nonconducting) state. The electric field generated by OET attracts the *Y. pestis* pathogen cells. By adjusting the light pattern, researchers can guide particles to the desired location.

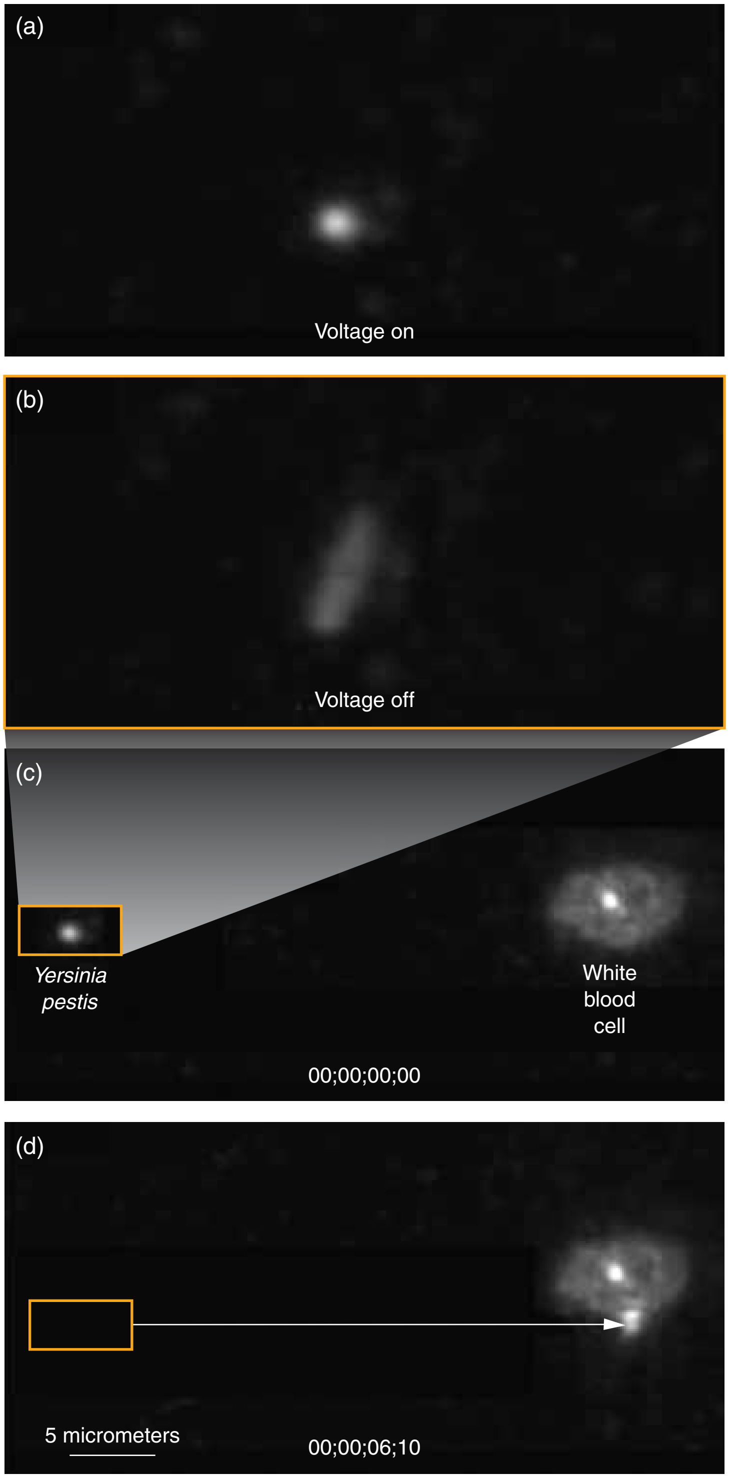
Peter Pauzauskie, a Lawrence fellow who received his doctorate from UC Berkeley, is modifying the OET design for Livermore's pathogen trapping system. When combined with optical microscopy, the OET device can sort particles or cells based on their luminescence, size, texture, or other visual attribute. For example, a standard technique called dark-field microscopy excludes unscattered light from the image of a *Y. pestis* cell. As a result, the field around the *Y. pestis* cell, which has no specimen to scatter the beam, is generally dark. This technique gives the researchers a clear image of the small *Y. pestis* cells relative to the large host cells.

Unfolding the Mystery

So far, the OET research team has used the new Livermore system to trap and manipulate fluorescently labeled *Y. pestis* cells



The OET device reflects light onto a photoconductive surface, causing it to act like a conducting electrode that attracts *Yersinia pestis* bacteria. (inset) A micrograph reveals the layers of the photoconductive surface designed to trap and sort cells.



Micrographs of a *Yersinia pestis* cell with voltage (a) on and (b) off show how the bacterium aligns with the electric field created by the two photoconductive surfaces of an OET device. The device can also (c) trap a *Y. pestis* cell and (d) transport it to form a junction with a human white blood cell.

and bring these trapped cells in contact with monocytes—white blood cells in the human immune system. In particular, says Chromy, the team wants to study the interaction between mutant strains of *Y. pestis* and healthy host cells to determine whether the mutant strains are deficient in a protein system called Type III secretion—the main mechanism by which the bacteria infect a host. The team also hopes this research will reveal if certain mutations reduce the ability of *Y. pestis* cells to adhere to a host. Examining interactions between wild-type plague bacteria and monocyte cells engineered to exclude host membrane proteins will also reveal how a host responds to plague.

"The OET trapping system could be used to examine other types of cell interactions," says Chromy, "for example, to isolate fetal cells in an expectant mother's blood sample or to sort out abnormally shaped cells from healthy ones. In the future, we want to use the system to study individual plague proteins as they interact with a host cell." Through this effort, the Livermore researchers will help answer some of the remaining questions about the plague disease.

—*Kristen Light*

Key Words: optoelectronic tweezers (OET), pathogen cells, plague disease, trapping system, *Yersinia pestis*.

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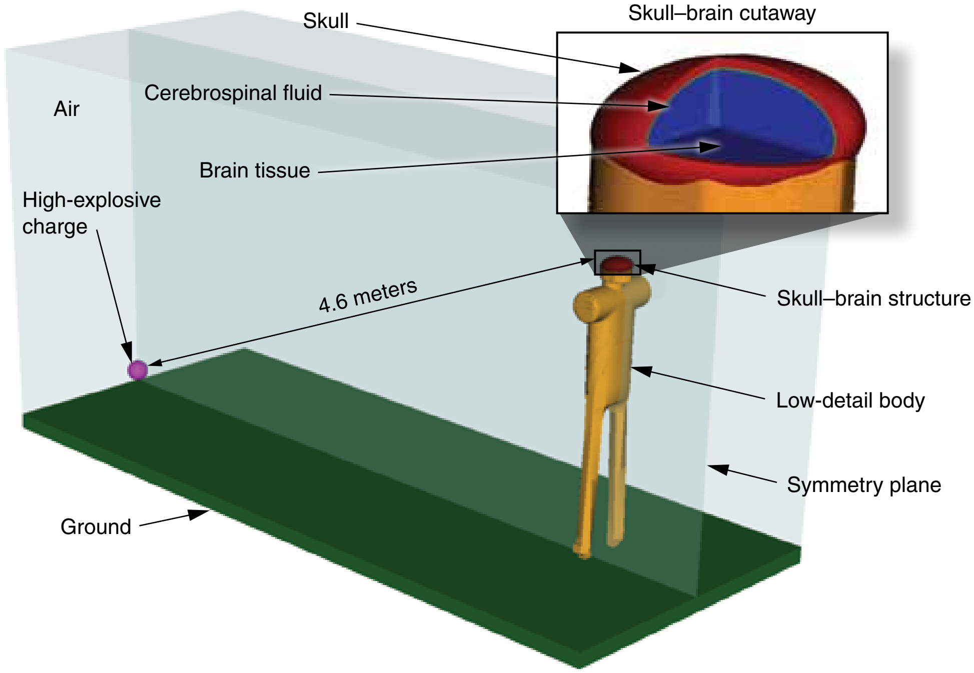
A New Application for a Weapons Code

THE fall and subsequent death last year of actress Natasha Richardson illustrates the complicated nature of traumatic brain injury (TBI). After falling during a ski lesson, Richardson stood up and appeared to feel fine. But a few hours later, she collapsed and eventually died from head injuries suffered in the accident.

Well before Richardson's death, Livermore physicist Willy Moss and engineer Mike King surmised that sophisticated computerized hydrodynamic codes—used for decades to study the fluidlike flow and shock responses of materials exposed to the effects of a nearby detonating weapon—might help researchers understand the mechanisms of TBI. Blast, such as from an improvised explosive device (IED) or a roadside bomb, affects the brain differently than the impact that Richardson experienced. However, in both types of head traumas, notes Moss, "The injuries often do not appear until well after the blast or impact itself."

Working with University of Rochester colleague Eric Blackman, an expert in TBI, Moss and King adapted ALE3D to study TBI. Developed at Livermore, this multiphysics software code is used to model fluid flow and elastic–plastic responses to structures. The TBI simulations unexpectedly revealed that the skull flexes when exposed to a nonlethal blast wave, even one generating pressures as low as 1 atmosphere (or 100 kilopascals) above ambient pressure. In fact, even without direct head impact, nonlethal blasts induce enough skull flexure to generate potentially



In the Livermore simulations of a blast-induced traumatic brain injury, a 2.3-kilogram spherical charge of C4 high explosive is located 4.6 meters from a simplified head consisting of a skull, cerebrospinal fluid, and brain tissue.

damaging pressure loads in the brain, which may contribute to trauma.

IEDs, which are just one cause of TBI, have come to symbolize the current wars in Iraq and Afghanistan. They detonate without warning, killing and maiming tens of thousands of civilians as well as thousands of soldiers. Much improved helmets and body and vehicle armor protect soldiers from shrapnel, bullets, and fragments. But a high incidence of injuries has replaced what would otherwise likely have been many deaths. Explosive devices injured about 65 percent of all Iraq and Afghanistan war veterans who were wounded in action. Overall, between 10 and 20 percent of Iraq war veterans have suffered some degree of head trauma or blast exposure during the war.

The effects of a head impact—hitting the steering wheel in an automobile accident, falling while skiing, or receiving a concussion during a football game—have been extensively studied. “But surprisingly,” says Moss, “blast-induced deformation of the skull has been neglected entirely, perhaps because of the perception that the hard skull protects the brain from nonlethal blast waves.”

Originally funded by the Departments of Defense and Energy under the Joint Munitions Program, the TBI research team has since received support from the Joint IED Defeat Organization (JIEDDO, rhymes with “pie dough”). This Department of Defense organization is dedicated to defeating IEDs as weapons of strategic influence. Other JIEDDO efforts include technology development to improve armor, jam enemy communications, and enhance troop awareness with sophisticated surveillance methods.

The Laboratory brings unique expertise to this research. Livermore’s hydrodynamic codes, which run on massively parallel computing hardware, can simulate how a blast generates waves of pressure and how those waves propagate and interact with any structures in their path, from armor and helmets to vehicles, buildings, and other soldiers. Complementing these computational capabilities are the High Explosives Applications Facility and Site 300, the Laboratory’s remote experimental test site, where experiments can be designed to replicate small-scale battlefield blasts.

The Skull under Pressure

Using ALE3D, the team examined the head’s response to impacts and blast waves. The simulation geometry (shown in the figure above), blast size, and standoff distance from the simulated head were chosen to generate a nonlethal blast wave similar to what might be encountered in the theater of war. The skull was modeled as a hollow elastic ellipsoid containing a viscoelastic brain surrounded by a layer of cerebrospinal fluid. A simplified face (with no lower jaw), neck, and body were included to capture blast-induced accelerations accurately and to appropriately shield the bottom of the braincase from the blast wave.

Anatomical details such as skull thickness variations, gray or white matter, and ventricles were not included, “although we hope to add them in the future,” says King. While these features are needed to predict specific medical traumas, the simplified model quantitatively distinguishes the different mechanisms that affect the brain during an impact or a blast. Says King, "We put in enough complexity to see the blast effects but not too much to prevent us from identifying the underlying mechanisms."

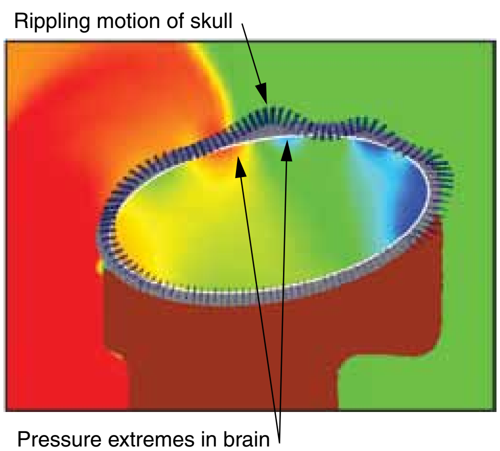
The simulation geometry also provides a means of exploring protective strategies. The head model was encased in a numerically devised steel-shelled helmet containing an inner layer of crushable foam. In the first simulations, the head and helmet were smacked against a rigid wall to duplicate an impact. At maximum deceleration, the brain collides with the decelerating skull and develops large positive pressure. The rebounding brain experiences pressure spikes, pressure gradients, and potentially damaging shear strains. The brain oscillates until the impact energy is dissipated.

An unprotected head—one without a helmet—responds very differently to a blast than to an impact, and the hard skull does not protect the brain from trauma. (See the figure below left.) The most surprising discovery was that the moving pressure wave causes the skull to flex much like dough being pressed under a rolling pin. "We saw it with the very first blast simulation," says Moss. As a result, adds King, "We began running lots of simulations, tweaking each one to make sure this result was neither a computational accident nor an anomaly caused by variations in material parameters or geometry."

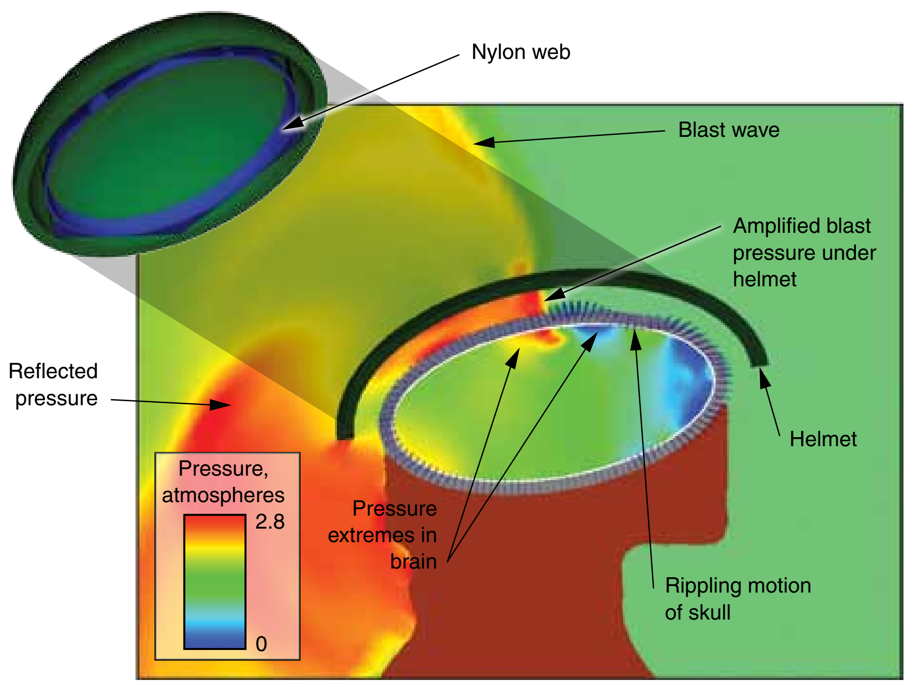
For example, they rotated the body and head 90 degrees to simulate a side-on blast and inserted holes into the skull to represent the spinal column and optical nerve passages. They also varied the material properties of both the skull and the brain, spanning the range of data available in the literature.

Still, every simulation showed the ripple effect from a blast, with the brain receiving the same pressure as it would in an injury-inducing impact. In some places, the pressure on the brain increased as expected, but in others, it decreased. The team discovered that the effect is similar to the pressure ripples on a train track as a train passes over it. "The ripples on the skull were only about 50 micrometers, or just a hair's width," notes Moss. "But even modest skull flexure from a nonlethal blast wave is enough to generate potentially damaging loads in the brain."

The simulations showed that impact creates much larger accelerations in the brain than a blast does, but blast causes much larger pressure gradients, which may cause tissue to rip and tear. Consequently, says Moss, "The metrics used to determine the severity of a TBI from an impact cannot be used to measure blast-induced trauma." Experiments by others have partially validated these findings. For example, blast experiments at Purdue University on a mock head structure derived similar data. Moss adds that further research by the medical community



In simulations of a blast such as from an improvised explosive device, an unprotected skull ripples where the pressure inside the skull is highest, just as pie dough is deformed under a rolling pin.



Simulations show that the older suspension-type helmet amplifies the blast pressure under the helmet, increasing the pressure extremes in the brain.

on cadavers or animals would provide valuable information to help refine the simulations.

Does a Helmet Protect?

Helmets are designed to protect soldiers from bullets, shrapnel, and other flying debris, a task they do well. However, in simulations using the type of helmet formerly worn by some ground troops, the gap created by the web suspension, so essential for ballistic protection, allows the blast wave to wash under the helmet. This underwash effect focuses the blast wave, causing pressure under the helmet to exceed that on the outside. (See the right-hand figure on p. 16.) The helmet does not prevent the rippling deformation of the skull but instead increases it.

Simulations using today's advanced combat helmet revealed that foam pads between the skull and the interior of the helmet prevent much of the underwash effect. However, the pads can become very stiff under the rapid pressure loading created by the blast wave. The blast causes the helmet to deform, and that energy is transferred to the pads. Although the pads block the underwash effect, the blast remains coupled to the skull.

To determine whether a foam's material properties affect the degree of skull flexure, the researchers varied the stiffness of the simulated foam by a factor of as much as 1,000. Stiffer foams transferred greater forces from the helmet to the skull. However, soft foams only partially reduced the blast-induced pressures and pressure gradients in the brain because the back and sides of the head are exposed. Says King, "Even a 'perfect' suspension would allow skull flexure because the helmet cannot completely cover the head."

This inexpensive blast sensor developed by the Livermore team includes a plastic peak-pressure display and is designed for a single use.

Gauging Damage

To correlate TBI cause, effect, and treatment, medical researchers need information on the blast environment around the soldier. The measurement systems currently used by the U.S. military are large, heavy, and of limited use for blasts. Moss and King have investigated two types of sensors to quantify the blast environment, which will help medical personnel diagnose the severity of injuries and triage patients. Both sensor designs are small and lightweight, and says Moss, "They may ultimately help improve the design of armor."

One new sensor uses a tiny microelectromechanical gauge developed by Livermore engineer Jack Kotovsky. Several of these devices could be mounted on a soldier's helmet to form a net of sensors that measure peak pressure, duration of the blast, and the direction from which it came. A companion sensor net placed inside the helmet would measure the stresses transferred to the skull by the helmet and whatever suspension is used. The microelectromechanical system has a patent pending, and the team is looking for funding to further develop and test the system.

The other new sensor (shown at left) is an inexpensive plastic cylinder about as tall as a stack of four quarters. Several of these disposable, easily replaceable devices could be mounted not only on a helmet but elsewhere on a soldier or even inside a vehicle. Each sensor contains a paper that changes color when exposed to specific levels of pressure, which would provide valuable information for medics treating patients in the field. Successful proof-of-principle experiments performed at the High Explosives Applications Facility demonstrated the value of this sensor.

The University of Rochester's Blackman notes, "By comparing the effects of blasts on the head with those from head impacts, we'd be able to make some sense of the distinct mechanisms of injury, the damage a soldier might incur, and how a helmet might be designed to minimize both."

—*Katie Walter*

Key Words: Afghanistan, blast wave, combat helmet, improvised explosive device (IED), Iraq, traumatic brain injury (TBI).

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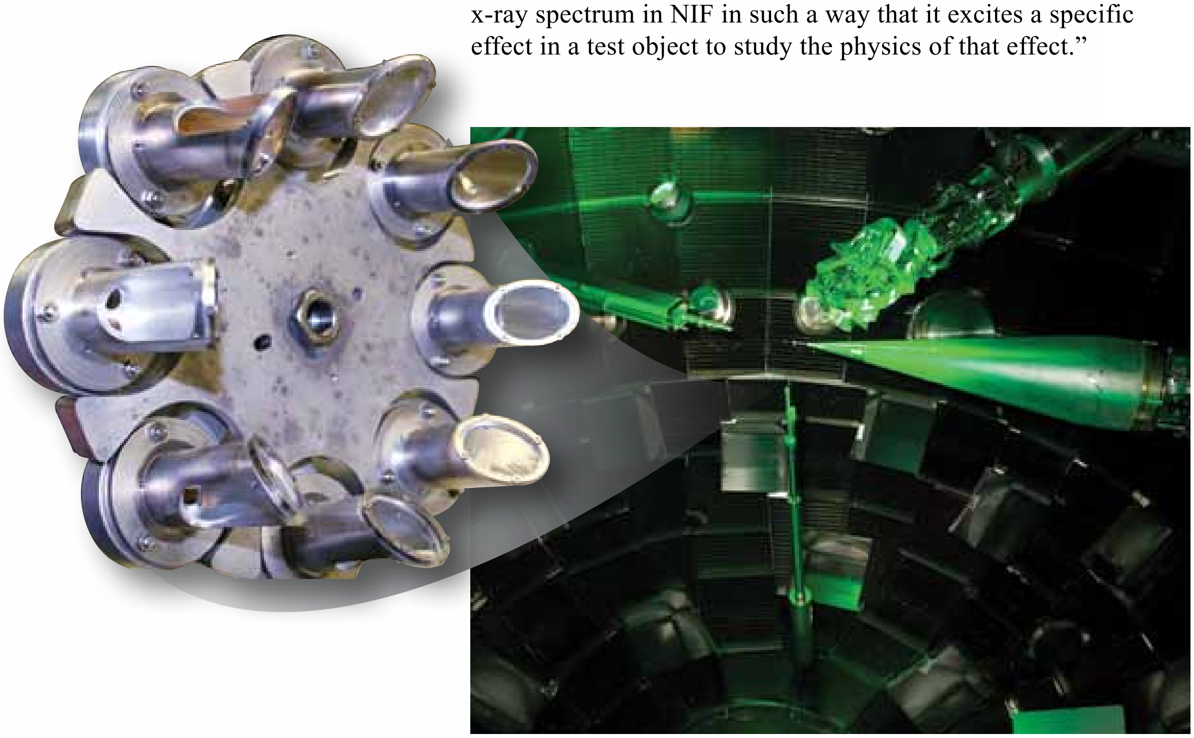
Testing Valuable National Assets for X-Ray Damage

HIGH-ENERGY x rays produced by high-temperature plasmas, such as the Sun or a nuclear blast in space, can damage surfaces, interfere with electronics, and disturb the interiors of valuable assets such as satellites, space-borne telescopes, solar panels, and components important to U.S. defense systems. Consequently, the Department of Defense's (DoD's) Missile Defense and Defense Threat Reduction agencies are interested in using lasers to create x-ray environments for studying the potentially damaging effects on such systems. DoD's interest aligns closely with the National Nuclear Security Administration's desire to produce advanced laser-based x-ray sources for diagnostic techniques and other applications.

The National Ignition Facility (NIF) produces these environments by using laser beams to heat a target that then releases a bath of x rays into the target chamber. "NIF is fantastic," says physicist Kevin Fournier, who leads the X-Ray Source Development Campaign for the Laboratory's NIF and Photon Science Principal Directorate. "We can make a tailored x-ray spectrum in NIF in such a way that it excites a specific effect in a test object to study the physics of that effect."



A test cassette, 25.6 centimeters in diameter, is assembled with samples and filters and inserted into the 10-meter-diameter target chamber (right) of the National Ignition Facility (NIF).

For example, mirrors coated with many reflective and protective layers on different substrates can be placed in the target chamber. "We can look at how the x rays produced by the laser hitting the target interact with the layers and use what we've learned to validate computer models for mirror survivability," says Fournier.

Specially Tailored Experiments

One reason NIF works so well for this application is that the experimental conditions are very reproducible. The laser energy produced from shot to shot varies less than 2 percent, and the x-ray output varies correspondingly by only 2 to 4 percent. Furthermore, because the laser pulse is highly configurable and thus flexible, experiments can be designed to have specific characteristics.

"If we want the x-ray energy to have a certain shape or the x-ray power to have a certain history," says Fournier, "we can run a pre-shot design calculation for the requested amount of laser power. In this way, we can tailor the x-ray pulse to be delivered precisely to the experimenter's requirement. And over time, we can continue to improve our sources, or targets, and develop new ones as needed by our users."

Before NIF was available, Fournier's group conducted experiments using the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics in New York, in collaboration with the two DoD agencies as well as researchers from Sandia National Laboratories and the United Kingdom's Atomic Weapons Establishment. One project at OMEGA studied aerogel targets doped with titanium or germanium. (See *S&TR*, October 2005, pp. 19–22.) "Part of the activity was to develop x-ray sources matched to available energy at OMEGA that would one day lead to tunable x-ray sources at NIF," says Fournier, "and now, we have just that."

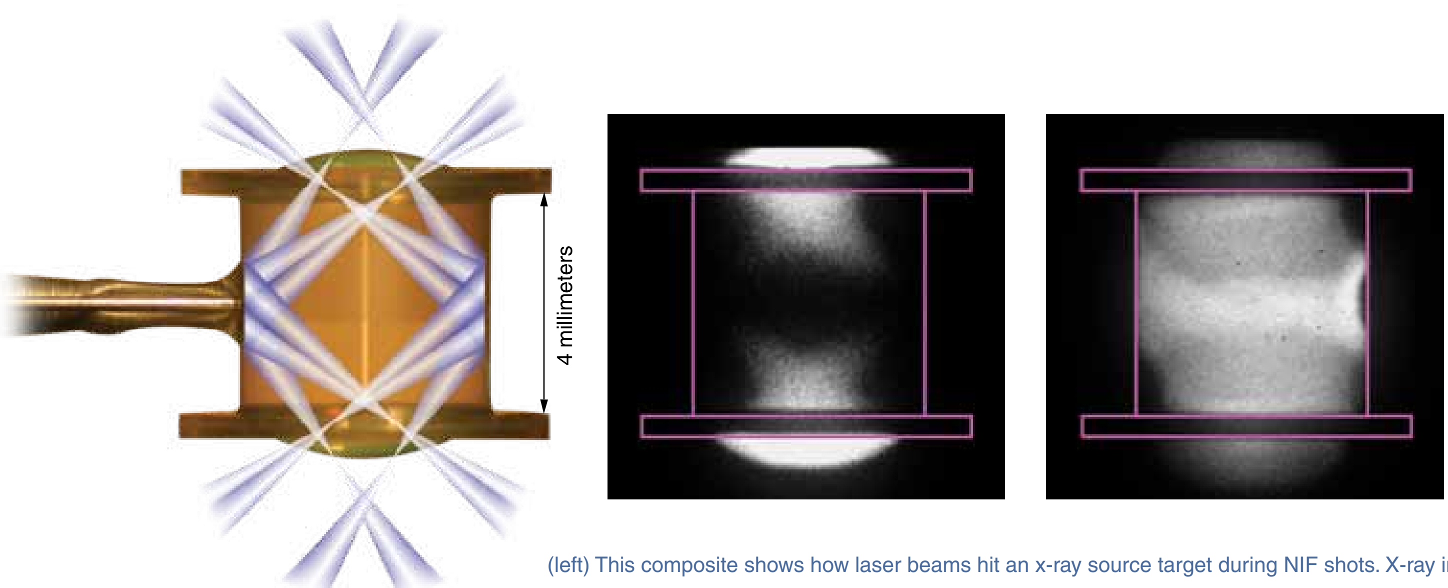
NIF experiments produce higher levels of x-ray energy than OMEGA, which is important for studying macroscopic test objects, and they offer greater flexibility in terms of controlling spectral content. "NIF also allows tailored x-ray pulses of longer duration than OMEGA," says Fournier. In addition, the high levels of x-ray output from NIF targets let researchers place test objects at a sufficient distance, depending on the size of the object, from the x-ray source so that the resulting flux of x rays onto a large object is very uniform across the entire test body.

Another important feature is NIF's target chamber. The 10-meter-diameter sphere is so large that in the future, full-sized subsystems could be placed inside—a setup called, "hardware in the loop," says Fournier. "Probes placed around a device to monitor it will provide us with data that reveal how the device functions during an x-ray event."

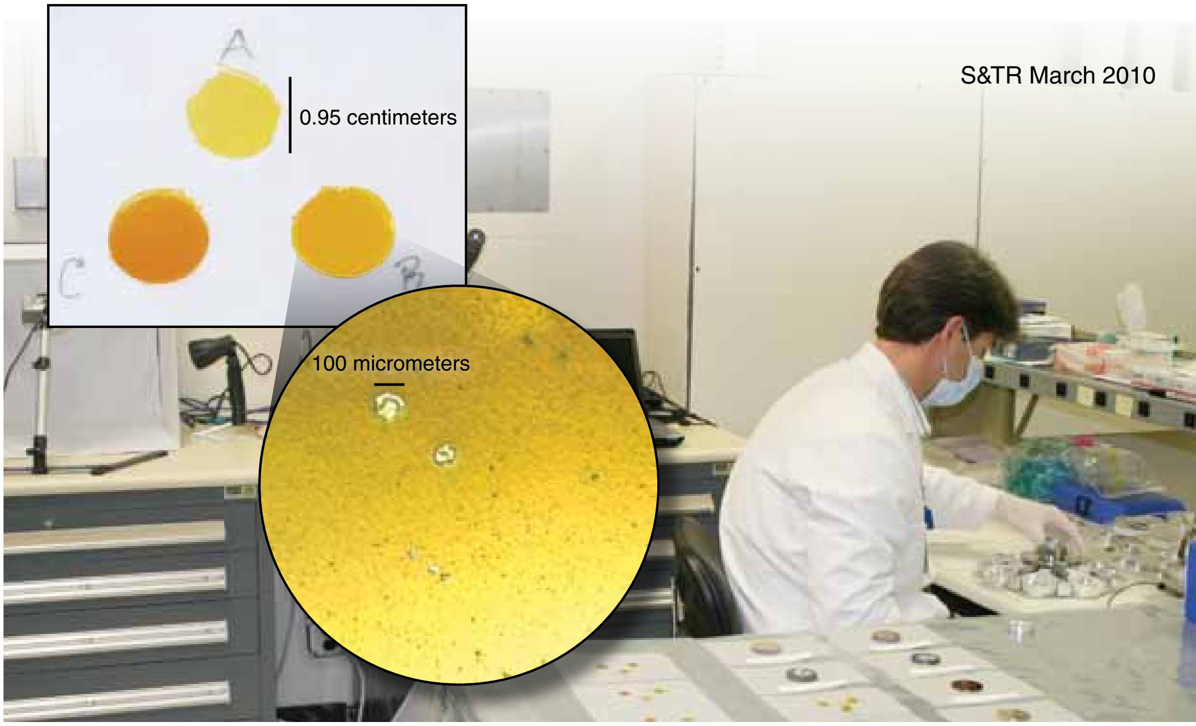
Unique Gas-Filled Targets

To produce the x rays needed for these studies, Fournier's team used a gas-filled tube containing a mixture of argon and xenon as the target. As laser beams propagate through the tube, they heat the gas and ionize material to produce a plasma, which at 50 million degrees, is an efficient source of x rays. This novel target design converts laser energy to x rays with efficiencies approaching 75 percent. Two diode-based detectors measure the x-ray yield during experiments.

The goal of these experiments is to develop and validate a platform for repeatedly exposing test objects to high-power, high-total-dose x rays with a specific energy and pulse shape. (For more information on NIF's experimental capabilities, see lasers.llnl.gov/for_users/experimental_capabilities/index.php.) One important aspect of these experiments is to determine if debris produced by



(left) This composite shows how laser beams hit an x-ray source target during NIF shots. X-ray images from an experiment captured the target's response at (middle) 0.80 and (right) 1.87 nanoseconds. The shot used 112 beams with a 5.2-nanosecond, 350-kilojoule square pulse.



Livermore collaborator Richard Horton works in the NIF laboratory set up for photographic and microscopic investigation of filter and sample surfaces. Filter films (top inset) shape the x-ray spectrum onto a sample. A micrograph (bottom inset, at 50× magnification) of a film's central region shows an intact surface and small amounts of splattered prefilter material.

the target could affect the results. A five-shot campaign completed in November 2009 fielded 24 to 48 witness films in the target chamber during each shot. "When we examined the films with a microscope, we found only tiny droplets of filter material and no target debris or pinholes," says Fournier. "We concluded that the platform will allow us to study x-ray interactions without the complication of target–debris interactions."

International Collaborations

Fournier's team has partnered not only with other U.S. agencies and laboratories but with researchers in other countries as well. For example, work with colleagues in France to develop metallic-foil-cavity targets shows great promise for efficient laser-to-x-ray conversion. "The United Kingdom is also strongly involved," Fournier says. "Both the Atomic Weapons Establishment and Ministry of Defence are interested in pursuing radiation-effects experiments at NIF."

When nuclear weapons were being developed in the 1970s and 1980s, scientists didn't have the computer simulation capability available today. "Now, we have the computing power to perform real three-dimensional simulations of components. What is unknown is the quality and validity of the detailed physics models in the computer codes," says Fournier.

"With NIF's precisely controlled environment, we can isolate the physical properties when radiation interacts with materials. These results can be modeled in the computer codes. We can then investigate the microphysics in the regimes of interest to see if the simulations are valid."

Fournier adds that Livermore has always excelled at high-temperature plasma physics. In fact, this expertise is one of the things that attracted him to work at the Laboratory. In 1992, while studying atomic spectroscopy and theory applied to high-temperature plasmas in a graduate program at Johns Hopkins University, Fournier was sent to Livermore for two weeks to learn how to run one of the Laboratory's computer codes. As it turned out, he never left. "I was like a kid in a candy store," he says. "Livermore was a wonderful place to complete my graduate work."

In 2001, Fournier jumped to experimental work under the guidance of scientists focused on weapons effects testing. Then he got involved with the NIF Radiation Science Users Group, which eventually led to his current assignment.

Fournier enjoys experimental work. "I like being able to do a test, get results, and write a report. I like the task-oriented, results-driven culture of DoD."

When discussing the team's recent experiments, Fournier realizes that "NIF time" is deceiving. The work had taken place only the previous week, although it seemed to him like a month ago so much had happened since. "We get so involved, we lose track of time."

Researchers working to develop x-ray sources continue to focus on the campaign's mission. "The end game is to demonstrate a robust, repeatable, tunable platform for generating x-ray-driven radiation effects testing," says Fournier. "The survivability of systems operating in a nuclear environment is key to our national defense."

—Cindy Cassady

Key Words: gas-filled target, National Ignition Facility (NIF), OMEGA laser, plasma physics, radiation effects testing, x rays, x-ray source.

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An Efficient Way to Harness the Sun's Power

SOLAR energy technologies have been around for ages. Since the discovery that sunlight passing through glass would start a fire, humans have been searching for methods to harness the Sun's radiant energy. Technologies that exploit solar energy are quite important in the modern world because, unlike fossil fuels, the Sun is a renewable, sustainable energy source.

[illegible] photovolta[illegible] [illegible]mbined with electric batteries provide energy [illegible] electronic devices, homes, and even the International Space Station. However, widespread use of the Sun as a primary energy source is hampered by two main factors. Solar electricity is expensive when compared to the cost of power produced by burning fossil fuels, and sunlight is intermittent—the Sun's energy can only be collected during daylight hours.

To address these problems, Livermore scientist Charles Bennett is developing a solar thermal technology that takes a new approach to storing and using the Sun's energy. Called GyroSolé™, the heat-powered engine and thermal-energy-storage system collects solar energy and stores it as unrefined heat instead of refined electricity.

Storing energy in the form of heat is particularly advantageous because most power consumption is devoted to thermal management—to heat and cool our homes, the food we eat, and the water we use throughout the day. In California, for example, approximately 85 percent of the total energy used in the average residence is devoted to thermal management rather than power generation. Because of this dominance, the thermal energy emerging from a heat-powered engine may be so well matched to the energy needs in a typical home or business that almost none of this heat need be wasted.

[illegible] Plan for Waste Hea[illegible]

[illegible] conventional electrical grid, centralized power plants transport electric power over wires, which often run hundreds of kilometers before reaching the business and residential areas that consume electricity. These power plants operate by burning fossil fuels to generate heat that is then refined into ele[illegible] refinement process produces a great deal of thermal energy tha[illegible] not distributed as electricity. Containing this heat for transport over a long-distance network would be too expensive to implement, [illegible] instead, power plants reject it, sending it to cooling towers [illegible] it to the environment. The magnitude of the rejected [illegible] is significant. In 2007, the U.S. alone lost almost 60 percent of the energy produced at power plants.

GyroSolé takes advantage of the waste heat to provide heating, cooling, and electricity independent of the grid. Rather than relying on centralized power plants with long-distance transmission and distribution networks, consumers would install the generator where energy is consumed—at their homes or businesses. The system would be particularly advantageous in remote locations, where a conventional network would be too expensive to build. It also could send any extra power to the grid, helping to further reduce fossil-fuel consumption.

Bennett estimates that GyroSolé can supply electric power for about six cents per kilowatt-hour and heating for two cents per kilowatt-hour. In contrast, the current retail price for residential electric power is about 10 cents per kilowatt-hour. Photovoltaic solar power would be even more expensive without government subsidies, plus solar panels do not directly produce heating or cooling.

GyroSolé was inspired by a concept for powering an aircraft through the night with solar energy collected during the day.

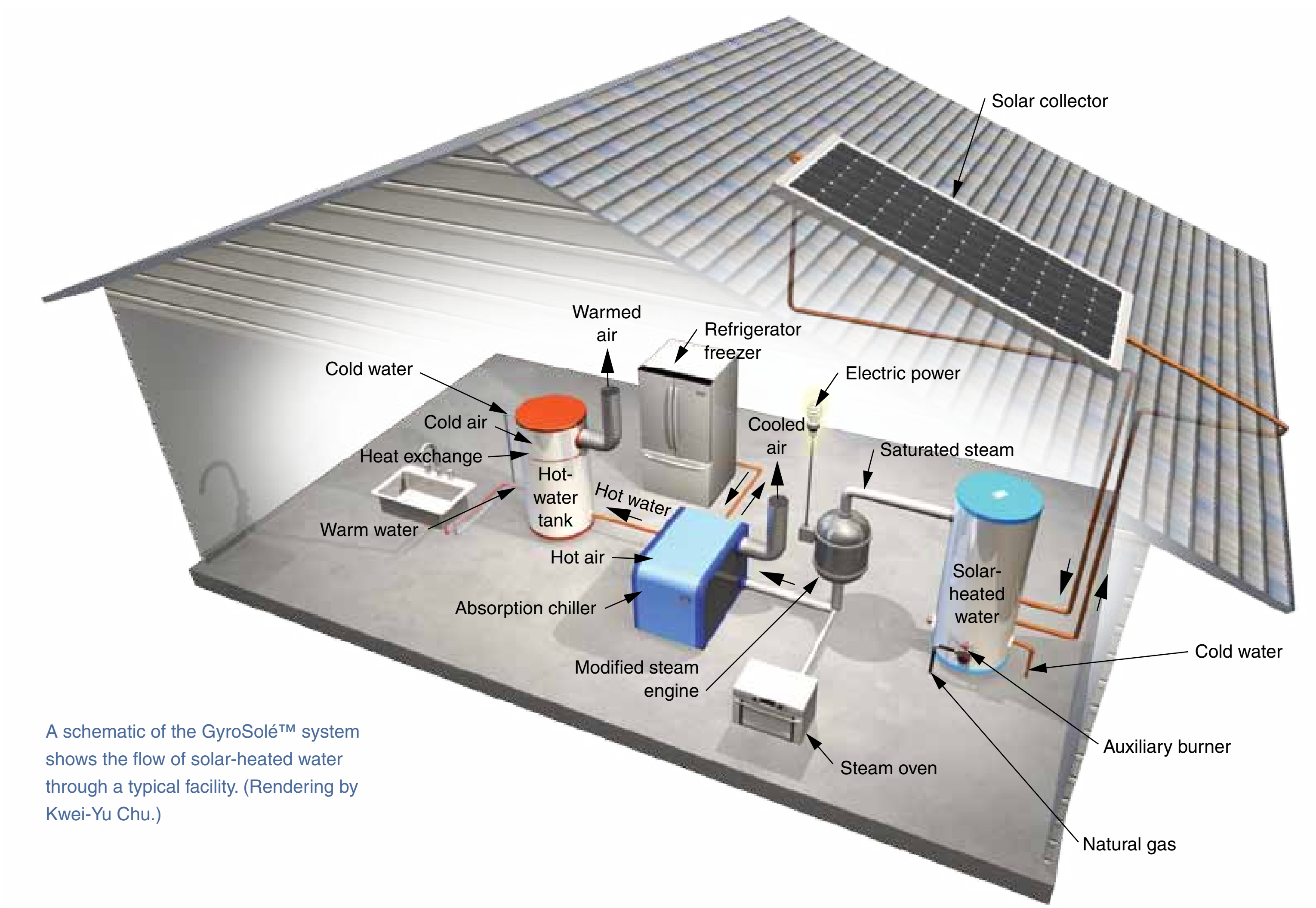
Key issues for the solar-powered aircraft were energy storage and efficiency to ensure that power was available through a 24-hour cycle. The solar aircraft project led to innovations that Bennett adapted for the residential application, which was initially funded by Livermore's Laboratory Directed Research and Development Program.

SUNsational Energy Technology

A key component of GyroSolé is the steam engine that drives the system's electric generator. The engine is a hybrid of old and new technologies, combining a reciprocating steam engine with some modern internal combustion engine parts and harmonic oscillator valves. "This design eliminates much of the mechanical gear used to actuate the valves in conventional reciprocating engines, which reduces the efficiency in those systems," says Bennett. The harmonic engine is tailor-made to deliver power at a fixed frequency, such as 60 hertz, and it operates with saturated steam, instead of the superheated steam required to protect the blades of conventional steam turbines. As a result, GyroSolé will attain the highest possible thermal efficiency for its temperature range of operation.

The GyroSolé system (shown in the figure below) is designed for the typical variations in power consumption, especially in winter, when demands for heat increase at night, while those for electricity are highest during the day. A solar collector traps radiant energy while the Sun is shining and uses it to heat water in boiler tubes. Steam from these tubes is apportioned between the modified steam engine, for immediate power production, and a hot water tank for later use. Consumers may also choose to install an auxiliary heating system powered by natural gas to have a backup energy source during periods of inadequate sunlight.

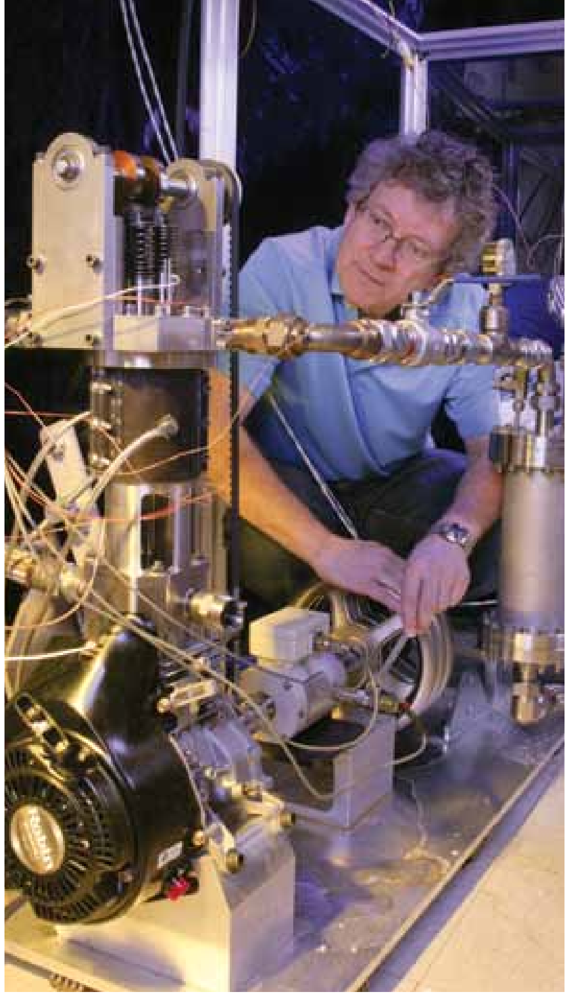
In a typical application, water is heated to about 180°C, which produces a pressure of 10 atmospheres, or 1 megapascal. Spent steam emerging from the engine at about 100°C and 1 to



A schematic of the GyroSolé™ system shows the flow of solar-heated water through a typical facility. (Rendering by Kwei-Yu Chu.)

2 atmospheres of pressure is available for various uses. It may pass through a steam-driven absorption chiller to provide cooling for air conditioning or refrigeration, or it may be condensed to produce hot water or heat for other purposes.

To test some of the GyroSolé components, Bennett built a laboratory-scale prototype steam engine using parts from a commercial gasoline-powered internal combustion engine. (See the figure at right.) Because the steam engine is clean enough to deliver potable water, GyroSolé is safe to use for cooking. Water not consumed in cooking, washing, or other domestic chores emerges at just above room temperature, and thus almost all of the collected solar energy is used.



Livermore physicist Charles Bennett checks out the laboratory-scale prototype steam engine, which is a key part of the GyroSolé system he designed. The prototype couples the crankcase of a commercial gasoline-powered engine to a custom steam expansion cylinder.

A Truly Bright Idea

Livermore's Industrial Partnerships Office (IPO) is using GyroSolé and another Livermore device—the flywheel battery developed by physicist Dick Post—in a different type of beta test: working with facilities to showcase Laboratory-developed technologies. Under a grant from the Department of Energy's Energy Efficiency and Renewable Energy Office, IPO is partnering with the Arc of Hilo, a nonprofit organization on the island of Hawaii, to integrate the two clean-energy technologies into the Hilo plant's food-processing operations.

"An important step in technology maturation is putting a prototype to work," says Annemarie Meike, a business development executive in IPO. "In the Arc of Hilo collaboration, we're focusing on specific applications. That way, we can see how the systems look in operation and more quickly identify ways to improve them."

The Arc of Hilo has leased a 1,700-square-meter warehouse where local farmers can develop food products, such as fruit leather, jams, and natural sweeteners. The plant will integrate both Livermore technologies into the food-processing scheme, which could reduce its electric bill by 50 percent. "Hawaii is a logical place to start," says Bennett. "The seven-island state imports the fuel it uses to generate power and thus has one of the highest electricity rates in the nation."

The Hilo plant is an especially good match for GyroSolé because food processing requires all facets of thermal management: cooling for refrigeration and air conditioning; heating for cooking, cleaning, and space heating; and electric power to operate the plant's equipment. In addition, excess electricity generated at the plant will be delivered to the Hawaiian power grid.

Meike adds that the collaboration offers benefits for everyone involved. "Our licensing partners can build production-scale applications that showcase their products incorporating the Laboratory's technologies," she says. "At the same time, our inventors have the opportunity to develop their ideas into working technologies with specific requirements even before the commercial application of ultimate interest to the licensee is in full production. In our beta test for this type of technology showcase, the Arc of Hilo is bringing a new resource to the island—one that will help create jobs and reduce the cost for developing food products."

Bennett hopes the GyroSolé system will expand the use of solar energy technologies. "A reliable solar heating system can save energy, reduce utility costs, and produce clean energy," he says. "This technology encourages the transformation of global energy production from a fossil-fuel-dominated architecture to one that is both indefinitely sustainable and free from greenhouse-gas production."

For GyroSolé, the future holds many sunny days.

—Kristen Light

Key Words: electric power, GyroSolé™, heat energy, renewable energy source, solar energy, solar thermal technology, steam-powered engine, technology transfer, thermal-energy storage.

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In this section, we list recent patents issued to and 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.

Awards

Laboratory engineer **Jeff Latkowski** received the **2009 Excellence in Fusion Engineering Award** from **Fusion Power Associates**. The award recognizes Latkowski's leadership and contributions to fusion energy programs and cites his work on Livermore's Laser Inertial Fusion Energy project, the final safety analysis for the National Ignition Facility (NIF), and the national High Average Power Laser Program—a collaboration with other national laboratories, universities, and industry to develop the science and technology for laser inertial confinement fusion.

Bill Goldstein, the associate director for Physical and Life Sciences, was named a **fellow** of the **American Association for the Advancement of Science** (AAAS), one of 513 members to receive the distinction this year. The honor, bestowed on AAAS members by their peers, was awarded to Goldstein for his work in plasma modeling and diagnostics and for his leadership in support of the Department of Energy's (DOE's) national security programs.

Goldstein was among the first to apply a set of atomic modeling codes to advance understanding of atomic processes in plasmas for high-energy-density applications. He later helped develop the first spectroscopic diagnostics for astrophysical photoionized plasma, designed early astrophysics experiments using high-power lasers, and pioneered the use of detailed atomic models for predicting energy balance in tokomaks. Goldstein was also instrumental in developing the nation's Stockpile Stewardship Program, and he outlined the first systematic program of high-energy-density science for NIF.

The **American Physical Society** (APS) selected five researchers from the Laboratory's Physical and Life Sciences Directorate as **fellows** for 2009.

Physicist **David K. Bradley** was honored for "the development and use of high-speed optical and x-ray instrumentation to discover new phenomena in high-energy density plasmas."

Laurence Fried, a group leader in the Chemical Sciences Division, was recognized for "outstanding contributions to the physics and chemistry of shocked materials; the high-pressure, high-temperature equations of state of solids and liquids; and the prediction of energetic material reactivity, most notably the existence of sub-picosecond chemistry in high-temperature dense liquids."

Laboratory retiree **Arthur Molvik**, who worked in the Fusion Energy Program, was cited for "outstanding contributions to diverse areas of plasma physics and technology, including MHD [magnetohydrodynamic] stability limits in mirrors, and the physics of gas and electron accumulation in the ion accelerators."

Christine Orme, a staff scientist in the Bioscience and Biotechnology Division, was selected for "outstanding contributions in understanding the fundamental physics of crystallization and materials assembly with application to biomineralization, biomimetic synthesis, and shape control of nanostructures."

Research scientist **Scott Wilks**, was honored for "pioneering contributions to the understanding of intense and ultra-intense laser–plasma interactions and their applications to high-energy-density science, including fast ignition, ion acceleration, and positron generation."

The APS selection process is extensive, and election to the fellowship is limited to no more than one-half of one percent of the society's membership for a given year. In 2009, APS designated more than 200 fellows.

Laboratory physicist **Omar Hurricane** received the **2009 Ernest Orlando Lawrence Award** in the field of national security and nonproliferation. The **DOE** award honors midcareer scientists and engineers for exceptional contributions in research and development that support DOE and its mission to advance national, economic, and energy security. Hurricane is a program leader in the Weapons and Complex Integration Principal Directorate.

Frank Wong, a nuclear engineer in the Physical and Life Sciences Directorate, received a **Director's Award** from the **Domestic Nuclear Detection Office**. The award honored a project team led by Wong for its contributions to the Summer Hard Problem Program (SHARP) for the Office of the Director of National Intelligence (ODNI) in the area of nuclear forensics and attribution. According to ODNI program manager Margaret Dillard, Wong's project "is to date, the most robust and professional SHARP ever planned and executed. He has set the bar high for future SHARPs—for which the ODNI is very grateful."

Abstract

Responding to an Attack Involving Chemical Warfare Agents

Lawrence Livermore scientists are working closely with federal, state, and local agencies to strengthen plans for responding to the possible use of chemical warfare agents. For example, chemists in the Forensic Science Center are helping the Environmental Protection Agency develop and validate reliable, accurate, and extremely sensitive methods for analyzing chemical warfare agents and their degradation products. The center is one of two U.S. laboratories internationally certified to identify these often-lethal compounds, which are sometimes referred to as "the poor-man's atomic bomb." Other Livermore researchers have applied their expertise to develop guidance documents and effective methods for response, remediation, and recovery following an attack. As part of a long-term demonstration project funded by the Department of Homeland Security, Livermore scientists participated in a three-day event that focused on procedures, plans, and technologies to rapidly restore a contaminated airport or major transportation center. The Livermore contribution included strengthening emergency conduct-of-operations models and elucidating the interactions between chemical agents and indoor surfaces and how they ultimately affect the environment.

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Star-Rated Performance

Recent experiments performed at the National Ignition Facility are demonstrating the laser's capabilities for bringing star power to Earth.

Also in April/May

• Researchers are discovering how wind turbines can extract more power from the wind.

• Carbon-14 dating reveals that less than half of our cardiomyocyte heart cells are replaced over a lifetime.

• A new bionanoelectronic device takes the first step toward converting biological signals into electronic impulses.

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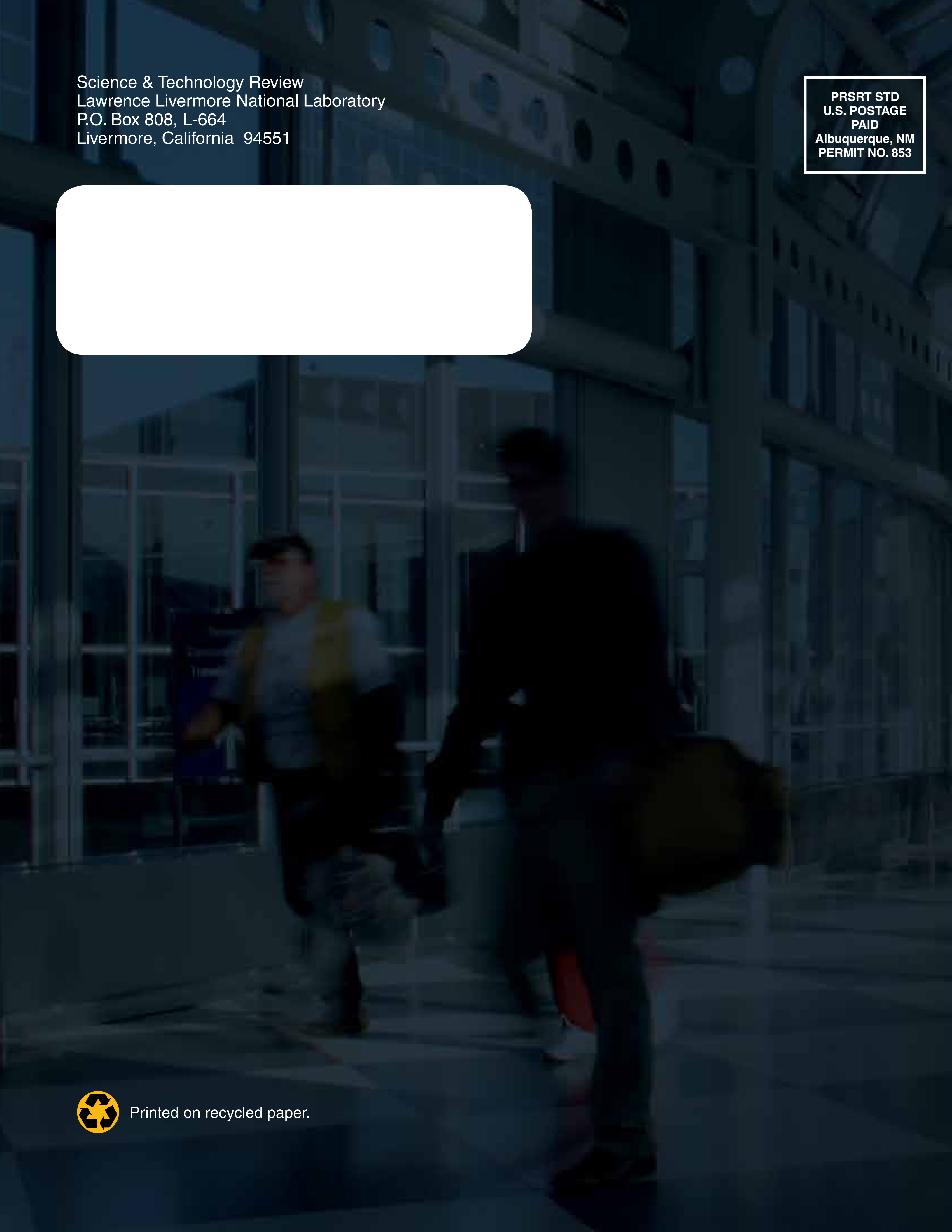

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