September 2007

Science & Technology REVIEW

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Orchestrating Hydrodynamic Tests

Also in this issue:

- Three-Dimensional Lithography Goes Nano
- Assessing the Threat of Biological Attack
- Space Hunt for Antiparticles
- Teller's Legacy in Applied Physics and Defense

About the Cover

Nonnuclear hydrodynamic (or hydro) tests are the most valuable experimental tool for studying the implosion performance of a nuclear weapon's primary stage. Researchers conduct these high-explosives tests at the Contained Firing Facility at Site 300, Livermore's Experimental Test Site. Ramrods, individuals with a broad technical and project management background, ensure that hydrotests are properly instrumented and are completed on time and within budget. The article beginning on p. 4 describes the duties of Livermore's ramrods and the challenges they face in obtaining maximal data from every experiment. On the cover, electronics technician and console operator Rich Rose (left) and ramrod Steve Bosson monitor the countdown to a hydrotest from the Contained Firing Facility control room.

Cover design: Alexandria Ballard

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 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 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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National Nuclear Security Administration

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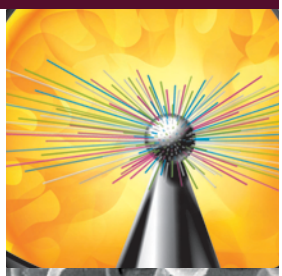

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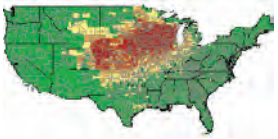

Teller Centennial Highlight

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Laboratory garners five R&D 100 awards

Livermore researchers turned in another strong showing in the annual R&D 100 awards competition, winning five awards. Each year, *R&D Magazine* presents these awards to the top 100 industrial, high-technology inventions submitted to its competition.

The five Livermore inventions honored are as follows:

• Microelectromechanical System–Based Adaptive Optics Scanning Laser Ophthalmoscope, an instrument developed in conjunction with five universities and Boston Micromachines Corporation, will enable clinicians to image microscopic structures of the living eye, such as individual photoreceptors and ganglion cells, and measure aberrations.

• Noninvasive Pneumothorax Detector is a handheld device designed to detect pneumothorax or collapsed lung, which if not promptly diagnosed and treated, can cause death within minutes.

• Continuous-Phase-Plate Optics with Magnetorheological Finishing, developed in conjunction with Zygo Corporation of Middlefield, Connecticut, and QED Technologies of Rochester, New York, is a precise system for fine-tuning the laser beam of kilojoule- and megajoule-class laser systems such as the National Ignition Facility.

• Large-Area Imager provides mobile radiation detection and imaging, allowing investigators to detect and interdict illicit nuclear materials.

• *Hypre* is a software library designed to solve the extremely large systems of linear equations that form the primary bottleneck to many large-scale computer simulations, enabling researchers using supercomputers such as BlueGene/L and ASC Purple to conduct simulations faster than ever before.

S&TR will devote its October issue to detailed reports on these award-winning inventions and the teams that created them.

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Adaptive optics illuminates black holes

Observations using a Laboratory-built laser at the W. M. Keck Observatory allowed Livermore researchers to pinpoint the location and composition of two supermassive black holes more than 300 million light years from Earth. Supermassive black holes have the mass of millions or even billions of suns and are thought to exist in the center of most galaxies, including the Milky Way.

The two black holes observed by the Livermore team are about 2,500 light years apart and are drifting toward one another. As their home galaxies collide, the pair will eventually merge into one even larger supermassive black hole. Results from this research appeared in the June 29, 2007, edition of *Science*.

The observations at Keck Observatory lend support to the theory that black holes at the center of galaxies reach their immense mass through mergers with other nearby black holes. Scientists are interested in studying galaxy mergers so they can better understand how galaxies evolve and what role black holes play in the process.

The technologies making these observations possible are adaptive optics, which corrects for the blurring effects of Earth's atmosphere, and the Livermore-developed artificial laser guide star, which allows adaptive optics to be used over a large fraction of the sky. The images produced are 10 times clearer than those produced with conventional imaging techniques.

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Reconstructing prehistoric fur seal behavior

In a collaborative study, researchers from Livermore's Center for Accelerator Mass Spectrometry, University of California at Santa Cruz, University of Washington, National Health and Environmental Effects Research Laboratory, Environmental Protection Agency, and Stanford University used nitrogen and carbon analysis to solve a puzzle previously raised by California's fossil record of northern fur seals. Today, these seals live and breed at high latitudes, mostly on islands in the Bering Sea. However, anthropological studies show that northern fur seals once bred in temperate latitude regions of California, the Pacific Northwest, and the eastern Aleutian Islands. The researchers found that northern fur seals in California were not visitors from other breeding grounds, but rather were year-round residents.

By studying the differences in nitrogen isotopic content found in the ancient bones, the scientists also determined that northern fur seals from breeding colonies in temperate latitudes weaned at a much older age than their modern counterparts, which are typically weaned at four months. Paired analysis of the stable carbon and nitrogen allowed the researchers to estimate where the seals were feeding in the ocean. They were able to reconstruct the species' prehistoric range and see changes in biogeography and behavior over longer timescales than previously was possible.

"The analysis demonstrates that northern fur seals had more temperate-latitude breeding colonies in the past, with breeding populations in California, the Pacific Northwest, and the eastern Aleutian Islands," says Tom Guilderson of Livermore. "In addition, these populations used a different reproductive strategy than modern populations." The team's results appeared in the June 5, 2007, edition of the *Proceedings of the National Academy of Sciences*.

Contact: Tom Guilderson (925) 422-1753 (guilderson1@llnl.gov).

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Ramrods Key to Extraordinary Record

IT seems that every scientific discipline is divided into many specialties. A physicist, for example, may specialize in such areas as nuclear reactions, lasers, computation, cosmology, or quantum mechanics. Bucking the growing trend toward specialization are Livermore ramrods, each of whom is a scientist, engineer, technician, diagnostician, and high-explosives, safety, and hazardous materials expert—all combined into one individual.

As described in the article beginning on p. 4, ramrods ensure hydrodynamic (or hydro) tests conducted at the Laboratory's Site 300 perform as designed. A hydrodynamic test uses nonnuclear materials to analyze the first phase of a nuclear weapon, the implosion of the primary stage. A fully integrated hydrotest can cost more than $1 million and require more than a year of planning, parts production, and assembly. Because the test involves blowing up the carefully instrumented experimental package, we have only one opportunity to get things right. In more than 55 years of hydrotests at Livermore, totaling several thousand tests, a handful of individual experiments have failed, but we have always obtained the data we needed from the test series. That amazing record is a tribute to the ramrods, Site 300 bunker crews, and design physicists.

Ramrods, who are unique to Livermore in the National Nuclear Security Administration (NNSA), warn the design physicist when an aspect of a proposed experiment doesn't make sense or can be done more efficiently. Ramrods are often asked to come up with a clever solution to a seemingly intractable problem. In solving a problem, they are just as likely to use a socket wrench as a sophisticated software program.

Before Livermore physicists, led by Seymour Sack, developed the first two-dimensional computer codes in the 1960s, scores of hydrotests were conducted in trial-and-error fashion prior to each nuclear detonation at the Nevada Test Site. Over the years, as our computer simulation power has increased, we have required fewer hydrotests for stockpile stewardship. At the same time, the amount of data obtained from each test has increased significantly.

Although we anticipate a continued decline in the number of hydrotests, we will always need them because they enhance our knowledge of how nuclear weapons operate and how materials behave under extreme conditions. Two types of data from hydrotests are fed into two- and three-dimensional supercomputer simulation codes. The first type concerns the properties of strongly shocked materials. The second type shows the integrated behavior of components comprising a certain primary design. These data are compared to those from other hydrotests and our theoretical models and are incorporated into our simulation codes.

The Laboratory's simulation capabilities have continued to grow as new generations of NNSA's Advanced Simulation and Computing supercomputers are installed. During last year's effort to design a reliable replacement warhead, 1,370 years (yes, years!) of computer runs were executed in less than six months to develop a prototype primary design for a hydrotest. This feat was possible only because of the miracle of tens of thousands of computers running in parallel. The hydrotest went off perfectly, generating data that were so outstanding we dispensed with the originally scheduled second test.

In 2006, we also conducted groundbreaking simulations of the growth of tantalum grains. We can't yet watch such an event occur experimentally. Neither can we figure out the dynamics theoretically. But we can watch grains grow on a computer, atom by atom.

This year, a team from the Defense and Nuclear Technologies Directorate's B Program accomplished a major breakthrough in understanding how a nuclear weapon functions. This discovery, which was not anticipated theoretically, was observed in ultrahigh resolution on our BlueGene/L machine, the most powerful supercomputer in the world.

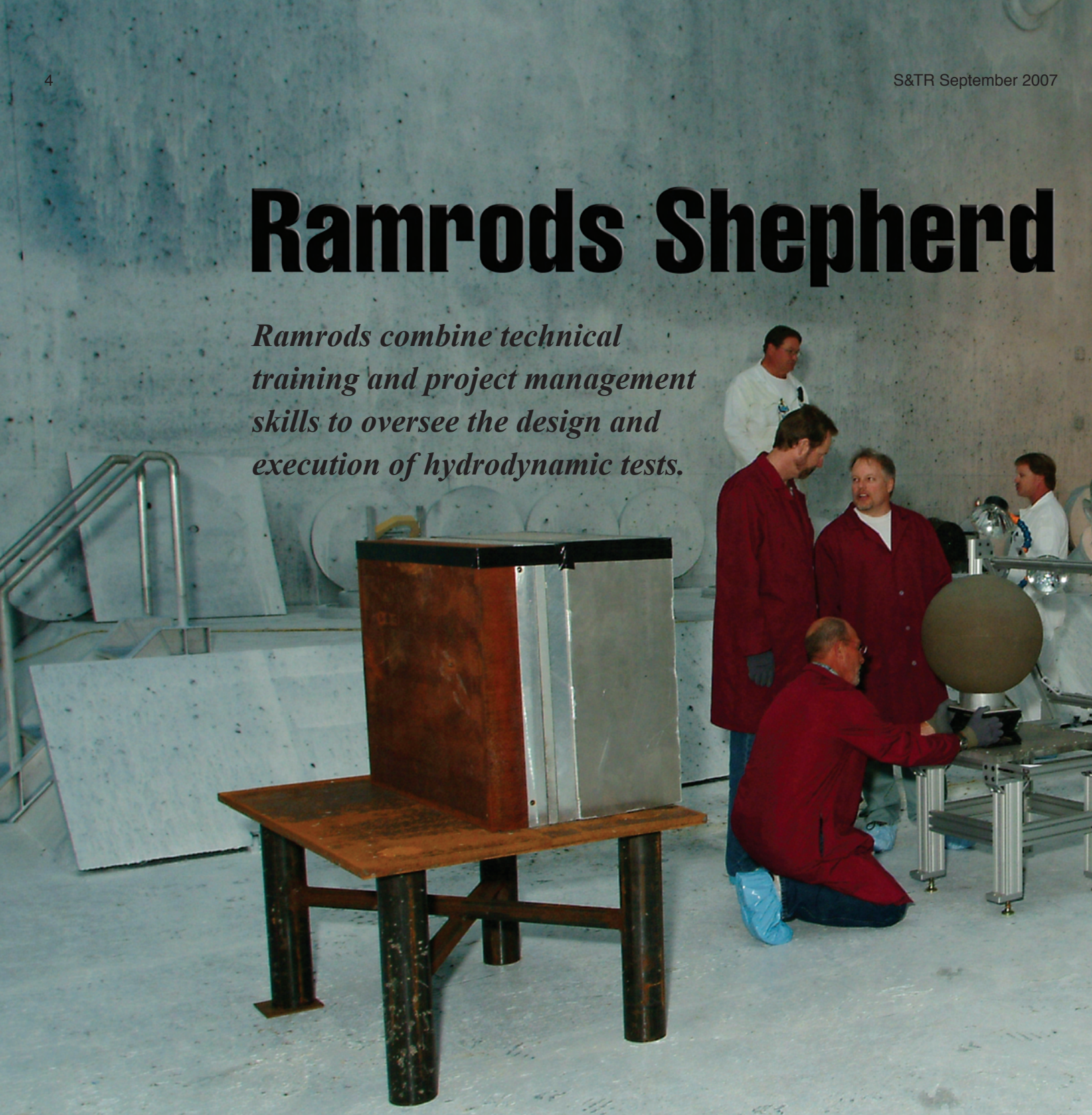
It's doubtful such advanced simulations would exist had it not been for Edward Teller. Teller understood that numerical simulation of physical problems would be invaluable to scientific discovery. Even before the Laboratory opened in September 1952, Teller and Ernest O. Lawrence placed an order for the first Univac computer.

I believe Teller would be pleased with our latest high-resolution simulations. I know he would be proud of our ramrods, who combine scientific acumen, experience, and practical know-how to advance national security.

■ Bruce T. Goodwin is associate director for Defense and Nuclear Technologies.

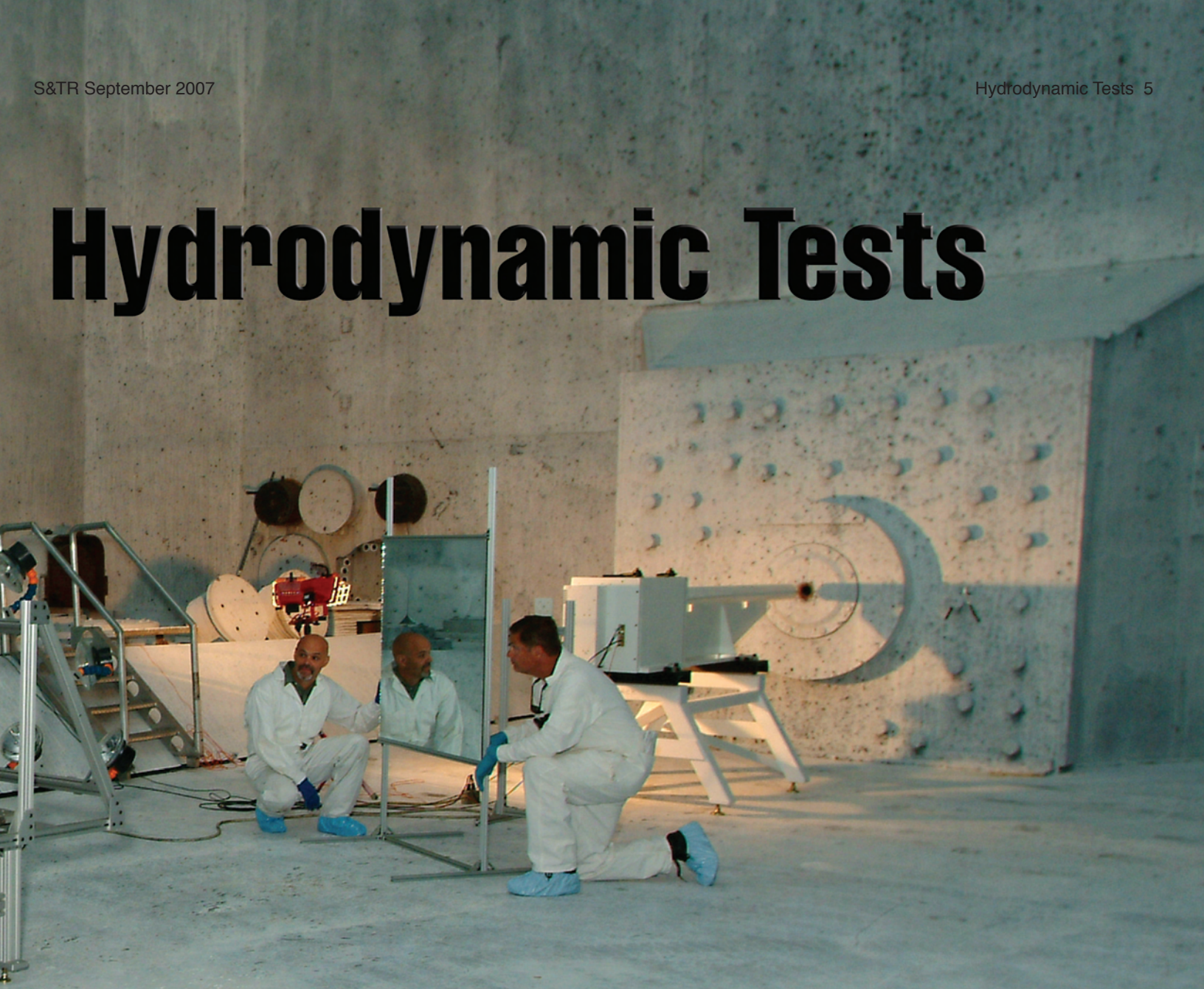
Ramrods Shepherd

Ramrods combine technical training and project management skills to oversee the design and execution of hydrodynamic tests.



Ramrod Steve Bosson (fourth from left) works with a crew at Site 300 to set up a hydrodynamic test of a mock weapon primary inside the firing chamber at the Contained Firing Facility. Top left to right are Steve Weinzapfel, Mike Wagoner, Jack Lowry, Bosson, Kevin Gunn, Rich Rose, and John Given.

Hydrodynamic Tests



IN the Wild West, ramrods oversaw cattle drives, keeping the herd moving over great distances and making sure it arrived at market on the scheduled date. For nearly a half-century, ramrods at Site 300, Livermore's Experimental Test Site, have kept crucial nonnuclear weapon tests moving on schedule. From the earliest experimental design discussion to the shot firing—at times a year or more later—ramrods are key to ensuring that hydrodynamic tests are completed on time and within budget and provide maximal data.

"Ramrods represent the design physicist in the field," says Steve Bosson, one of four Livermore ramrods. Two other ramrods, Bob Kuklo and Stan Ault, also work on hydrodynamic tests, while ramrod Robert Mailhot works on dynamic tests of plutonium conducted at the JASPER (Joint Actinide Shock Physics Experimental Research) Facility at the Department of Energy's Nevada Test Site.

During a hydrodynamic test, the detonation of high explosives sends a shock wave through the test material, causing it to flow like a liquid. Liquid behavior is described by hydrodynamic equations, so the experiments are called "hydros." For each experiment, Bosson works closely with engineers, technicians, design physicists, and crews at Site 300's firing facilities. He works primarily at Bunker 801, which is the site of the Contained Firing Facility. (See the box on p. 7.)

Bosson's responsibilities include helping weapon physicists design a test, creating a detailed experiment "preshot" (an exhaustive list of test specifications), supporting experiment design and readiness reviews, assisting and monitoring the experimental setup, and choosing diagnostic instruments and overseeing their emplacement. He also defines important environmental, safety, and health procedures for the experiment and

documents these procedures for the team's use. Finally, Bosson is responsible for reducing test data, reviewing test results with design physicists, and ensuring that test data are archived.

"The job of ramrod requires technical training as well as project management experience," says Jim Janzen, who leads the hydrotest experiments group in the Defense and Nuclear Technologies (DNT) Directorate. When Livermore researchers first began hydrotesting in the 1950s, weapon design physicists were assigned on a rotating basis to ramrod the experiments. By the early 1990s, the ramrod role became highly specialized, and the hydrotest group was formed in DNT.

"The ramrod is the interface between the designer and the bunker world of Site 300," explains Janzen. "He must be able to quickly identify problems or risks when he looks at an experimental setup.

"A great deal of experience is needed to perform the job of ramrod well," says Janzen. "Ramrods need an enormous amount of training in many subjects such as electronics, pressure, fabrication, safety, and classification. If a ramrod makes a mistake, he can't fix it because the shot is over in less than a thousandth of a second. Months of work can be wasted."

Most Valuable Experimental Tool

Bosson works mainly on nonnuclear hydrodynamic tests for the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program, although he also supports experiments on shaped charges and new munitions development for the Department of Defense. For stockpile stewardship, hydros are the most valuable experimental tool for diagnosing device performance of the primary stage in modern nuclear weapons. Primaries typically contain a sphere of plutonium called a pit. Hydrodynamic tests are conducted to study the behavior of surrogate primary-stage materials in response to extremely high temperatures and pressures. These tests are essential for the continued refining of computational models that simulate nuclear weapon performance. (See the box on p. 8.)

Design physicist Juliana Hsu says, "In the 1950s and 1960s, long before we had good computer codes, we did a hydro a week. We would fire one, change the design, build another, and fire it. As our codes got better, hydros got fewer in number." In the absence of underground nuclear testing, Livermore scientists today rely on computational models validated by previous nuclear data and nonnuclear experiments such as hydros to certify the stockpile.

Hydros allow scientists to characterize the energy delivered from a layer of high explosives surrounding a mock pit, the response of this pit to hydrodynamic shocks, and the resulting distribution of pit materials when they are highly compressed. In this way, the experiments reveal the behavior of a nuclear weapon design from high-explosive detonation

At Livermore's Site 300, Bunker 801 became the Contained Firing Facility when the bunker's open-air firing table was enclosed in 2000. The enclosure reduces emissions to the environment and minimizes the generation of hazardous waste, noise, and blast pressures. Construction of the firing chamber required 3,200 cubic meters of concrete and more than 2,000 metric tons of steel reinforcement. Equipment and diagnostic upgrades at the facility have greatly improved the quality of data gathered from hydrodynamic tests of mock weapon primaries.

to the beginning of the nuclear chain reaction. In most tests, scientists study a full-scale weapon mock-up, including the secondary, the other key section of a weapon, even though the experiments focus on the primary.

The experiments involve first detonating chemical high explosives that surround a pit made of inert (nonfissile) material. The pit's surrogate metal has mechanical properties similar to those of plutonium, but it cannot produce nuclear reactions. "We test these surrogates to understand what the differences are so that the designers can confidently model the experiments for the surrogate metals," says Hsu.

Except for the nonfissile materials, experiments use the same parts and materials as stockpile devices, including the same high explosives. "We want the experimental device to be as close to the actual nuclear device as possible without using fissile material," says Matt Wraith of the Defense Technology Engineering Division in the Engineering Directorate.

Starts with Concept

Bosson works closely with three to five weapon design physicists a year. He monitors simultaneously three to four shots that are in various levels of readiness for testing. He and other ramrods are physically located near the design physicists in DNT to enhance coordination. "Steve and I have offices in the same building so it's easy for one of us to visit the other and stay on top of developments as a test date approaches," says Hsu.

Contained Firing Facility Protects the Environment

Most hydrodynamic tests, especially those that contain potentially hazardous materials, are conducted at the Contained Firing Facility (CFF). Constructed in 2000 at Bunker 801, this facility allows the Laboratory to conduct explosives tests indoors to minimize noise and reduce the emission of hazardous materials in the environment. While emissions from open-air testing at Site 300 meet current environmental standards, the CFF ensures that testing can continue as environmental regulations change.

A staging area and diagnostic equipment rooms with ports into the firing chamber are included in the facility, along with a support area, offices, and a control room from which the shot is fired.

At the heart of the facility is the firing chamber. Measuring 16 by 18 meters wide and 10 meters high, the chamber contains the blast overpressure and debris from detonations of up to 60 kilograms of high explosives. About 3,200 cubic meters of concrete and 2,000 metric tons of steel were used to construct the firing chamber, enough to build the frame of a 16- by 18-meter, 60-story office building. The firing chamber has 2-meter-thick floors and doors. Detonations are conducted above a 150-millimeter-thick steel surface (shot anvil) embedded in the floor. In addition, movable 50-millimeter-thick steel plates protect the chamber from shrapnel traveling as fast as 1.5 kilometers per second.

John Given adjusts gas flow that feeds into the firing chamber on the other side of the wall.

Rich Rose, Steve Bosson, and John Given monitor test preparations from the control room in the Contained Firing Facility.

Hydrodynamic experiments comprise several types of tests. Integrated weapon experiments (IWEs) re-create the exact specifications of a nuclear device except for the special nuclear material. IWEs can simultaneously address multiple performance-related questions. About six IWEs are conducted annually at Site 300's Bunker 801. Each one can cost more than $1.5 million.

IWEs are devoted to current stockpile stewardship issues or to refining supercomputer codes. The tests can evaluate new safety or security features or the aging of critical parts. Studying the effects of aging is important because many weapon systems are older than their intended design lifetimes. Over decades, materials can experience unanticipated changes from the intense radiation of nuclear devices.

IWEs include pin shots and core-punch tests as diagnostics. Pin shots evaluate the implosion of devices with a pin dome, a small sphere placed at the center of the implosion region. The sphere has hundreds of protruding radial pins of different lengths. (See the figure on p. 11.) The high explosive implodes the mock pit onto these timing pins. When the mock pit strikes each pin, the signals created track the implosion of material as it moves toward the center, thereby providing data about the temporal and spatial uniformity of the implosion.

In a core-punch test, scientists combine high-energy radiography and ultrasensitive diagnostics to capture the detailed shape of the pit as it is highly compressed near so-called bang time, when an actual device would go nuclear. This deep-penetration radiography yields a small (40- to 45-centimeter) digital image that is compared to images generated by hydrodynamics simulation codes.

Bosson also works on focused hydrodynamic experiments that address a particular component or material associated with the primary. Focused experiments typically occur in a series. They may be studies of a certain material or a certain shape such as a cylinder. About 10 to 20 focused experiments per year are conducted at Site 300. Although focused tests cost less because of their engineered simplicity, they often require as many diagnostics as IWEs and thus are just as challenging to field.

Chronology of a Hydrotest

Once the decision has been made to conduct a particular test in support of stockpile stewardship, a design physicist develops a conceptual plan to field the experiment. At a conceptual review meeting, the design physicist, ramrod, device engineer, and design drafter discuss the proposed test. "We discuss whether the proposed plan makes sense," says Wraith. "Is there a better way to obtain the desired information?"

If a decision is made to proceed, discussions then focus on the required shock pressure, how much high explosive will be needed to create that pressure, the thickness of key parts, the materials involved, and the diagnostic instruments needed. "I depend on Steve to tell me what the appropriate diagnostics are for the experiment I'm proposing," says Hsu. (See the box on p. 10.)

After the conceptual review, mechanical designers from the Engineering Directorate begin drafting the required parts. The design physicist refines computer simulations to ensure that the experiment will have a reasonable probability of returning the desired information. Bosson focuses on the diagnostic requirements, such as ensuring clear lines of sight for the optical cameras. In this early stage, he creates the first of several three-dimensional computer-aided design (CAD) layouts that give a detailed mock-up of the experimental setup. The CAD layout includes the strategic placement of the

Nuclear Device Primary: Where It All Begins

In the past, to ensure that a nuclear warhead would function according to its design, Livermore scientists tested it underground at the Nevada Test Site. In the absence of nuclear testing, scientists must rely on advanced supercomputer codes, validated by nonnuclear experimental results and benchmarked against past nuclear test data, for the continued certification of the stockpile.

A modern nuclear weapon comprises a primary explosive device and a secondary. In the primary device, a pit of fissile material is surrounded by chemical high explosives. A nuclear explosion starts with the detonation of the high explosive, which generates a high-pressure, high-temperature environment. The high-explosive shock waves can travel up to 10 kilometers per second, forcing the enclosed fissile material to compress into an increasingly smaller space. The pit responds in a complex manner as it implodes to an extremely compact shape. In the process, materials deform, become extremely dense, and can even melt.

The uniform compression process of the fissile material leads to a nuclear fission chain reaction, which generates tremendous energy. The energy released from the primary triggers the secondary to produce the overall nuclear yield of a device.

Because the implosion geometry is crucial, implosion tests called hydrodynamic experiments are needed to ensure that the weapons in the nation's nuclear stockpile will perform as expected. Hydrodynamic experiments reveal the behavior of a nuclear weapon from the ignition of the high explosives to the beginning of the nuclear chain reaction. Data concerning the velocity of the imploding material and energy flow during the implosion help weapon scientists assess the ultimate performance of the device, better understand the implosion process, and refine computer models.

device, mirrors that reflect images to the optical cameras, and other diagnostic equipment. It also includes detailed drawings for various support structures, which are constructed from extruded aluminum.

Two to three months after the first conceptual review meeting, a design review is held. Participants review drawings for the required parts and decide if any modifications are needed. Bosson checks the orientations of the experimental package and its parts, such as the baseplate, to determine if equipment must be moved to ensure clean lines of sight for all diagnostics. "We don't want any parts to interfere with camera views," he explains.

Most of the parts are classified and must be manufactured by machinists in Livermore's onsite shops or obtained from other NNSA sites. Some parts, because of their materials or complicated designs, have a long manufacturing lead time. A few unclassified parts are manufactured by commercial shops.

"Steve is the integrator," says Hsu. "He is always in touch with people at Site 300, the participating engineers, and the Laboratory shops."

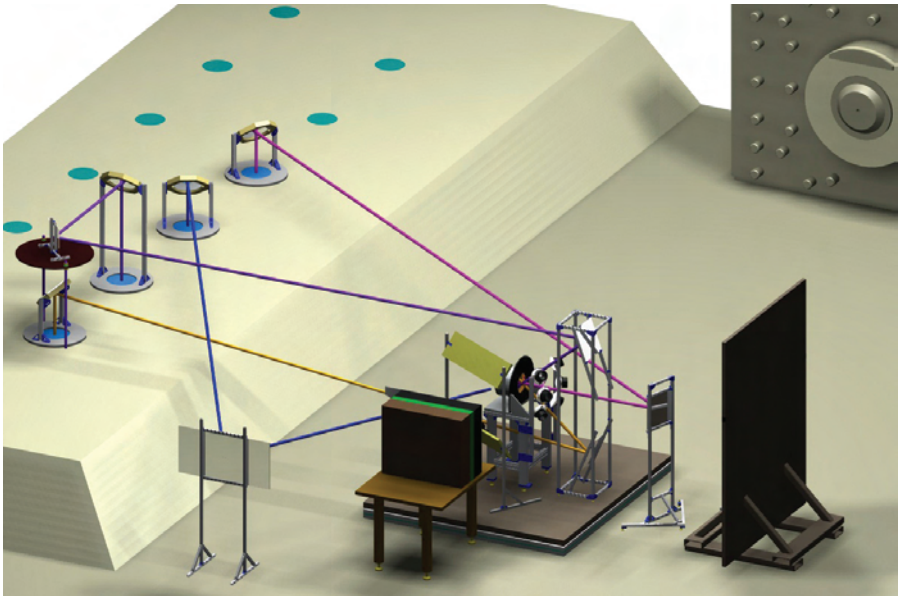
About one month before the scheduled firing date, Bosson completes an exhaustive preshot report. The report includes all timing specifications for the required diagnostics and lists the kind and amount of high explosives to be used. In addition, over the weeks leading up to the shot, Bosson briefs the bunker crew.

While the experiment is being assembled, Bosson serves as a representative for the design physicist. The bunker crew assembles various support structures based on Bosson's CAD layout. These stands and frameworks vary in shape and size to accommodate detectors and diagnostics such as mirrors for directing the optical views and lamps for illumination.

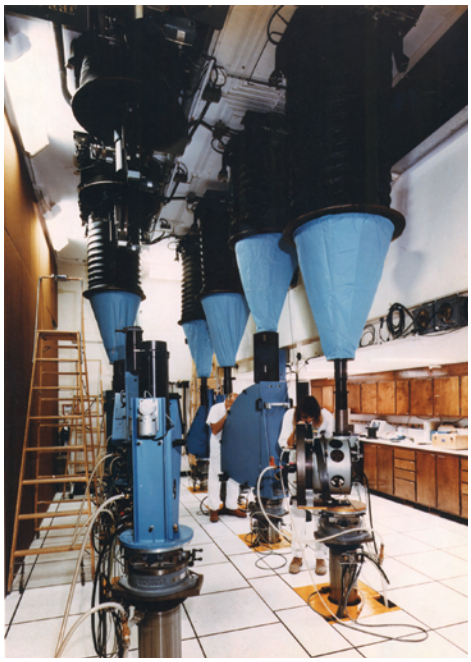
During the final hours of the countdown, Bosson stays in the control room with other bunker personnel and the design physicist. The team monitors the final preparations of the diagnostics and other systems. The firing, measured in tens of microseconds, culminates many months of design, preparation, manufacturing, and reviews.

After a Shot

Personnel who enter the firing chamber shortly after a test must don protective garb to protect themselves from any hazardous materials as they recover the radiographic film cassettes. After removing the remains of the experiment, they turn on a wash water system to remove any particulate matter



A computer-aided design layout shows placement of the experiment, which is surrounded by mirrors on stands, flashlamps, and a radiographic film cassette. Extremely energetic x rays emerge from the Flash X Ray machine through a port (upper right). Behind the experiment is the protective enclosure for radiographic film. Images from a series of mirrors are reflected to four optical cameras, providing different viewpoints. Each optical path is indicated by a different color. The cameras are located directly below the four ports on the left.



A room underneath the firing chamber houses high-speed optical cameras. Images from the hydrodynamic test are directed with mirrors in the firing chamber to ports at the tops of the black shrouds.

Diagnostics Track Events Microsecond by Microsecond

Scientists have only a fraction of a second after a detonation to gather data before the hydrodynamic test target and some of the diagnostic supports are destroyed. The Contained Firing Facility at Livermore's Site 300 has one of the most extensive suites of diagnostic equipment in the nation for studying explosive tests. Multiple diagnostic devices can be deployed simultaneously to measure different aspects of an experiment. Each diagnostic provides a different look at the implosion process, including its velocity and detailed images of inside and outside movement.

The most important diagnostic is the Flash X Ray (FXR), which was dedicated in April 1982 as the nation's most powerful linear-induction electron beam accelerator. FXR enables scientists to see into the heart of test objects at an exact moment after detonation, revealing data about implosion symmetry. The FXR source requires very high peak power available in a single pulse, and the timing and firing of the source in concert with the implosion of the device requires an extremely sophisticated system design. Because only one radiograph can be captured per experiment, timing is everything. Ramrod Steve Bosson says, "The x-ray pulse length is about 60 nanoseconds, and the test is over in 100 microseconds, so we need very precise timing to obtain the image at the right time."

The machine's x rays enter the firing chamber from a port in the chamber wall. The x rays penetrate more than 30 centimeters of steel in an intense flash of high energy and can freeze action in 65 nanoseconds. FXR's peak power is 500 rads (equivalent to 30,000 times a medical x ray), and its maximum resolving power is about 2 millimeters. Any x rays that pass through the event unattenuated are recorded on photographic film or, in the case of core-punch experiments, on the recording surface of a gamma-ray camera that is 70 times more sensitive than film. Fewer x rays pass through dense areas, resulting in darker regions of an image. Thick aluminum plates protect the film cases from shrapnel.

Radiographs taken with FXR can capture an entire target or concentrate on a small area. To focus on specific areas, as with core punches, scientists collimate the beam to make the image size less than 2 centimeters square.

Complementing the FXR images are those provided by optical cameras located below the firing chamber. Many fine-scale features, including instabilities and the breakup of material during the fast-moving explosion, are progressively captured by these ultrahigh-speed cameras. The images are directed to the underground cameras by a series of mirrors arrayed around the experimental package. To capture the fleeting reactions, each camera uses a spinning mirror with an equivalent frame rate of up to 2 million frames per second; the mirrors relay light to a stationary arc of conventional photographic film.

The hydrotest firing is dependent on the instant when all optical cameras' mirrors are perfectly in synch. At that moment, the high explosive is detonated to begin the implosion process. Mirrors must be sacrificed by small explosive charges, or the cameras will keep recording, thereby overwriting the film. Two types of cameras are used. The first projects 26 frames onto 70-millimeter film; the second projects 80 frames onto 35-millimeter film. Each frame is typically separated by a microsecond.

Most experiments also involve heterodyne measurements, which track and record the velocity of moving surfaces. In these measurements, laser light passes through a probe at the end of an optical fiber focused on a selected spot on a surface. The same probe picks up the reflected light signal, and the light's color (frequency) is shifted in proportion to the instantaneous velocity of the surface moving toward the probe. The technique can measure velocities of up to 5 millimeters per microsecond.

Mechanical technologist Keith Lewis works on the Flash X Ray (FXR) accelerator, an important diagnostic tool for hydrodynamic testing. The firing chamber is behind the wall at the far end of FXR.

John Given, Steve Bosson, and Jack Lowry adjust the quality of the FXR beam, which enters the firing chamber through the port behind them. FXR is on the other side of the wall to protect it from explosive debris.

from the walls and floor. A filtration system removes dust and particulates from the wastewater, which is recycled. At the same time, ventilation fans flood the chamber with fresh air and process exhaust gases through high-efficiency particulate air filters. (See *S&TR*, June 2004, pp. 21–24.)

Members of the hydrotest group scan the radiographic and photographic film to make digital images. The individual frames from the photographic film are combined to create a short movie. In addition, pin-shot test data are converted to a useful form for the design physicist. Physicists then study the experimental data for months, incorporating results into supercomputer codes.

As Bosson continues his work at Site 300, he is also supporting Livermore-designed hydrotests at Los Alamos National Laboratory's Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility. DARHT's first axis began producing single, two-dimensional images of the device implosion in the fall of 2000. The second axis, which is perpendicular to the first, will capture four images in succession over 2 microseconds. One of these images, taken at the same time as the image from the first axis, can be used to generate a three-dimensional view of the device at a given time. The other images from the second axis can be combined with the fourth to generate a short movie of the device implosion.

"Ramrods really tie the program together," says Hsu. In the end, the long record of successful hydrotests shepherded by ramrods ensures the continued confidence in the nation's aging nuclear weapons stockpile.

—Arnie Heller

Key Words: Contained Firing Facility (CFF), core-punch test, Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility, Flash X Ray (FXR), high explosive, hydrodynamic experiments, integrated weapon experiment (IWE), nuclear weapon, pin test, primary, ramrod, Site 300.

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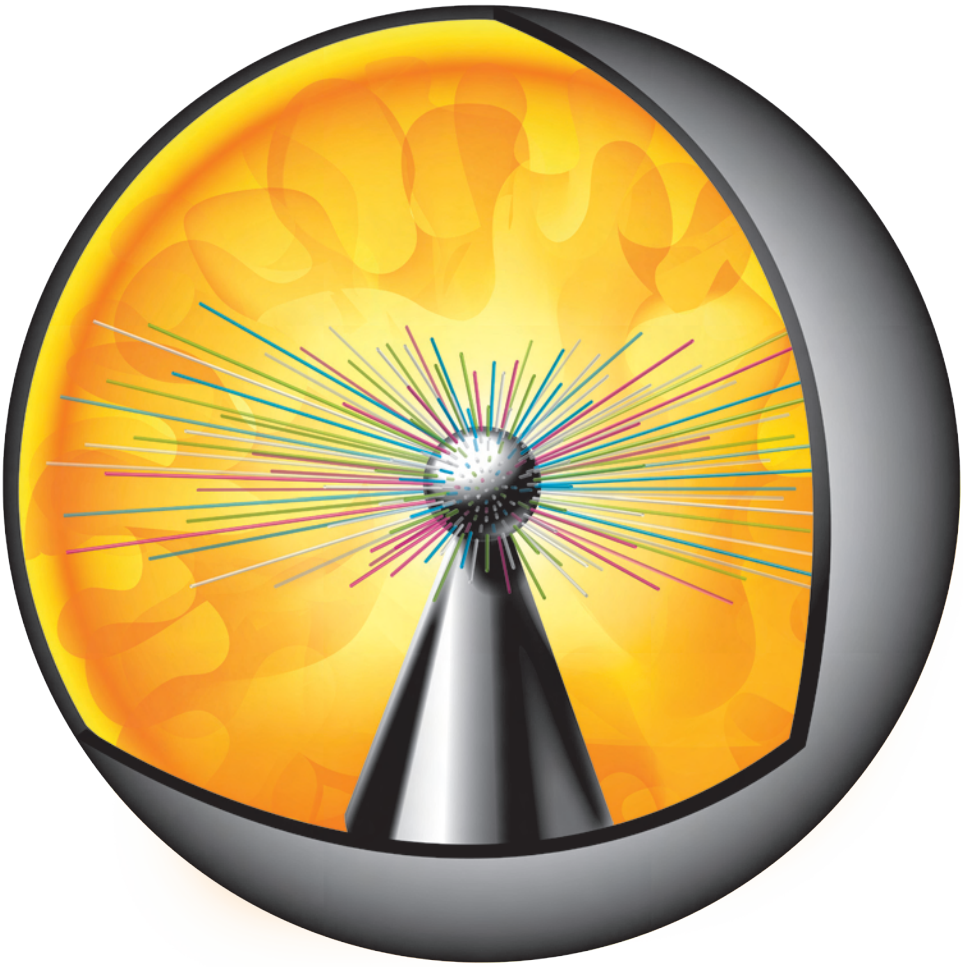
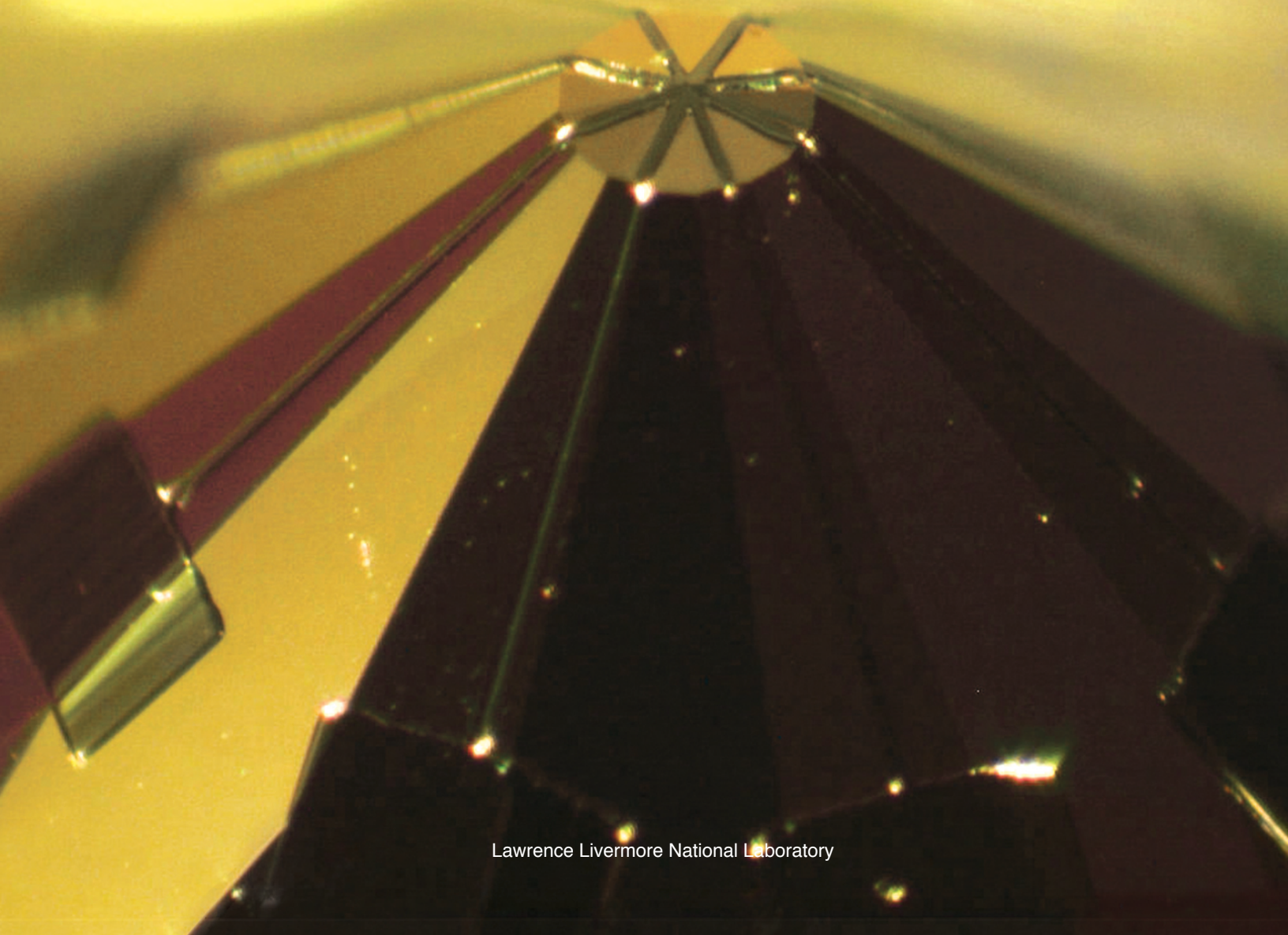


A cutaway of an experimental device shows a pin-dome diagnostic for evaluating the implosion of a device. As the sphere implodes, signals from the pins track the imploded material moving toward the center, thereby providing data about the temporal and spatial uniformity of the implosion.

Three Dimensional on the Nanoscale

New micro- and nanolithographic techniques are expanding Livermore's current expertise in three-dimensional lithography.



MAKING smaller and smaller micro- and nanodevices requires a tool for precisely adding and removing material. Standard lithographic "writing" processes, combined with chemical deposition and etching, can do the job for very small objects, if they are flat. However, the world isn't flat, and neither are most of the things in it.

In the 1980s, Livermore needed a tool to write electronic circuitry on tiny, three-dimensional (3D) devices. Laboratory engineers applied laser technology to create a 3D lithographic system, which they dubbed laser pantography (LP).

Livermore engineers still use LP for 3D patterning and are now adding other sophisticated 3D lithographic techniques. Together, these techniques will be useful for fabricating experimental targets at the National Ignition Facility (NIF). (See *S&TR*, July/August 2007, pp. 12–19.) NIF targets are small spheres, the size of a poppy seed, or about a millimeter in diameter. Design specifications for targets are extremely stringent, in part because of the high temperatures, pressures, and energy densities the targets will face inside the NIF target chamber. Entirely new materials and fabrication techniques, including 3D micro- and nanolithography, are needed to meet these specifications.

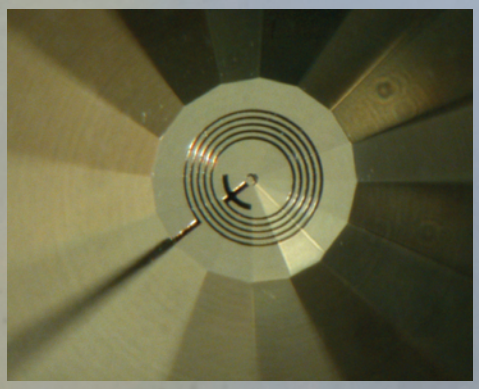
"NIF is the driver of our current focus on 3D micro- and nanolithography," says Anantha Krishnan, director of the Laboratory's Center for Micro- and Nanotechnology. "We are building on Livermore's history of expertise in 3D lithography."

The impetus for LP was the Strategic Defense Initiative of the 1980s. Today, it is finding very different uses. For example, LP is used to pattern coils in portable nuclear magnetic resonance spectrometers for detecting weapons of mass destruction and in catheters for treating stroke and heart attack patients. In addition, LP is used to pattern tungsten microprobes on the walls of diamond anvil cells, which compress a material to extremely high pressures. (See *S&TR*, December 2004, pp. 4–11.) Equation-of-state experiments with diamond anvil cells tell researchers how materials behave under extreme conditions. To create the probes, researchers use LP to pattern wires from the tip of the diamond down the steep walls, a process that is impossible to mimic with standard 2D lithography.

Grayscale lithography and projection microstereolithography (PμSL) are being added to the Laboratory's 3D micro- and nanolithography repertoire. Both methods were developed elsewhere and are being customized at Livermore to meet the needs of NIF. The Laboratory is also enhancing the performance and resolution of the PμSL technique.

A Look Back

LP was developed to support a number of creative research programs at the Laboratory. Under the Strategic Defense Initiative, Livermore researchers delivered many new materials and technologies—such as lighter-than-air aerogels—for Brilliant Pebbles and other facets of the missile shield program. They applied LP technology to fabricate metal interconnects on multiple electronic chips. These devices were designed for use as sensors and other control systems aboard the tiny Brilliant



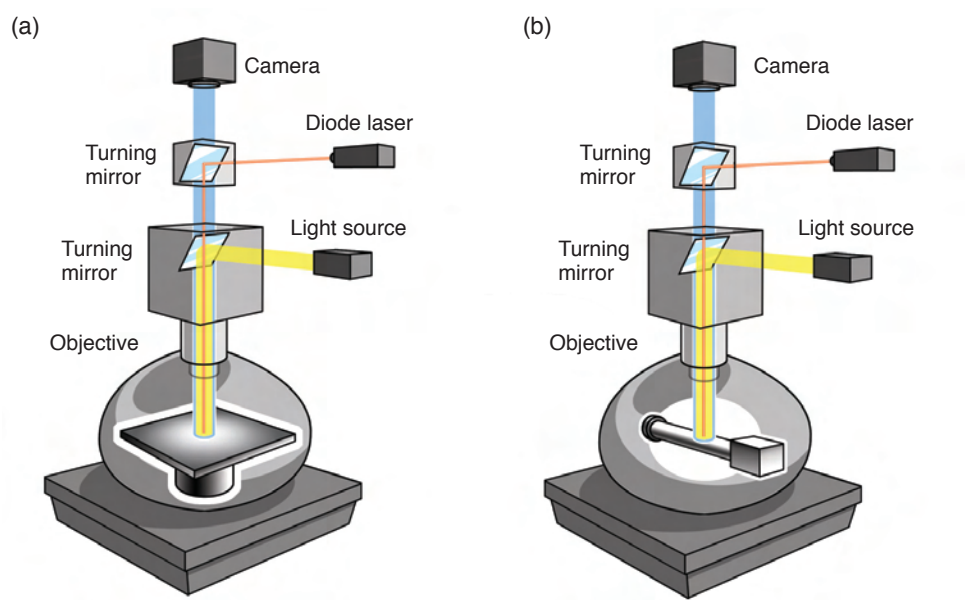
A designer diamond anvil is made by lithographically fabricating tungsten microcircuits on the diamond's flattened tip.

Pebble satellites, whose goal was to home in on an incoming missile and intercept it. At that time and until well into the 1980s, LP was the only 3D lithographic system available and one of just a few laser writing systems.

Several major corporations were interested in putting LP to work. "IBM wanted to use LP's 3D capabilities for writing circuitry on the side of stacked, multichip modules to reduce problems with inductance," says Vince Malba, program leader for 3D lithography at Livermore. Texas Instruments, Hewlett-Packard, Micron Technology, and Honeywell also partnered with the Laboratory to develop advanced 3D interconnect capabilities using LP. Micron Technology expressed considerable interest in commercializing the technology for dynamic random access memory (DRAM). "However, semiconductor companies like Micron could increase DRAM densities faster and less expensively than we expected to do with LP, which was a new tool," says Malba.

In the 1990s, LP was used in two major weapons-related programs: the W87 Life-Extension Project and enhanced surveillance for the Department of Energy's Stockpile Stewardship Program. The W87 Life-Extension Project involved refurbishing the W87 warhead, the warhead design with the most modern safety features in the stockpile. The goal was to extend the lifetime of the weapon to beyond 2025. The Laboratory developed and certified the engineering design of the W87 modification through a combination of nonnuclear experiments, flight tests, physics and engineering analyses, and computer simulations. A number of miniaturized electronic devices used for telemetry and flight tests were fabricated with LP.

After nuclear weapons testing ended in 1992, nonnuclear experiments, testing of weapon components, and computer simulations became the primary tools for ensuring that the nation's nuclear stockpile remains safe, secure, and reliable. Surveillance of the nuclear stockpile was enhanced. During the middle to late 1990s, LP was used to fabricate microscale actuators and sensors for monitoring the health of nuclear weapons in the stockpile.



The laser pantography system can be configured either as (a) a mill for patterning flat surfaces or (b) a lathe for patterning cylindrical surfaces. The light source allows for the camera image to be seen on a computer screen.

A Hot New LP

Over the years, Livermore engineers have improved LP with new exposure tools, chemical processes, and control systems. The LP system today has a motion control system whose accuracy is better than 1 micrometer. The system can function either as a lathe or as a five-axis mill. A 405-nanometer diode laser acts as the "cutting" tool, which exposes the photoresist coating. The mill configuration patterns noncylindrical substrates.

The lathe setup—known as the LaserLathe™—is used to pattern cylindrical objects. Any design can be patterned on a compound curvature surface with the LaserLathe's programmable multiaxial controller.

When a coil or wire must be fabricated on a tube, the tube is first exposed to an oxygen plasma to roughen the surface and remove impurities prior to sputter deposition. A coating about 50 nanometers thick of titanium is laid down, followed by a copper layer of about 200 nanometers. This "seed" layer creates a conductive surface on which a positive electrodeposited photoresist can be electroplated. The photoresist is exposed with the computer-controlled laser and then chemically developed to form the desired patterned mask. Copper is electrolytically deposited through the photoresist mask, after which the mask is chemically removed. The sputtered copper is removed from the field with a proprietary solution that etches sputtered copper faster than plated copper. Finally, the titanium is chemically removed, leaving a microcoil firmly adhered to the tube.

The challenge lies in getting the photoresist onto a 3D surface. In the manufacture of computer chips, depositing photoresist is usually

accomplished by spinning the chips. To coat more complicated parts that are not flat, Livermore uses the self-limiting electrophoretic process. "Electrodeposition of photoresist makes 3D lithography possible," notes Malba.

The photoresist is a colloidal suspension of polymer, surfactant, sensitizer, and plasticizer. During the electroplating process, anionic micelles—the surfactant molecules dispersed in the colloid—move toward an anode in the presence of an electric field. The micelles "fall apart" on the conductive substrate, coating it. Because the coating is a dielectric material, its thickness is uniform, which inhibits further deposition as its thickness increases. The thickness of the photoresist, from 5 to 30 micrometers, is controlled by the plasticizer content and temperature setting. The sensitizer diazonaphthoquinone changes the polymer solubility as a function of absorbed light. Adding the sensitizer lowers the polymer's solubility, while photolysis increases it. At 35°C, 1 percent sodium carbonate (an electrolyte) develops an image in 2 to 3 minutes.

Guiding Catheters

In a collaborative effort with researchers from the University of California (UC) at San Francisco, Livermore engineers are using LP for patterning magnetized microcatheters. (See the figure at right.) Computerized interventional magnetic resonance, developed in 2001, helps surgeons remotely guide a catheter to collapsed veins and arteries.

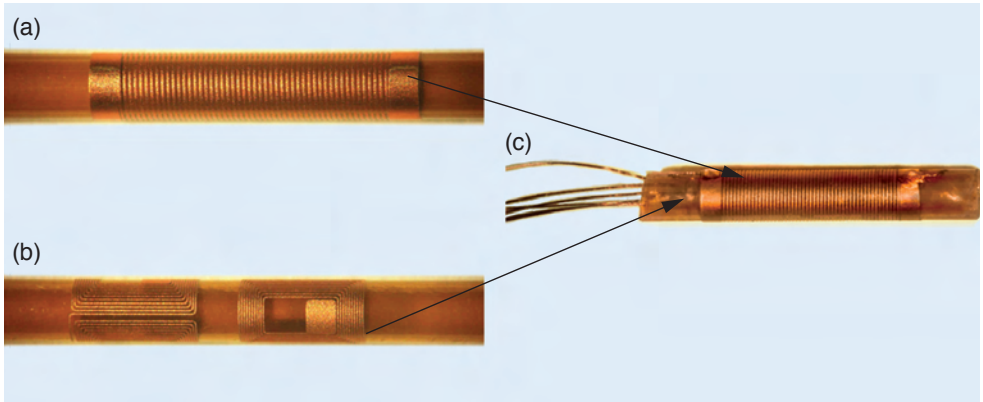
Coils patterned on the tips of catheters create magnetic moments when energized by direct current pulses. In the presence of an external magnetic field, these magnetic moments cause the catheter to bend. Having one helical coil and two saddle coils perpendicular to one another allows the catheter tip to be bent in any direction. The surgeon can thus remotely manipulate the catheter through complex anatomy to reach a particular blood vessel branch.

"Early attempts at manufacturing catheter tips required hand-winding fine copper wire into coils," says Malba. A helical solenoid can readily be made using this method, but hand-winding a saddle coil is quite difficult. Hand-wound saddle coils are one-of-a-kind products because of the difficulty in reproducing the number of turns, the pitch of the wire, and the coil's orientation with respect to other coils. In addition, even very fine wire adds appreciably to the diameter of the catheter tip.

Fabricating saddle coils directly on polyimide tubing with microlithography makes the coils more precise and reproducible, with much smaller line widths than can be attained with hand-winding. Additionally, coils can be precisely oriented with respect to each other, guaranteeing their perpendicular orientation. Livermore's work with UC San Francisco has involved simulations of heating and coil design as well as development of fabrication tools and manufacture of both helical and saddle coils.

Recent experiments showed that the current required to deflect the catheter tip has the potential to cause damaging heating effects to the patient. Raising the temperature of the blood even a few degrees could result in blood coagulation or vessel-wall damage. The team is experimenting with manufacturing procedures and materials that should eliminate these possible heating effects. The simplest change is to increase the thickness of the electroplated copper, thereby decreasing the coil's resistance and, consequently, the heat generated per ampere. Says Malba, "Making this change will require significant modifications to the microcoil manufacturing process. But ultimately it will result in a factor of two reduction in the heat generated."

A complementary approach is to remove the heat as it is generated with a constant saline flow through the catheter. However, the polyimide tubes used as the substrate for the microcoils are poor thermal conductors and would not provide an adequate thermal path to the flowing saline. The team has experimented with ceramic tubes, which have better thermal conductivity. Thus far, results show a substantial reduction in temperature elevation. "Combining thicker copper windings with flowing saline should eliminate the possibility of heat damage," says Malba.

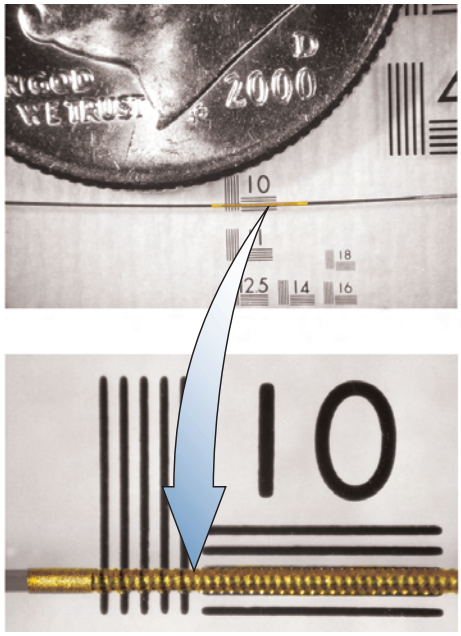


For the magnetic resonance imaging microcatheter, laser pantography was used to fabricate (a) a helical coil and (b) two perpendicular side-by-side saddle coils. (c) The saddle coil tube is placed inside the helical coil tube to produce a magnetized catheter tip that will bend in any direction when in the presence of an external magnetic field.

Identifying Chemical Signatures

The team also has been contributing for several years to work on sensors for portable nuclear magnetic resonance (NMR) used in onsite identification of signatures from nuclear, chemical, and biological weapon agents, narcotics, explosives, toxins, and poisons. NMR is a powerful technique for revealing the identity of chemical molecules. However, to date, NMR is significantly less sensitive than mass spectrometry or other spectroscopic techniques. In addition, when sample sizes are very small, which would be the case with trace quantities from a warfare agent, NMR's lack of sensitivity makes it even less useful.

One solution to increasing sensitivity is creating a much more powerful small helical radio-frequency (RF) coil, which is at the heart of any magnetic resonance system. Many techniques have been tried since the mid-1990s to reduce the coil size. Hand-winding works well, but the process is slow, tedious, and not reproducible. Other more easily reproducible fabrication methods resulted in coils that were less sensitive than their hand-wound cousins.



The latest microcoils for a portable nuclear magnetic resonance chemical sensor measure just 100 micrometers in diameter.

Using the LaserLathe, Malba's team has had great success in fabricating RF coils with adjustable widths and line spacings. The team's first RF microcoils were fabricated on tubes ranging from 1.3 millimeters down to 850 micrometers. The latest, third-generation microcoils are just 100 micrometers in diameter. Line widths are 20 micrometers with 100 turns in the coils.

A challenge with small magnets, however, especially low-cost ones, is that they tend to generate inhomogeneous magnetic fields, which conceal much of the useful spectral information. Because the goal of this work is a portable, readily available NMR detector, cost is a critical factor. Livermore engineers and chemists teamed up with researchers from Lawrence Berkeley National Laboratory and UC Berkeley to produce such a probe. They explored various designs to improve the magnetic field, including combining an RF coil with a shim coil. Shim coils reduce the overall probe size and improve durability.

The optimal design proved to be a helical coil connected to a coaxial cable placed within a ceramic tube. The tube is patterned with shim coils connected to twisted pair cables. The shim coils are visible in the completed probe assembly, shown in the figure at the top of p. 17. The team's tabletop system uses a commercial, single-resonance RF spectrometer, the first such portable spectrometer available. The system runs on a laptop computer with software for instrument control and data processing. The device is being tested at both the Laboratory and UC Berkeley. "We have improved the sensitivity of the latest probe design to less than 10 parts per million," says Malba. "We expect the latest improvements to result in 1-part-per-million detection, the desired benchmark."

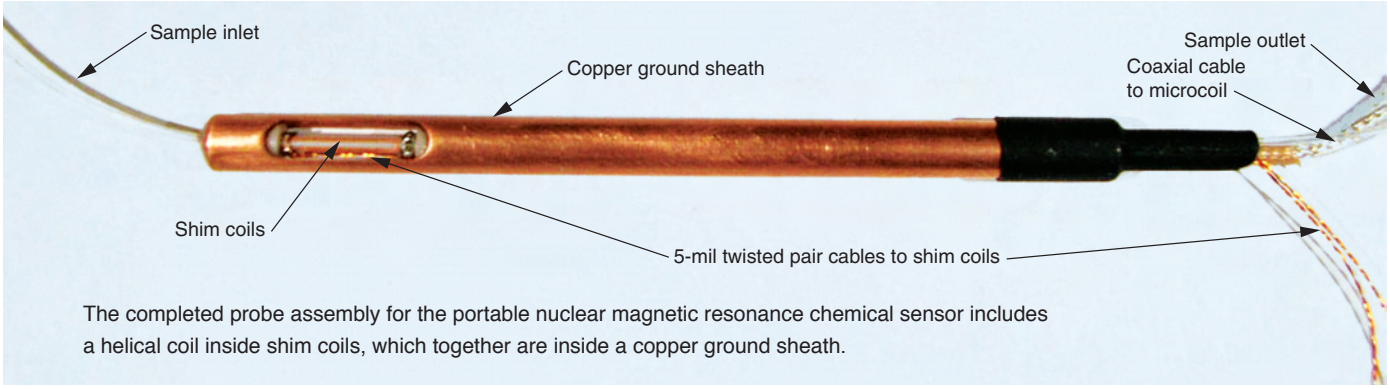
New Kids on the Block

Joining the well-established LP at Livermore are grayscale lithography and, more recently, PμSL. Engineer Chris Spadaccini is leading both development projects.

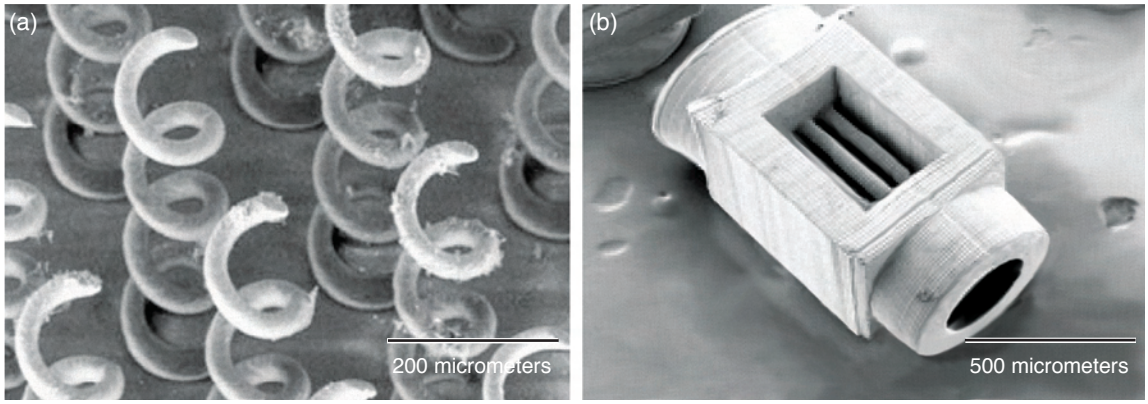
Grayscale lithography is a modification of conventional 2D photolithography. (See *S&TR*, October 2006, pp. 18–26.) That process, which involves exposing a coated, masked silicon wafer to ultraviolet light, is typically all or nothing, so all features have a uniform height. In grayscale lithography, the light's intensity can be adjusted to produce 3D photoresist profiles with varying shapes. After chemical etching, the profiles can be transferred to a substrate. Spadaccini anticipates using these 3D structures not only for NIF targets but also to create microoptical devices.

In addition, Spadaccini expects to start work soon on PμSL research that is directed primarily toward target fabrication for ignition and high-energy-density experiments on NIF. Spadaccini will be working with Malba, engineers Robin Miles and Todd Weisgraber of Livermore, and Nicholas Fang of the University of Illinois at Urbana–Champaign and its Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems.

PμSL has already produced objects such as microscale coils and a bioreactor. Thus far, the technique has a resolution limit of about 400 nanometers. Spadaccini's goal is to reduce this limit to less than 50 nanometers. His team aims to fully understand the physics and chemistry of the PμSL process and the physical and chemical properties that limit its resolution. The team will also explore PμSL's use for a range of materials, including



The completed probe assembly for the portable nuclear magnetic resonance chemical sensor includes a helical coil inside shim coils, which together are inside a copper ground sheath.



Projection microstereolithography can produce objects such as (a) microscale coils and (b) a bioreactor. (Scanning electron micrographs courtesy of Nicholas Fang, University of Illinois at Urbana–Champaign.)

graded-density foams and highly porous metallic foams that are being considered for NIF targets. In addition, PμSL will be augmented with "superlenses" and digital holographic nanolithography, new processes designed to improve resolution as well as the speed with which objects can be fabricated.

Within the next few years, NIF experiments will require hundreds of targets. Researchers throughout the Laboratory are working to replace the current labor-intensive target fabrication process with a high-throughput production process to meet NIF's needs. PμSL and Livermore's other 3D fabrication tools will play an important role in making this happen.

—Katie Walter

Key Words: grayscale lithography, LaserLathe™, laser pantography (LP), magnetic resonance imaging, National Ignition Facility (NIF), nuclear magnetic resonance (NMR), projection microstereolithography (PμSL).

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Assessing the Threat of Biological Terrorism

AS part of its national security mission, Lawrence Livermore conducts research directed at protecting against a broad range of methods terrorists might use in an attack against the U.S. Among the most potentially devastating scenarios is the dispersion of pathogenic biological organisms in densely populated areas. Biological warfare agents might be attractive to terrorists because the microbes can inflict high mortality rates, yet exposure cannot be detected by our physical senses. The organisms' ease of dissemination combined with the often delayed onset of symptoms after exposure would allow a terrorist to cause a high-consequence event with minimal risk of being detected.

Although several types of bioorganisms have the potential to kill or sicken humans or livestock, some are more difficult than others to produce for a large-scale attack. The Department of Homeland Security (DHS) is interested in knowing which microbes would be more accessible and easier for a terrorist to grow and disperse. Federal officials also want to develop tools to track the spread of a disease geographically over time and to devise better methods to distinguish a natural disease outbreak from an intentional release.

Coordinating Biodefense Knowledge

In 2004, DHS established the Biodefense Knowledge Center (BKC) at Livermore to coordinate biothreat assessments and biodefense information. The center is part of the Nonproliferation, Homeland and International Security (NHI) Directorate's Threat Awareness Program, which includes other modeling and assessment activities, including system studies and epidemiological and food-process modeling efforts. In the BKC, teams of scientists and engineers matrixed from across the Laboratory coordinate the development of authoritative biothreat assessments. This effort often includes input from external subject-matter experts from industry, academia, government institutions, and other national laboratories. Collaborators also include analysts and experts in

President George W. Bush signed the Project BioShield Act of 2004 on July 21, 2004.

information technology, bioinformatics, and computer simulation from DHS centers located at the University of Minnesota, University of Southern California, and Texas A&M University.

According to BKC director Tom Bates, "The BKC provides decision makers with rapid access to vetted technical information so they can better understand current and emerging bioterrorism threats." The infrastructure includes a 24-hour technical support line to DHS, in-depth threat analyses, awareness bulletins focused on potential nefarious uses of biotechnologies, and information management tools that provide unique knowledge discovery capabilities.

Threat Awareness and Characterization

DHS is concerned about agents that may have been involved in foreign state-sponsored bioweapon programs: *Bacillus anthracis* (anthrax), *Yersinia pestis* (plague), *Francisella tularensis* (tularemia), *Burkholderia* species (glanders and melioidosis), *Brucella* species (brucellosis), *Variola major* (smallpox), and *Clostridium botulinum* (botulism). As part of the Project BioShield Act of 2004, DHS is responsible for determining potential threat scenarios in which these agents and others could be used in attacks against the U.S. The BKC has conducted a series of threat assessments to consider the technical and operational feasibility of launching an attack using various biological agents. The assessments also estimate the number of people who could be exposed in a hypothetical attack.

A major goal of developing plausible bioterrorist scenarios is to help the Department of Health and Human Services prioritize countermeasure procurements, such as acquiring and stockpiling vaccines and antibiotics. "These assessments identify knowledge gaps that reduce our ability to accurately prepare countermeasures against a biological attack," says Livermore molecular biologist Erik Burnett.

Results and supporting research from the threat assessments are entered into a Web-based document management system that the BKC has developed to serve as a national biodefense library. The secure system will allow the biodefense community to view and update reference materials, store reports, and provide live feeds to other sources. The library will also help DHS's National Bioforensics Analysis Center in its effort to build a microbial forensics capability. (See *S&TR*, September 2006, pp. 13–19.)

Determining Threat Impact

Because bioterrorist events have been rare, statistical characterization of risks based on historical data alone is often inadequate to develop countermeasures for similar events in the future. Therefore, the systems analysis team in Livermore's Threat Awareness Program conducts system studies that examine the interplay between threats and defensive responses over time, from preattack through postattack consequence management. The team's analysis includes factors such as the type of biological agent used, how it is dispersed, the number of people exposed, and the potential human health and economic impacts. The goal of the studies is to recommend countermeasures to prevent or respond to such attacks.

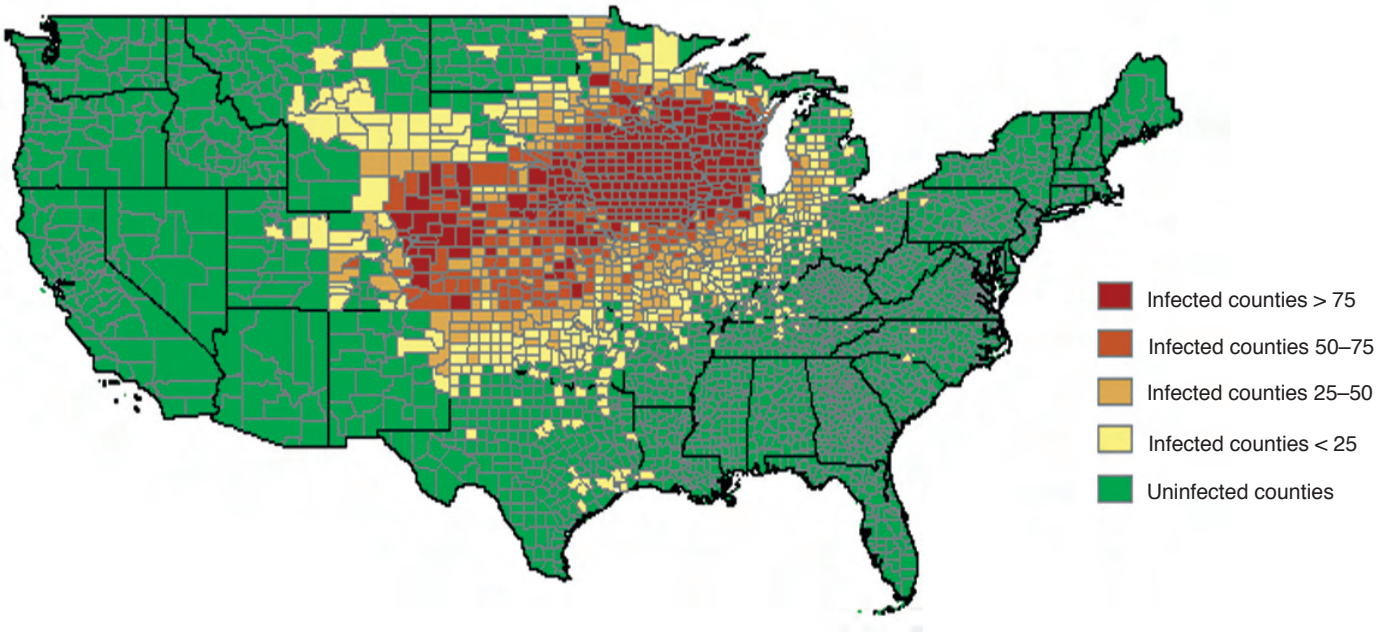
The systems analysis team includes researchers with a range of industry and academic experience in areas such as operations research, statistics, mathematics, economics, engineering, computer science, and the physical sciences. The team applies statistical methodologies for modeling the behavior of natural and engineered systems to assess the impact of catastrophic events on populations and critical infrastructure. "Systems studies link a threat to a response strategy," says systems analyst Richard Wheeler, who leads the team.

A response strategy can include investments in new technologies. "For example, a detector with enhanced capabilities might sense a threat earlier than is now possible," says Wheeler. "Mitigation could then happen more quickly, preventing the spread of the disease." Wheeler's team collects data from experiments, observational studies, simulations, and experts. "A good systems study can help inform system requirements in the design stage, especially when there are design trade-offs—for example, improved sensitivity versus speed of measurement in a detector," says Wheeler. The decision models outline possible alternatives and define uncertainties in the outcomes. Findings from the studies help influence programmatic and policy decisions.

Analyzing the Spread of Disease

In conducting systems studies on hypothetical agroterrorism attack scenarios, scientists in the Threat Awareness Program saw a need for a national-scale model to assess the potential impacts of an intentional release of a highly contagious threat agent. One disease that could have a catastrophic economic impact is foot-and-mouth disease (FMD), which affects livestock. Although it has not infected U.S. livestock since 1929, the disease is endemic in many areas around the world. (See *S&TR*, May 2006, pp. 11–17.) While the FMD virus could enter the U.S. unintentionally or intentionally, recent concerns regarding its use as a means of economic bioterrorism have stimulated a desire to better understand the potential threat and determine the best mitigation strategies for an intentional release.

Computer scientists Doug Speck and Carl Melius are working with a team that has developed a national-scale model to simulate various scenarios for the intentional introduction of FMD. The Livermore software, called Multiscale Epidemiological/Economic Simulation and Analysis (MESA), will be used by the U.S. Department of Agriculture (USDA), DHS, and other federal and state agencies to evaluate response options and countermeasures for controlling the extent and duration of outbreaks. MESA could also help the agencies form policies for preventing outbreaks by



The Multiscale Epidemiological/Economic Simulation and Analysis (MESA) model simulates outbreaks of foot-and-mouth disease. A simulation map shows the percentages of infected animal facilities by Day 50. Areas in red represent counties in which more than 75 percent of the facilities have been infected.

providing recommendations on issues such as how much vaccine should be stockpiled or the number of animals that must be tested and the frequency of tests to certify with confidence that a facility is free of disease. MESA uses census data provided by the USDA's National Agricultural Statistical Service on the nation's 1.2 million agricultural facilities. "MESA has a unique scaling capability," says Melius. "Other disease transmission simulations that model FMD scale to a maximum of 50,000 facilities."

Disease can be spread directly through animal-to-animal contact or indirectly, for example when a human or vehicle travels from an infected facility to another animal facility. MESA uses the contact data as one of the primary parameters to generate results. Because most disease progression occurs during the "silent spread," the period before the disease is detected, the team generates a model whose time frame begins two weeks before the disease was first observed and projects forward approximately one year. MESA displays a map showing the likely spread of an outbreak on a national scale and provides recommended response measures.

Livermore conducts its FMD research in close collaboration with DHS's Plum Island Animal Disease Center. Veterinarian Pam Hullinger of NHI has worked with researchers at Plum Island as well as around the world. In the 2001 outbreak of FMD in the United Kingdom, Hullinger assisted authorities in their investigations. Data from the outbreak are being used to verify MESA modeling results.

The Threat Awareness Program's systems studies and modeling efforts combined with BKC's material threat assessments and knowledge discovery tools help the homeland security community understand how adversaries of the U.S. might use biological organisms in an attack. Says Bates, "The tools we build are helping the nation construct effective measures to understand and counter emerging bioweapon threats."

—Gabriele Rennie

Key Words: Biodefense Knowledge Center (BKC), bioterrorism, foot-and-mouth disease (FMD), Multiscale Epidemiological/Economic Simulation and Analysis (MESA), systems studies, threat assessment, Threat Awareness Program.

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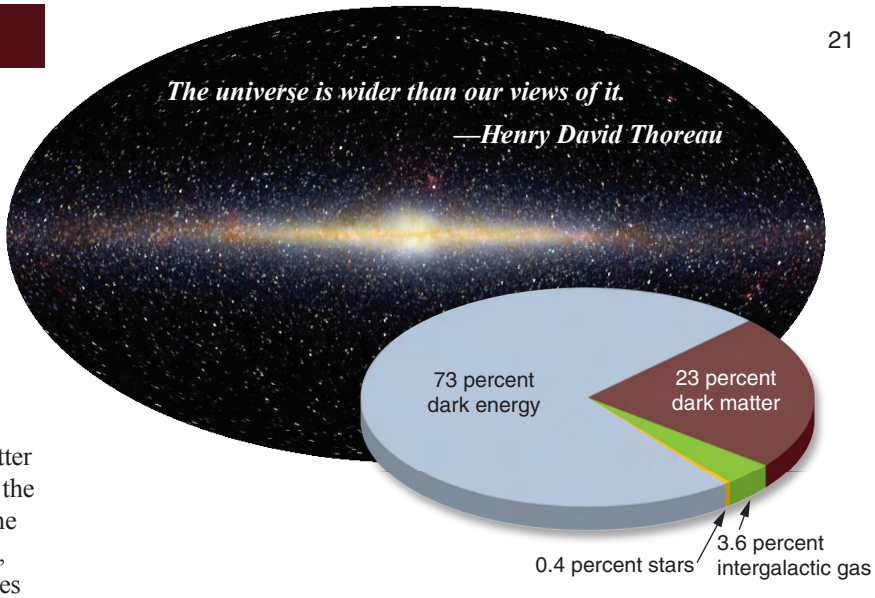
Shedding Light on Dark Matter



Only about 4 percent of the matter in the universe is composed of visible substances. The balance is dark matter and dark energy, although the exact compositions of dark matter and dark energy are yet to be determined. Researchers have proposed several kinds of particles as dark-matter candidates, including a weakly interacting massive particle. (Image of Milky Way Galaxy courtesy of the National Aeronautics and Space Administration.)

THE "stuff" that makes up the universe is mostly invisible. Matter that we can see or detect, such as the substances that make up the planets, stars, and interstellar dust, comprises only 4 percent of the total. The rest of the mass in the universe, most scientists believe, consists of dark matter—matter of unknown composition that does not emit or reflect electromagnetic radiation and is therefore difficult to observe directly. Determining the nature of this "missing mass" is one of the most important problems in modern cosmology and particle physics. Several kinds of particles have been proposed as dark-matter candidates, and many experiments and searches are under way to detect them. One candidate is some kind of a weakly interacting massive particle (WIMP). Because WIMPs do not interact with electromagnetism or interact strongly with matter, they are nearly impossible to detect directly.

At Lawrence Livermore, physicist William Craig is the principal investigator of an effort to indirectly detect dark-matter WIMPs in cosmic rays by looking for the antiparticles the WIMPs produce when they interact with each other. To this end, Craig, his team of researchers from Livermore, and researchers at Columbia University have developed a novel general antiparticle spectrometer (GAPS) to shed light on the possible constituents of dark matter in the universe.

Antiparticles, Unite!

Dark matter has been detected by its gravitational lensing of distant galaxies, in which unseen matter "magnifies" galaxies behind it. Theory points to a concentration of dark matter in the middle of the Milky Way Galaxy. Still, determining exactly what constitutes this dark matter is not easy.

A leading candidate for dark matter is a hypothetical particle called the neutralino. The neutralino—a stable, heavy WIMP predicted by some models in particle physics—has properties similar to those of neutrinos and is similarly difficult to detect. Efforts are under way by other researchers to detect the neutralino by looking for the recoil experienced by a target atom when a neutralino hits it. Unfortunately, the recoil from a neutralino cannot be distinguished from the recoil produced by a neutron. Therefore, these recoil experiments must be conducted deep underground and shielded as much as possible from the neutrons produced by cosmic-ray reactions and natural radioactivity.

Another way to chase down the neutralino involves indirect detection—this method is the path that Craig and his team have taken with GAPS. In their experiments, the focus is not on detecting the neutralino itself, but on identifying the unique "fingerprint" produced when one neutralino hits another. During the annihilation of the neutralinos, a bevy of particles and antiparticles is produced, including antiprotons and antineutrons. These two antiparticles—antiprotons and antineutrons—combine to form antideuterons. Antiparticles have the same mass but opposite charge from their particle cousins. For example, a proton has a positive charge, while an antiproton has a negative charge.

If neutralinos are indeed a major component of dark matter, then these antideuterons should be found in the cosmic rays originating from the galactic center of the Milky Way. "According to theory and calculations," says Craig, "the flux of antideuterons from dark-matter neutralino annihilation is large enough that our GAPS technique, when used in a modest space-based experiment, should not have any trouble detecting it."

However, these neutralino-produced antideuterons are not the only particles in the cosmic rays that shower Earth. "Secondary" antideuterons result from other cosmic-ray interactions. These secondary antideuterons tend to have a higher kinetic energy than the "primary" antideuterons produced by the dark-matter neutralinos. "So if we search for the primary antideuterons at low enough energies," says Craig, "we don't have to worry about contamination from the secondary antideuterons."

GAPS could also be used for detecting other antiparticles such as antiprotons. Because antiprotons are another primary product of neutralino annihilation, their detection could help bolster the argument for neutralinos comprising dark matter. "Theory and

models indicate that the antiprotons produced in these annihilations dominate at energies below 100 megaelectronvolts," says Craig. "Any antiprotons detected below this energy threshold are probably from neutralino collisions."

Covering the Energy GAPS

Detecting antiparticles requires extremely reliable identification amid enormous quantities of other particles. For instance, the antiproton flux is about 10^5 times lower than the proton flux, while approximately one antideuteron might be observed for every 10^9 protons and 10^5 deuterons. An antiparticle spectrometer must distinguish the types and energies of particles. The GAPS system does so with elegant simplicity, in a lightweight and straightforward package. GAPS consists of a time-of-flight system, an energy degrader, and a chamber filled with a target gas or solid. The chamber is surrounded by spectrometers.

The time-of-flight system measures the velocity of an incoming particle. The particle then enters an energy-degrading block made of a material, such as lead, that slows the particle. The degrader's thickness is chosen so that it will slow down antiparticles of a specific type and energy by a specific amount of time. The slowed antiparticle enters the chamber, where it bumps into an atom of the target material, knocking out and replacing an electron in the atom's outer electron shell. However, the antiparticle is much more massive than the ejected electron it replaces—for instance, an antiproton is about 1,800 times heavier than an electron. As a result, the atom—called an "exotic" atom—is unstable, and the antiparticle in the atom's outer orbit is in a highly excited energy state. The captured antiparticle emits x-ray photons with discrete energies of 25 to 250 kiloelectronvolts as it decays from energy level to energy level, displacing bound electrons as it goes. Finally, the antiparticle decays directly into the nucleus, annihilating itself and emitting a shower of pions in the process.

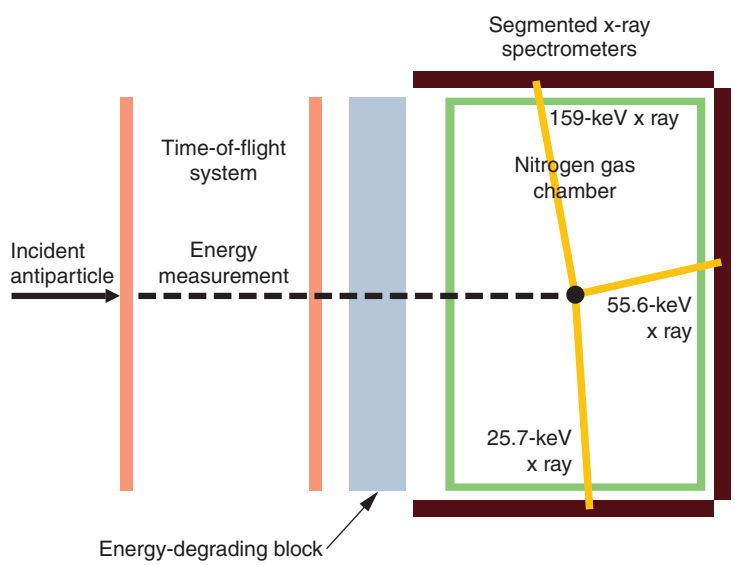
The emission of x rays and pions takes just a few nanoseconds. In fact, the total time is about 7 nanoseconds from when the particle enters the time-of-flight system to when it is annihilated. Segmented x-ray spectrometers surround the target chamber on all sides except for the one the particles enter through the time-of-flight system. These spectrometers measure and record the energy levels of the emitted x rays and the pion shower.

The energies of x rays and pions differ for each type of antiparticle, providing a fingerprint for particle identification. "For instance," says Craig, "when a captured antiproton decays in an atom of nitrogen gas, it will emit, nearly simultaneously, three well-defined hard x rays of 159, 55.6, and 25.7 kiloelectronvolts. This set of signals, when detected in the presence of emitted pions, provides a clear fingerprint of a primary antiproton that originated from a neutralino annihilation."

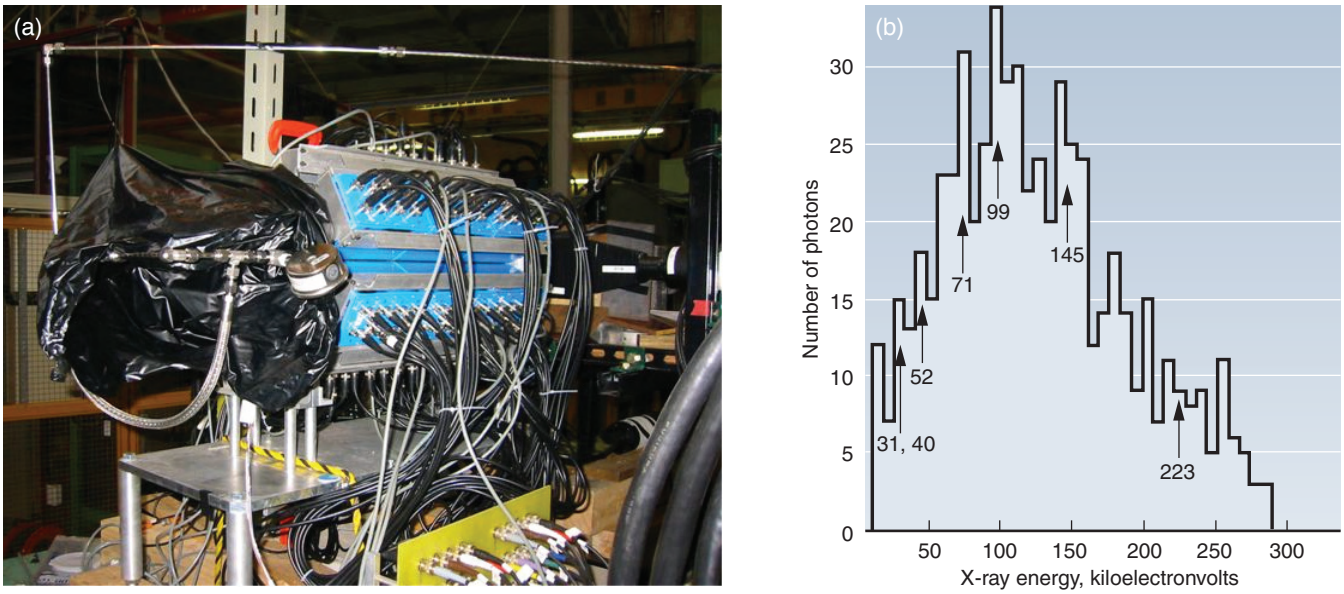
GAPS can easily separate cosmic antiparticles from those produced by the solar system. "We designed the x-ray detectors to be sensitive to a narrow energy band and time window," explains Craig. "The time-of-flight system records when an antiparticle of interest enters the system and its velocity. We can then observe the distinctive fingerprint of x rays and pions to determine if this antiparticle is the one we are seeking. We expect one antideuteron for every 10^9 protons. GAPS allows us to search for antideuterons, for the first time, in a definitive manner."

Space—the Final Frontier

Livermore's Laboratory Directed Research and Development (LDRD) Program funded the initial work on GAPS. As part of their LDRD project, Craig and his team completed a proof-of-concept prototype and tested it at the KEK Accelerator Test Facility in Japan. They looked for antiprotons resulting from the interaction of KEK's antiproton beam with the GAPS target material. High-quality antiparticle events were detected from four different targets. The experiment proved that GAPS could detect a specific type of antiparticle and energy amid a high flux of other particles. "The KEK tests also showed us that we could obtain good results using solid and liquid targets," says Craig, "which greatly simplifies our design challenges. The original design used high-pressure gas as the target, which meant we had the 'dead



The General Antiparticle Spectrometer (GAPS) developed at Livermore can capture and identify a single antiparticle in a large flux of other particles. GAPS consists of a time-of-flight system to determine the energy of incoming antiparticles, a degrader to slow down antiparticles of interest in a specific amount of time, and a chamber filled with a target liquid or solid to "capture" the antiparticle. The captured antiparticle gives off x rays of specific energies (measured in kiloelectronvolts, keV) as it decays, and the x-ray energies are recorded by surrounding spectrometers.



(a) A proof-of-concept GAPS system was tested at Japan's KEK particle accelerator. The system successfully recorded unique x-ray "fingerprints" of antiprotons using a variety of solid, liquid, and gas targets. (b) An x-ray spectrum shows the decay of captured antiprotons in the solid carbon tetrabromide target material with peaks at the expected frequencies.

weight' of a gas-handling system. With liquid or solid targets, GAPS not only weighs less but also is easier to operate and more efficient and sensitive."

In a multinational collaboration that includes groups from several institutions in the U.S. and Japan, a high-altitude balloon test in Antarctica will bring GAPS closer to space. The 20-day experiment will gather more data with more detectors—20,000 detectors versus the 128 on the prototype. Because most galactic cosmic rays have energies too low to penetrate Earth's atmosphere, this balloon test will be the first opportunity for GAPS to detect a sizable number of antideuterons. "We might detect about a dozen antideuterons," says Craig. "We'll detect thousands of antiprotons, which will allow us to do some interesting cosmic-ray physics." The experiment is scheduled in the 2010–2011 time frame.

The team's ultimate goal is to use GAPS on a space-based experiment. According to Craig, the National Aeronautics and Space Administration has expressed interest in the project. "We take our work one step at a time. This experiment is not an easy one to build," says Craig. "Still, we're excited that the answer to the big question 'what is the universe made of?' may be within our grasp."

—Ann Parker

Key Words: antideuteron, antimatter, antiparticle, antiproton, cosmology, dark matter, general antiparticle spectrometer (GAPS), Milky Way Galaxy, neutralino, particle physics, weakly interacting massive particle (WIMP), x-ray detector.

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From Fission to Fusion and Beyond

Teller's Contributions to Applied Physics and Defense

January 15, 2008, marks the 100th anniversary of Edward Teller's birth. This highlight is the sixth in a series of 10 honoring his life and contributions to science.

THE discovery of nuclear fission in Germany in 1939 was a turning point for scientists. Nuclear physicists quickly recognized the potential for a fission weapon of previously unimagined power.

In 1939, Edward Teller was teaching quantum mechanics at George Washington University in Washington, DC. In the four years since completing his Ph.D. in theoretical mechanics, he had made groundbreaking contributions to chemical, nuclear, and solid-state physics. In the summer of 1939, Teller participated in Leo Szilard's famous visit with Albert Einstein, during which they encouraged Einstein to write to President Franklin D. Roosevelt about fission's possibilities as a weapon. Because Szilard did not drive, he asked his good friend Teller to chauffeur him to Einstein's home. Teller was happy to do so, but not for any political reasons. At that time, Teller was thoroughly apolitical.

A Nation at War

His attitude changed, however, with the terrifying Nazi Blitzkrieg into Holland, Belgium, and Luxembourg. Teller listened intently when Roosevelt issued a call for scientists to "act together to protect and defend, by every means at our command, our science, our culture, our American freedom and our civilization." Teller commented in *Memoirs*, "I had the strange impression that he was talking to me." He was quickly drawn into the center of scientific events that led to the Manhattan Project at Los Alamos.

A question from Enrico Fermi in 1941 about using a fission device as a trigger for a fusion weapon set Teller to thinking about what would become the hydrogen bomb. Although Teller made significant contributions to the development of the atomic bomb, he considered that weapon largely "an engineering problem." Most of his weapons work during the 1940s focused on the thermonuclear superbomb known as the Super.

Teller spent years trying to design a practical hydrogen bomb. After the Russians tested their first atomic bomb in 1949, President Harry S. Truman decided to proceed with development of the hydrogen bomb although the U.S. did not yet have a design. Finally, in 1950, Teller had the crucial idea of radiation implosion, which, when combined with Stanislaw Ulam and Teller's idea of "staging," produced a workable design for a thermonuclear device. Teller was at the University of California at Berkeley during the first major test at Bikini Atoll on November 1, 1952. A seismograph registering the detonation thousands of kilometers away spoke to the success of the Teller–Ulam design.

A New Laboratory

Just months before, a second weapons laboratory had been cofounded at Livermore by Ernest O. Lawrence and Teller, who helped

Edward Teller received the Presidential Citizens Medal from President Ronald Reagan in 1989.

convince the government to accelerate the development of thermonuclear explosives. Teller served as the Laboratory's director for two years, from 1958 to 1960, and acted as a spark plug for new ideas for more than four decades. In 1955, it was Teller who assured the Navy that the Laboratory could develop a nuclear warhead small enough to be carried on a missile fired from a submarine. The scientists back at Livermore stepped up to the challenge. They quickly came through with the small, strategic Polaris warhead for submarines, thus providing a secure second-strike force.

Livermore scientists also responded imaginatively to another concern of Teller's—defense against incoming weapons. In the 1960s and 1970s, Livermore worked with the Army on a ballistic missile defense system. However, the new multiple independently targeted reentry vehicles, first developed at Livermore, soon outstripped available defense systems.

Teller was the impetus behind the miniaturization of nuclear weapons for launch from submarines.

Strategic Defense

President Ronald Reagan's introduction of the Strategic Defense Initiative (SDI) in 1983 gave a boost to Teller's vision of security through defense: "Better a shield than a sword." Working with the Strategic Defense Initiative Organization and scientists from several laboratories, Livermore explored many possible concepts for SDI, including a nuclear-pumped x-ray laser and a constellation of tiny nonnuclear satellites dubbed Brilliant Pebbles. When activated, a Brilliant Pebble would intercept and destroy an attacking missile before the weapon could deploy its warheads. Less than two years after the Brilliant Pebbles concept was proposed, the Berlin Wall fell, and soon after, the Cold War was over. However, the legacy of SDI lives on in the dozens of new materials and devices that have since been commercialized and continue to find use in Laboratory research.

So, too, does Edward Teller's legacy live on at Lawrence Livermore in innovative ideas, fertile minds, and superb science.

—Katie Walter

Key Words: Edward Teller, hydrogen bomb, multiple independently targeted reentry vehicles, Strategic Defense Initiative (SDI).

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Continued from p. 2

Study shows how dormant bacterial spores awaken

Collaborative research led by Livermore scientists Marco Plomp and Alexander Malkin revealed the alterations that occur in the spore coat and germ cell wall of bacterial spores when they break out of their dormant state and reenter the vegetative mode of replication. The study, which included researchers from Children's Hospital Oakland Research Institute and Northwestern University, will help scientists better understand the spore germination process and develop countermeasures for spore-mediated diseases, such as botulism, gas gangrene, and pulmonary anthrax.

When *Bacillus* cells are starved of nutrients, their rod-shaped cells undergo a series of genetic, biochemical, and structural changes that create metabolically dormant spores. These dormant spores are not affected or destroyed by exposure to high temperatures, radiation, or toxic chemicals. When favorable conditions reoccur, the spores will germinate and replicate.

The Livermore-led study used atomic force microscopy (AFM) to examine single germinating spores of *Bacillus atrophaeus* in vitro. The AFM images showed with unprecedented resolution how the spore coat breaks down and how the new bacterium emerges from a disintegrating spore. In examining the disassembly of the outer spore coat, the researchers found that the bacteria's rodlet structures are similar to amyloid fibrils, which are associated with neural degenerative diseases such as Alzheimer's. The team's results appeared in the June 4, 2007, issue of the *Proceedings of the National Academy of Sciences*.

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New insight into crystal structures of actinide metals

Results from a study involving Lawrence Livermore and Oak Ridge national laboratories and Daresbury Laboratory in the United Kingdom are helping researchers better understand how the crystal structure of some metals becomes stable through magnetism. Magnetic stabilization of a metal's crystal structure is rare. However, in a few metals such as manganese, iron, and cobalt, the magnetic interaction energy is high enough to change the crystal structure. Previous studies also indicate that the heavy actinide element curium belongs in this category. When curium is placed under pressures of up to 100 kilopascals, it will transform between five crystal phases.

The Livermore-led collaboration took the previous research one step further. In this study, the researchers combined transmission electron microscopy, electron atomic calculations, and density functional theory to probe the electronic and magnetic structure of curium.

The results are indicative of Hund's rule, a principle of atomic chemistry. According to Hund's rule, the lowest energy state of an atom has large spin polarization with the maximal number of electrons in the outer shell unpaired and aligned in spin. This spin state dictates the crystal structure of curium under pressure and its magnetic properties. Results from the team's research were published in the June 8, 2007, issue of *Physical Review Letters*.

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Scientists improve electron-emission devices

A collaboration involving Livermore researchers may have found a way to improve electron-emission devices such as flat-panel displays and electron microscopes. This study, which included scientists from Stanford University, Lawrence Berkeley National Laboratory, Chevron Technology Ventures LLC, and Justus-Liebig University Giessen, examined the photoemitted electrons from monolayers of diamondoids on metal electrodes. Diamondoids are molecules with cage structures where the carbon atoms can be superimposed on bulk diamond lattice positions. These diamond nanoclusters are terminated at the surface by hydrogen.

Previous calculations and experiments on diamondoids predicted that the molecules would have a negative electron affinity, with the lowest unoccupied states at the surface of the clusters. These results motivated scientists to explore electron emission from diamondoids because the molecules offer the potential to combine the properties of diamond surfaces and nanomaterials.

For the Livermore-led study, researchers chemically modified pure diamondoids to form a uniform, well-ordered, layer of the diamond nanoclusters on gold and silver surfaces. The observed emitted energy spectrum—an intense monochromatic electron photoemission—confirms that diamondoids are negative-electron affinity materials.

Livermore researcher Trevor Willey, who worked on this study, says, "Our results suggest that diamondoid monolayers may eventually be used in devices that depend on highly efficient, monochromatic electron emission." The study's results were published in the June 8, 2007, issue of *Science*.

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Proton therapy made more accessible to cancer patients

Livermore's compact proton therapy system, which was developed in collaboration with the University of California (UC) Davis Cancer Center, has been licensed to TomoTherapy, Inc., of Madison, Wisconsin. TomoTherapy will fund development of the first clinical prototype, which will be tested on cancer patients at the UC Davis Cancer Center. If clinical testing is successful, TomoTherapy will bring the machines to market. These compact units are designed to fit in any major cancer center and cost one-fifth as much as a full-scale proton therapy machine.

Proton therapy is the most advanced form of radiation therapy available. In cancer research, this treatment yielded disease-free

survival rates comparable to those of surgery or conventional radiation but with minimal to no side effects. Unfortunately, the size and cost of proton therapy machines have limited the technology's use to only six cancer centers nationwide.

The proton therapy system developed by Livermore is a spin-off from a defense-related project. This compact machine will accelerate proton particles to an energy of at least 200 megaelectronvolts within a lightweight, insulator-based structure about 2 meters long. The system under development will also allow researchers to vary the energy, intensity, and spot size of the proton beam used to treat tumors.

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Livermore a partner at bioenergy research center

Lawrence Livermore, in partnership with Lawrence Berkeley and Sandia national laboratories, UC Berkeley, UC Davis, and Stanford University, will operate one of three new Department of Energy (DOE) bioenergy research centers. Funded by DOE's Biological and Environmental Research Genomics:GTL Program in the Office of Science, the new center will be known as the DOE Joint BioEnergy Institute (JBEI) and is expected to receive $125 million in DOE funding over the next five years.

Livermore scientists will support the basic research at JBEI, which will focus on producing biofuels from cellulosic materials. In particular, the Laboratory's microbiologists and biochemists will collaborate with researchers at UC Davis to look for new lignocellulose-degrading enzymes in natural microbial communities found in compost. Experts in computational biology will analyze the regulatory networks in microbial communities that effectively process lignocellulosic biomass. Laboratory scientists will also study the genetics and metabolism of microbes that produce long-chain hydrocarbons and explore the possibility of developing practical sources of nonethanol liquid fuels.

Livermore will use its secondary ion mass spectrometry imaging capabilities to examine cell-wall structure and degradation dynamics. In addition, the Center for Accelerator Mass Spectrometry will provide accelerator-based isotope measurements and ion-beam microbe analysis. Finally, the Livermore MicroArray Center will provide JBEI with technology to rapidly synthesize DNA-based microarrays and will perform subsequent analyses to provide data relating to gene expression.

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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.

Awards

The **International Association of GeoChemistry** has selected a paper authored by Environmental Radiochemistry Group members **Keara Moore**, **Brenda Ekwurzel**, **Brad Esser**, **Bryant Hudson**, and **Jean Moran** as the recipient of the **Hitchon Award,** a new international prize. The paper, "Sources of Groundwater Nitrate Revealed Using Residence Time and Isotope Methods," was recognized as the most important piece published last year in *Applied Geochemistry*, the association's monthly journal. The research leading to the paper, performed at Lawrence Livermore on local groundwater, involved using isotopic tracer techniques to examine groundwater flow patterns and timing of nitrate inputs to groundwater. Research results suggest that synthetic fertilizer and naturally occurring nitrogen in soil are more significant sources of groundwater nitrate contamination than previously thought.

Three Livermore teams have won **Nano 50™ awards**, which are given for the top 50 technologies, products, and innovations that have significantly impacted or will impact key nanotechnology commercial markets, from automotive and electronics to biomedical and materials. The awards are sponsored by the journal *Nanotech Briefs*.

Greg Nyce of the Chemistry, Materials, and Life Sciences (CMLS) Directorate was recognized for the development of new nanoporous, low-density materials. Designed for use in experiments at the National Ignition Facility (NIF), these materials have a wide range of potential for electronic, catalytic, and sensor applications.

Olgica Bakajin of CMLS was recognized for the discovery and experimental demonstration of ultrafast transport in carbon nanotubes. This nanotechnology has the potential to considerably improve the efficiency of water purification and desalination.

Jeff Tok of CMLS and **George Dougherty** of Engineering were recognized for their work on pathogen-sensing nanosensors based on multistripped metallic nanowires. This technology may enable rapid and sensitive single- and multiplex immunoassays for biowarfare agents and simulants and has applications in basic biology research and genetic screening.

George Chapline of the Physics and Advanced Technologies Directorate was named the winner of a **Computing Anticipatory Systems 2007 Award** for his work on neural networks and the brain. A computing anticipatory system computes its current states, taking into account not only past and present but also potential future states. Chapline's work in this area could have applications for treating mental illnesses and lead to profound improvements in education.

John Lindl, chief scientist for the NIF Programs Directorate, received the **2007 James Clerk Maxwell Prize for Plasma Physics** from the **American Physical Society** (APS). APS established the prize to recognize outstanding contributions to the field of plasma physics. Lindl's certificate says, "For 30 years of continuous plasma physics contributions in high-energy-density physics and inertial confinement fusion research and scientific management."

Before assuming his current role at NIF, Lindl served as scientific director for the Laboratory's Inertial Confinement Fusion Program. He is the author of numerous scientific journal articles and a seminal book entitled, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*.

Abstracts

Ramrods Shepherd Hydrodynamic Tests

Ramrods at Site 300, Livermore's Experimental Test Site, are key individuals who ensure that hydrodynamic tests are completed on time and within budget and provide maximal data. Hydrodynamic experiments reveal the behavior of a nuclear weapon from ignition of the high explosives to the beginning of the nuclear chain reaction. Data concerning the velocity of the imploding material and energy flow during the implosion are important to assessing a device's performance and for improving scientific understanding of the implosion process. Ramrods work closely with design physicists, engineers, technicians, and crews at Site 300. Their responsibilities include helping weapon physicists design a test, creating a detailed list of test specifications, supporting experiment design and readiness reviews, assisting and monitoring the experimental setup, choosing diagnostic instruments, and documenting environmental, safety, and health procedures.

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Three Dimensional on the Nanoscale

Livermore is beefing up its micro- and nanolithographic capability to assist in fabricating targets for experiments at the National Ignition Facility (NIF). Laboratory engineers developed laser pantography, a three-dimensional lithographic process, in the 1980s for the Strategic Defense Initiative. Laser pantography was later used to fabricate miniature electronic devices for both the W87 Life-Extension Project and enhanced surveillance for the Stockpile Stewardship Program. This versatile process is used today to pattern coils in portable nuclear magnetic resonance spectrometers that can detect weapons of mass destruction and in catheters for treating stroke and heart attack patients. Laboratory researchers are also customizing grayscale lithography and projection microstereolithography, processes developed elsewhere, for use in NIF experiments.

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Livermore's Award-Winning Technologies

Laboratory researchers received five awards in *R&D Magazine*'s annual competition for the top industrial inventions:

- Microelectromechanical System–Based Adaptive Optics Scanning Laser Ophthalmoscope
- Noninvasive Pneumothorax Detector
- Continuous-Phase-Plate Optics with Magnetorheological Finishing
- Large-Area Imager
- *Hypre* Software Library

Also in October

• Livermore scientists lend their expertise on peaceful nuclear applications to their counterparts in developing countries.

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