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Lawrence
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National
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Science & Technology

REVIEW



**Simulations &
Experiments
Supporting
Stockpile
Stewardship**

Also in this issue:

- Molten Salt Destruction of Explosives
- Electronic Security Clearances
- Crosshole Electromagnetic Induction

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About the Cover

The DOE's Stockpile Stewardship and Management Program will assure that we can depend on experiments and simulations to predict, detect, evaluate, and correct problems affecting nuclear weapons without nuclear testing. An example of the simulations activities at Livermore is the molecular-level sequence of a shock wave from a piston driving into a piece of metal shown on the cover. What we see are the effects on a nanometer-size void or defect (the empty circle). Developing molecular dynamics simulations using elements of the DOE's Accelerated Strategic Computing Initiative (ASCI) is made possible through partnering of massively parallel processing, software development, and data storage among the nation's three nuclear weapons laboratories. For a complete report on Livermore's contributions to stockpile stewardship, turn to [page 6](#).



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About the Review

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. *Science and Technology Review* (formerly *Energy and Technology Review*) is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments, particularly in the Laboratory's core mission areas—global security, energy and the environment, and bioscience and biotechnology. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (510) 422-8961. Our electronic mail address is hunter6@llnl.gov.

S&TR Staff

SCIENTIFIC EDITOR
Becky Failor

PUBLICATION EDITORS
Sue Stull and Dean Wheatcraft

WRITERS
Lauren de Vore, Arnie Heller,
Dale Sprouse, and Katie Walter

ART DIRECTOR
Ray Marazzi

DESIGNERS
George Kitrinos and Ray Marazzi

GRAPHIC ARTIST
Treva Carey

COMPOSITOR
Louisa Cardoza

PROOFREADER
Jill Sprinkle

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The Laboratory is playing a major role in the Department of Energy's Stockpile Stewardship and Management Program, which is designed to ensure that the nation's nuclear stockpile remains safe, secure, and reliable without new weapons development or the use of underground nuclear testing.

Research Highlights

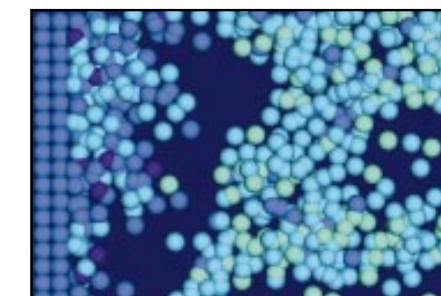
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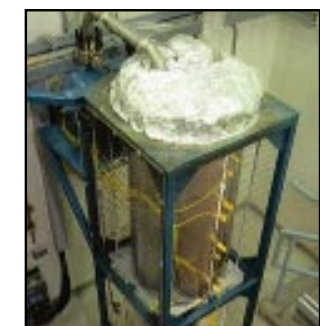
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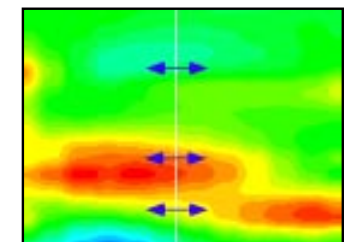
Abstract



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California science summit looks to future

National laboratories like Livermore offer powerful resources to partner with industry and help community leaders meet regional economic goals—but only if the labs can first fulfill the missions given them by the federal government.

That was the view expressed by Lawrence Livermore Director Bruce Tarter at the first California Coalition for Science and Technology Summit. Tarter's remarks came during a session focusing on research–industry partnerships in Northern California and the challenges they face.

The May meeting in Sacramento, California, was co-sponsored by the Department of Energy, the University of California, Lawrence Livermore, and many other organizations. The summit, which drew more than 300 attendees from government, academia, and industry, explored how those sectors can work together to build support for scientific research and enhance growth of high-technology industries in California.

Contact: Jeff Garberson (510) 423-3125 (garberson1@llnl.gov).

Livermore successfully test-fires petawatt laser

Lawrence Livermore opened a new chapter in the history of laser research this spring with the successful demonstration of its petawatt laser. For a brief instant, the Laboratory's petawatt laser produced pulses of more than 1.25 quadrillion (peta) watts of power, more than 1,300 times the entire electrical generating capacity of the U.S. The laser pulse lasts less than half a trillionth of a second, more than a thousand times shorter than that typically produced by Lawrence Livermore's giant Nova laser.

The laser employs a new technique called chirped-pulse amplification, which has revolutionized high-power laser research. The technique consists of producing a high-

bandwidth, low-energy pulse of extremely short duration (femtoseconds, that is, 1×10^{-15} seconds), stretching the pulse for amplification, and recompressing it back to its original duration.

The Lab's petawatt laser begins with a low-energy pulse less than one-tenth of a trillionth of a second in duration, stretches it 30,000 times to 3 nanoseconds, and then amplifies it by more than a trillion times. The petawatt uses one of the beamlines of the Nova laser for the final amplifier stage.

The petawatt laser will be used for research in areas such as inertial confinement fusion, high-energy x-ray generation, nuclear physics, and relativistic plasma physics. Technology developed for the petawatt has provided many unexpected applications—from new approaches to laser medicine to the use of diffractive optics on the proposed National Ignition Facility.

Contact: Michael Perry (510) 423-4915 (perry10@llnl.gov).

Lab team sets crystal growth record

Using a rapid-growth technique that Laboratory physicist Natalia Zaitseva helped pioneer in her native Russia, a Lawrence Livermore team has grown a 44-centimeter-wide KDP (potassium–dihydrogen–phosphate) crystal in a record-setting 27 days. Under standard growing conditions, it would take 18 to 24 months for a crystal to reach such proportions.

KDP crystals are a critical design element in the proposed 192-beam National Ignition Facility (NIF), which will play an important role in the nation's science-based approach to stewardship of its stockpiled nuclear weapons.

The team in the Laboratory's Advanced Laser Materials Group now has its eyes set on creating a 50-centimeter-wide crystal using the rapid-growth method. Fifty centimeters is the largest size required for NIF and also the capacity of the platforms in the KDP team's three growth chambers. It also is believed to be the size of the largest crystal ever grown.

Contact: Natalia Zaitseva (510) 423-1505 (zaitseva1@llnl.gov).

Lab hosts international Python conference

Lawrence Livermore played host earlier this year to the fourth international conference and workshop on Python, a computer programming language often compared to Java, Perl, and similar languages used to communicate in cyberspace.

Attractive because of its portability and versatility, Python runs on many systems, including UNIX, Windows, DOS, OS/2, Mac, and Amiga. The Laboratory is interested in its use for the Accelerated Strategic Computing Initiative (ASCI), the supercomputing project that is part of the DOE's science-based stockpile stewardship program.

According to conference organizer Paul Dubois, a key to Python's success is its availability to people and organizations free of charge. "The Laboratory frequently collaborates with researchers who don't have a lot of funds for software," said Dubois. "Python facilitates those collaborations."

The June conference attracted computational physicists and programmers from the U.S., Canada, Europe, and Australia. Among the attendees was Python's developer, Guido van Rossum of the Netherlands.

Contact: Paul Dubois (510) 422-5426 (dubois1@llnl.gov).

Meltdown may have formed Earth's metallic core

The separation of Earth's metallic core and its rocky, silicate mantle and crust is probably the result of massive melting caused by a violent collision between the Earth and huge celestial bodies at the time of the Earth's formation, about 4.5 billion years ago.

That is the conclusion Laboratory researchers reached after completing high-pressure experiments aimed at helping understand how most of Earth's metal became part of the planet's core, while most of the rocky material has settled in the mantle and crust.

The experiments involved squeezing metal and a sample of olivine (a silicate mineral that makes up most of the present Earth's upper mantle) in a multi-anvil press that is capable of generating pressures of more than 2 million pounds per square inch. As part of the study, temperatures of 2,700°F were generated within the sample. The molten metal that was produced beaded up at the corners of the silicate

grains and remained suspended—much as surface tension causes water droplets to form on a freshly polished car.

The results cast doubt on the theory holding that after Earth's formation molten metals trickled down between solid silicate mineral grains and eventually made their way to the center of the planet. In turn, the results support the view that an immense melting of much of the planet allowed molten metals and molten silicates to separate in the same manner as do oil and water. An interplanetary collision is the leading theory on the cause of such melting. For more information and graphics, see the specific Web page at http://www-ep.es.llnl.gov/www-ep/igpp/core/Core_Science.html.

Contact: Bill Minarik (510) 423-4130 (minarik1@llnl.gov).

Earth's crust modifies volcano chemistry

Collaborative research by Lawrence Livermore and Australian scientists indicates that the Earth's lower crust plays a significant role in modifying the chemistry of volcanic lava.

Led by Livermore geochemist Annie Kersting, the research team studied basaltic rock from magma that had erupted from a chain of volcanoes in Japan. By measuring the isotopic signatures of the cooled magma, or basaltic rock—specifically, the ratios of the lead, strontium, and neodymium isotopes in the rock—the researchers found evidence of changes in the signatures caused by their passage through two chemically different crusts.

Their research on the chemical interaction between the thin crust (approximately 30 kilometers thick) beneath most volcanic regions of the Earth and volcanic magma that makes up newly formed crust is described in the June 7 issue of *Science*. Kersting describes the team's findings as "helping us better understand how the Earth works and how the interaction of the crust and mantle influences the development of the continents." This study was funded by the Institute of Geophysics and Planetary Physics.

Contact: Annie Kersting (510) 423-3338 (kersting1@llnl.gov).



George H. Miller
Associate Director,
National Security

Meeting the Laboratory's Newest Challenge

FOR four decades, the excellence of DOE's three defense laboratories—Livermore, Los Alamos, and Sandia—has provided the assurance that the U.S. nuclear weapons stockpile was safe and reliable. This assurance was provided by the knowledge we gained from nuclear testing and by developing new weapons that responded to new defense requirements. Even though nuclear testing has ceased, no new weapons are being designed or developed, and the stockpile of nuclear weapons is being reduced in accordance with the START I treaty and START II agreement, we must continue to ensure that the nation's stockpile is safe and reliable. This is a very challenging task.

These events led President Clinton in August 1995 to reaffirm that the continued vitality of the three nuclear weapons laboratories is essential for meeting the challenge of ensuring the safety and reliability of our nuclear weapon stockpile by other means.

The DOE responded to this challenge with the Stockpile Stewardship and Management Program (SSMP). This program specifies a science-based approach, whose goal is to keep the stockpile safe and reliable by replacing weapons development and nuclear testing with weapons life extension and with intensive computational and experimental research that provides a fundamental understanding of all elements of nuclear weapons safety, performance, and maintenance.

Today national security is a principal integrating theme of Lawrence Livermore National Laboratory, with stockpile stewardship its major element. Livermore's role in the overall program is described in the article beginning on p. 6. A wide spectrum of activities is being integrated strategically and tactically within the Laboratory, requiring an unprecedented application of our teamwork. We are coordinating these endeavors through LLNL's Council on

National Security, whose members are the Associate Directors of all of our major national security directorates, comprising more than half of the assets of the Laboratory.

We should not underestimate the risks involved in science-based stockpile stewardship without nuclear testing. Sidney Drell, the chairman of the University of California President's Council on the National Laboratories, in describing SSMP as a major challenge for the Laboratories, said, "The Cold War may be over, but the weapons laboratories still face a tough challenge to maintain confidence in our enduring nuclear deterrent as safe and reliable as it shrinks in size and ages."

At this point in history, DOE's three Defense Programs laboratories have committed to an enormous undertaking: to make their best effort to safely and reliably maintain the U.S. nuclear stockpile without nuclear testing. There are risks involved in this challenging undertaking as well. Responding to the challenge requires virtually every part of the Laboratory to apply our can-do culture to a fundamental system change. This means we will be evolving rapidly and efficiently from the former underground-test-based culture of new weapon development to the science-based culture of stockpile stewardship. It is our job now to develop the highest quality stockpile certification process possible, based on high-quality and innovative scientific and engineering techniques including advanced computer modeling, aboveground experiments, advanced device surveillance, and advanced remanufacturing of weapon parts.

We believe our well-trained nuclear weapon experts are up to this challenge. Our hope is that future generations of weapons scientists, even though they may never have experienced a nuclear test, will be able to assure the citizens of our country that the nuclear deterrent is safe, secure, and reliable.

Livermore's New Course

C. Bruce Tarter, Director, LLNL

"Today I am announcing my decision to negotiate a true zero-yield comprehensive test ban. . . . The United States will now insist on a test ban that prohibits any nuclear weapons test explosion, or any other nuclear explosion. . . . I am today directing the establishment of a new annual reporting and certification requirement that will ensure that our nuclear weapons remain safe and reliable under a comprehensive test ban."

President Clinton

Press Conference, August 11, 1995

"I am assured by the Secretary of Energy and directors of our nuclear labs that we can meet the challenge of maintaining our nuclear deterrent under a CTB [Comprehensive Test Ban] through a science-based stockpile stewardship program without nuclear testing."

President Clinton

*in a statement read by Robert Bell,
Press Conference, August 11, 1995*

With these words last summer, the President of the United States charted a new course for Lawrence Livermore and DOE's other two Defense Programs laboratories. This course is the Stockpile Stewardship and Management Program (SSMP), whose goal is for computational and experimental research to provide the fundamental understanding that will enable us to predict in detail—without the benefits of nuclear testing—the complex nonlinear performance of nuclear weapons.

At Lawrence Livermore, we all know what an enormous challenge this presents. This undertaking is clearly not risk-free. At the same time, however, the SSMP offers an unprecedented opportunity for Livermore to serve the nation with our scientific and technological excellence.

I believe that our scientists and engineers are up to this challenge and that, with adequate support and close teamwork, our people will successfully carry the U.S. stockpile, secure and reliable, into the 21st century. It is an enormous responsibility. As we now unfold LLNL's SSMP roadmap involving significant changes in our national security mission, I am depending upon all Laboratory employees to accept the SSMP challenge and apply to it their characteristic skill, determination, and enthusiasm.

Keeping the Nuclear Stockpile Safe, Secure, and Reliable

In the absence of nuclear testing, the Department of Energy's Stockpile Stewardship and Management Program will use enhanced computational and experimental capabilities to help assess the status of the stockpiled weapons and predict, detect, evaluate, and correct problems affecting them. For Lawrence Livermore, the program represents a fundamental change from its historic nuclear weapons mission.

It is not often that the Department of Energy's Assistant Secretary of Defense Programs visits the Laboratory to deliver a pep talk on a newly announced national security program of paramount importance to the department and the country. But that's what happened last October when Vic Reis told a packed assembly of more than 350 employees that the "awesome responsibility" for decisions regarding the safety and reliability of the nation's nuclear weapon stockpile "has been put right back where it belongs—with the labs."

Reis was referring to the DOE's far-reaching plan to make every effort possible to ensure that the nation's nuclear force remains safe, secure, and reliable without new weapon development or the use of underground

testing. The plan, formally called the Stockpile Stewardship and Management Program (SSMP), is the result of close collaboration among the DOE and scientists from Livermore, Los Alamos, and Sandia National Laboratories. Indeed, in his address to employees, Reis credited LLNL Director Bruce Tarter and many top Livermore managers for their work to delineate for President Clinton, the Joint Chiefs of Staff, and the Congress the viability of the program, based on the projected capabilities and resources of the DOE weapon laboratories.

The SSMP will use enhanced computational and experimental capabilities to help predict, detect, evaluate, and correct problems affecting nuclear weapons in the national arsenal but without additional nuclear testing.

For Lawrence Livermore, the program represents a fundamental change from its historic mission of nuclear weapon development, nuclear testing, and surveillance. Stewardship of the U.S. nuclear stockpile is now this laboratory's "foremost responsibility," according to Tarter.

Specifically, the ambitious goals of the nation's SSMP are to:

- Provide the capabilities for the maintenance, assessment, and certification of the stockpile, including sources of nuclear weapon expertise to provide independent, critical reviews.
- Provide the capability to address the full range of stockpile problems that may arise.
- Minimize to the greatest extent possible the risks involved in maintaining the U.S. nuclear stockpile

Vic Reis, Department of Energy's Assistant Secretary of Defense Programs, visited Lawrence Livermore last October to underscore the importance of the Stockpile Stewardship and Management Program. While at LLNL, Reis visited the preferred site of the National Ignition Facility, a key component of the program.



under the constraints of no additional nuclear testing, no new-design weapon production, and limited budgets.

- Preserve the essential technical expertise unique to nuclear weapons.
- Provide a supply of tritium to replenish the inventory reduction caused by radioactive decay of tritium in existing weapons.
- Support U.S. nonproliferation, arms control, and nuclear weapon-related intelligence efforts.
- Provide the ability to reconstitute U.S. nuclear testing and weapon production capacities, should national security so demand in the future.

This new program addresses the U.S. nuclear stockpile, which is shrinking dramatically from Cold War levels. In the desire to conclude the Comprehensive Test Ban Treaty (CTBT), the U.S. has unilaterally halted the development and

deployment of new nuclear weapon systems, begun closing elements of the nuclear weapon production complex no longer needed for a much smaller stockpile, stopped underground nuclear testing, and been involved in unprecedented nuclear arms limitation agreements between the U.S. and the nations of the former Soviet Union.

The program received powerful support last fall when President Clinton said that his decision to pursue a CTBT was based on assurances that the DOE nuclear weapon labs can meet the challenge of maintaining the nuclear deterrent under a CTBT through a Stockpile Stewardship and Management Program that does not include nuclear testing. This April President Clinton reaffirmed his determination to achieve a worldwide CTBT in a joint declaration with Russian President Boris Yeltsin.

Urgency, Risk Underlie Program

An urgency underlies the program that can best be understood by realizing that the average age of the weapons in the U.S. stockpile next year will be greater than at any time in the past and will continue to increase until it soon exceeds the base of experience of the nation's weapon scientists. This is because the U.S. has no new weapons planned or in production to replace the oldest stockpile weapons.

Also, it must be anticipated that the reliability of the stockpile may degrade as the weapons age beyond their designed lifetimes. Problems could be caused, for example, by radioactive decay, slow chemical changes, or incompatible materials. Serious consequences could arise from

common-mode failures, ones that occur when similar materials or fabrication processes are used in several weapon systems. Because recently concluded arms control agreements have sharply reduced the number of weapons, such common-mode failures can affect a larger portion of the stockpile than in previous eras.

It seems likely that problems will arise over the next few years. Of the nuclear weapon systems introduced into the U.S. stockpile since 1970, nearly half have required post-development nuclear testing to verify whether a problem existed, or to resolve or fix ones relating to safety or reliability. Furthermore, all of the weapon systems that are candidates for the enduring stockpile (those weapons permitted as a result of the START II agreement with Russia) have already been retrofitted to some degree, including

the replacement of major nuclear components in some cases.

Weapon scientists must be able to accurately evaluate the severity of problems and devise the right "fixes," whether they be a remanufactured component, modification to a component to extend its lifetime, or substitution of a more reliable or safer part. In the past, the extent of a problem or the effectiveness of a "fix" could be determined with an underground nuclear test at the Nevada Test Site. If the problem proved to be particularly severe, a new warhead or weapon system could be developed. With nuclear testing and new weapon development no longer options, stockpile stewardship must rely on an improved understanding of nuclear weapons based on greatly improved facilities and computational models.

In addition to urgency, some areas of risk were folded into the President's decision. It is known that in some cases there is no adequate substitute for nuclear testing. The weapon recertification process will take these risks into account.

Key Thrust Areas

The national stockpile stewardship program has three main thrusts: laboratory experiments, computer simulations, and stockpile inspections. In each, Lawrence Livermore has particular responsibilities.

Upgrading Experimental Facilities and Capabilities

Defining the stockpile stewardship program has required extensive cooperation and coordination among

The Human Factor: Preserving Key Skills and Assuring Sound Judgment

The Stockpile Stewardship and Management Program (SSMP) places a premium on skilled, experienced people. As Lawrence Livermore Director Bruce Tarter said in April, "Stewardship of an aging stockpile is a heck of a different job than innovative research and design. It will rely—even more than in the past—on people throughout the Laboratory, the universities, and industry."

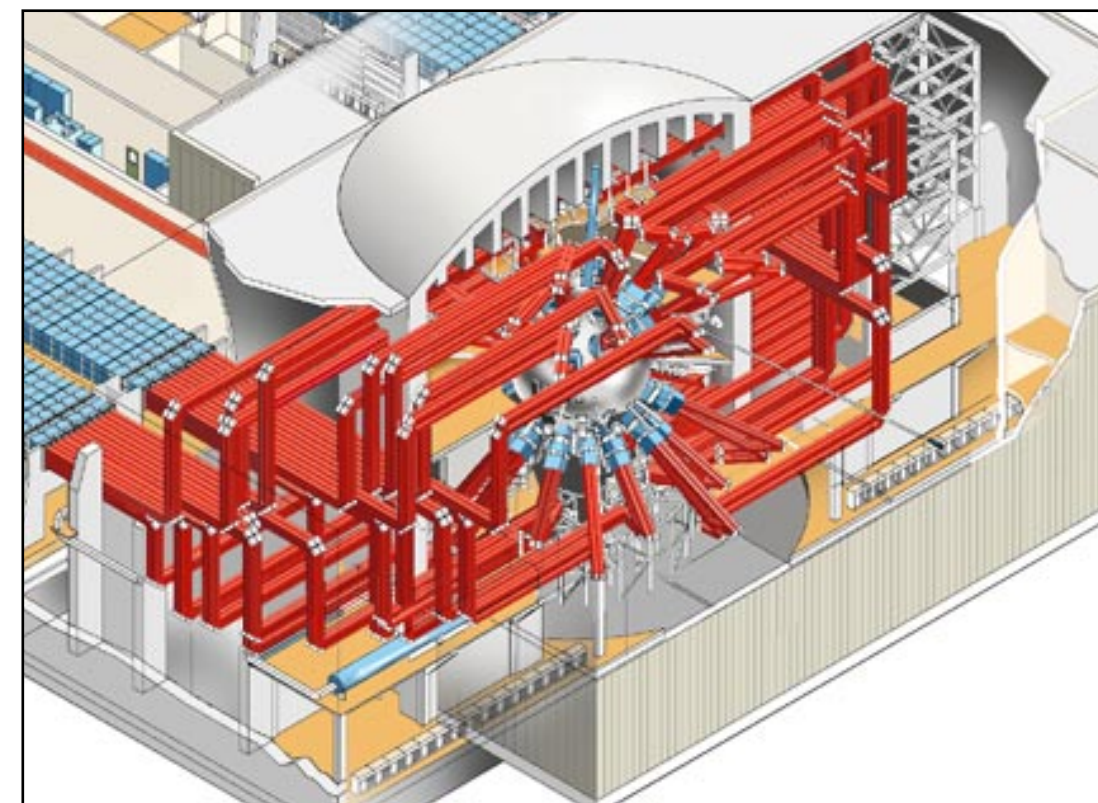
However, nuclear weapon science is a highly circumscribed field; there exists no broad industrial or university base from which to draw nuclear weapon expertise. U.S. weapon scientists have no true peers other than their colleagues at the three DOE weapon laboratories.

In the last few years, many of LLNL's most experienced weapon scientists and engineers have retired or left the Laboratory, and further retirements of experienced staff are expected in the next 10 years. To prepare for this situation, Livermore, Los Alamos, and Sandia are archiving their nuclear design data, knowledge, and skill bases. Lawrence Livermore, for example, is videotaping classified interviews of retired weapon designers explaining their craft and the steps leading to key design decisions. Scientists and engineers new to the weapon program will

be able to draw upon archival data as well as their experienced colleagues as they acquire the expertise to maintain the enduring stockpile in a time of no nuclear testing or new weapon development.

The SSMP places a premium on expert judgment in another important way. Throughout the history of the U.S. nuclear weapon program, interlaboratory peer review has helped to compensate for incomplete knowledge about nuclear weapon physics. Without nuclear testing, an independent review process is even more important.

Livermore and Los Alamos continue to be responsible for the weapon systems each laboratory originally designed, while Sandia has responsibility for the non-nuclear components and integration of all systems. At the same time, under a process called dual revalidation, Livermore and Los Alamos (aided by Sandia) formally examine and assess the safety and reliability of each other's weapon systems under the auspices of the Project Officer Groups of the Departments of Defense and Energy. The program offers another layer of confidence in safety, security, and reliability provided by some of the best researchers in the nation.



The target chamber of the National Ignition Facility (NIF). When operational in 2002, the NIF will permit experiments with conditions of pressure, temperature, and density close to those that occur during the detonation of a nuclear weapon.

Livermore, Los Alamos, and Sandia weapon experts. They recognize that the science of nuclear explosives is extremely complex. Even after more than four decades of work by hundreds of very capable scientists, gaps remain in understanding nuclear weapon behavior.

As a result, to provide needed data and simulations capability, a major thrust of the program is to upgrade existing experimental and computational capabilities at the three weapon laboratories and to design and construct several new facilities by providing insight into specific physics regimes. These strengthened capabilities will compensate, to the greatest degree possible, for the absence of nuclear testing. Together, the facilities will give the ability to investigate most phases of nuclear weapon operation. (See the box on p. 12 for a list of key facilities.)

Enhanced experimental facilities will provide the ability to evaluate safety

and performance issues that could have significant stockpile consequences. The new data will be combined with past data from experiments and nuclear tests and used to validate new and evolving computational models. Also, enhanced experimental and computational capabilities will help the weapon laboratories maintain the knowledge and skill base that are essential for training new people and assuring continued support for stockpile stewardship.

It must be remembered that laboratory experiments cannot duplicate a nuclear test. Even the most advanced non-nuclear experiment can access only a small portion of the physics regimes or materials dynamics relevant to nuclear weapons. Scientists and engineers face the new challenge of interrelating and extrapolating data from many different experiments to provide an overall evaluation of weapon safety and performance.

Also important to the DOE and its laboratories is the planning under way now to develop and build the National Ignition Facility (NIF), which will provide more than ten times the power of the Nova laser at a greatly decreased unit cost. Site selection will occur after public review of a program-wide

environmental impact statement and record of decision are completed later this year. The preferred site for NIF is Livermore, although wherever it is located, all of DOE's nuclear researchers will be using NIF to further understand nuclear weapons.

The need to obtain better data on the properties of plutonium and how it performs in an aging nuclear warhead is crucial. Experiments planned by Livermore and Los Alamos will reveal new information about the properties of plutonium at conditions close to those during weapon implosion. LLNL researchers also plan to conduct subcritical experiments on plutonium. Examples of this work include diamond-anvil-cell pressure measurements, equation-of-state studies, and metallurgical evaluations of aged plutonium.

Simulating Nuclear Testing

In the absence of nuclear testing, computer simulation is the only way to assess the performance of a complete nuclear weapon system. Numerical simulation also provides an essential tie to data from past nuclear tests and is an important means of predicting the performance and changes that might occur in the stockpile due to aging, environmental exposure, materials incompatibilities, or other reasons.

However, even today's most advanced supercomputers are not adequate to do the job. Increases of up to 10,000 times in computational speed, network speed, and data storage capacity are needed to provide

simulations of weapon safety and performance of the required complexity and detail when testing is not an option. New generations of supercomputers, especially those employing many parallel processors, will greatly increase the accuracy, completeness, and resolution of computer calculations as they simulate nuclear weapon phenomena in three dimensions.

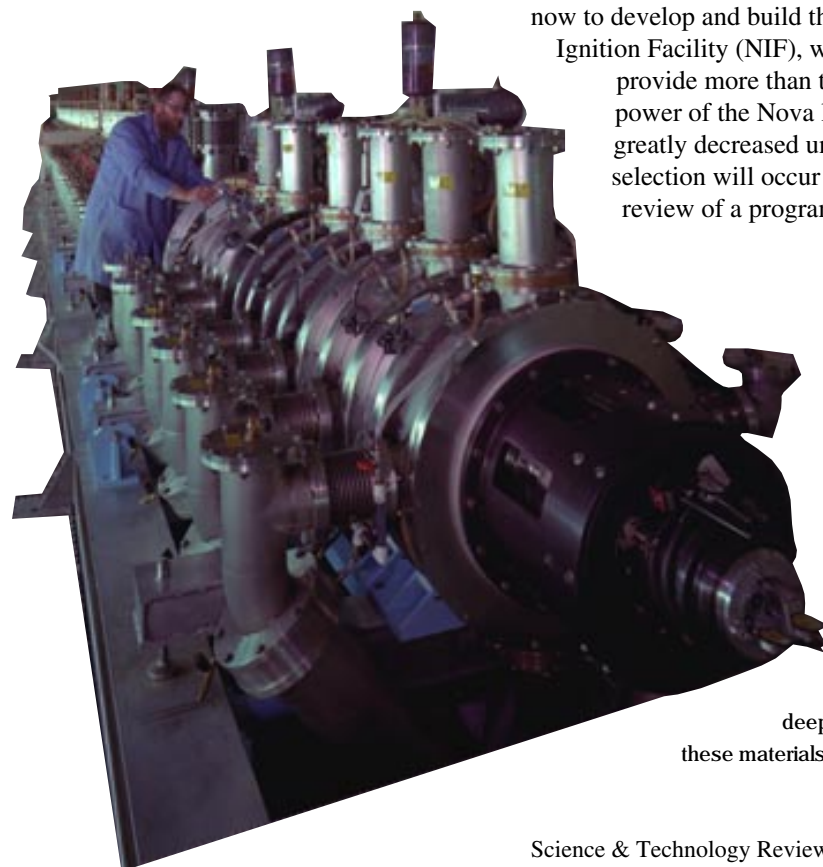
The objective of DOE's Accelerated Strategic Computing Initiative (ASCI) is to vastly improve the weapon simulation capability at the national security laboratories to the level required for stockpile stewardship. The goals are to develop advanced computational models and to work with industrial partners to develop the requisite technologies, including processors, software, and data storage to implement them.

Enhancing Stockpile Surveillance and Maintenance

The standard surveillance effort of the SSMP is focusing on the real-time status of weapon components in the stockpile through inspections and testing. Scientists also need a better understanding of how materials change and interact over time and how such changes affect weapon reliability and safety. An improved understanding of aging and material compatibility will help experts predict which parts need to be replaced or refurbished long before they severely impact weapon performance.

Stockpile weapons will be disassembled, examined, and evaluated. Some components will be remanufactured in order to fix problems that will inevitably arise. In past years a large weapon production complex

An addition to the FXR, the Contained Firing Facility, at Livermore's Site 300, will permit fully contained high-explosive tests with up to 60 kilograms of energetic explosives. This upgrade is desirable in light of increasingly restrictive environmental regulations.



LLNL's Flash X-Ray (FXR) machine, located at Site 300, is a part of the most capable high-explosives test facility in the world. The facility uses powerful x rays to penetrate deeply into dense materials and record the configuration of these materials at a chosen time during the operation of a test device.



Stockpile Stewardship: Advanced Experimental Facilities Needed by the program

A number of current and proposed experimental facilities are needed by the DOE-wide program to support assessments about weapon safety and reliability in the absence of nuclear testing. These include:

Laser Facilities

- *Nova Laser*. The Nova laser, located at Livermore, is used for weapon physics and weapon effects experiments in addition to research on inertial confinement fusion (ICF).
- *National Ignition Facility (NIF)*. NIF, a 192-beam laser facility planned for Livermore, will simulate on a small but diagnosable scale conditions of pressure, temperature, and energy density close to those that occur during a nuclear explosion. It will also serve ICF researchers.

High-Explosives Facilities

- *Contained Firing Facility (CFF)*. The CFF, an addition to the Flash X-Ray (FXR) facility at Livermore, will provide for well-diagnosed, fully contained high-explosives testing of up to 60 kilograms of energetic explosives.
- *Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility*. The DARHT Facility at Los Alamos will provide enhanced radiography of the high-explosive implosion, including data on implosion symmetry as a function of time.
- *Sub-Critical Experimental Facility (SCSS)*. This facility at the Nevada Test Site will provide capability to gather data on fissile materials in explosive-driven experimental geometries.
- *Advanced Hydrotest Facility (AHF)*. An AHF would provide three-dimensional time-radiography of high-explosive implosions. Its location is not yet determined.

Accelerator and Pulsed-Power Facilities

- *Los Alamos Neutron Science Center (LANSCE)*. LANSCE provides an accelerator-based neutron science capability for materials science studies of weapon components and for development of the technology for accelerator production of tritium.
- *Atlas Facility*. The Atlas pulsed-power facility at Los Alamos will provide implosions of cylindrical assemblies to obtain physics information that apply to weapons.
- *High-Explosive Pulsed-Power Facility (HEPPF)*. HEPPF will be used to study weapon physics issues of shock pressures and velocities close to actual weapon conditions.
- *Advanced Radiation Source (ARS)*. An ARS facility would provide high-energy, high-temperature, x-ray pulses for experiments in weapon physics, radiation effects, ICF, and pulsed power technology.

provided the means to rapidly fix any problems with new stockpile weapons. Today significant elements of the production complex have been shut down, and manufacturing capabilities are being consolidated at fewer sites because it is not practical or cost effective to meet manufacturing needs by keeping many of the old processes or facilities on standby. These new practices differ considerably from those in the past.

Clearly, investment is needed to develop manufacturing processes that are flexible, that minimize the production of hazardous waste, and that do not require extensive facilities and infrastructure. Concurrent engineering, in which the development of advanced manufacturing and material processing proceeds apace with the development of weapon components, is under active study. Where warranted, some production responsibilities are being reconfigured to rely on the laboratories' capabilities in manufacturing technology and their facilities for handling nuclear materials.

The Challenges for LLNL

For LLNL, says Associate Director for Defense and Nuclear Technologies Michael Anastasio, the job of stockpile stewardship will be "as challenging as anything we have done." The work at Lawrence Livermore centers on seven major efforts: extension of weapon lifetimes, enhanced stockpile surveillance, revalidation of existing weapon systems, flexible manufacturing, high-explosives experiments, the NIF, and supercomputers (including ASCI).

Extending Weapon Lifetimes

The Department of Defense (DoD) typically has expected weapons to be fielded in the stockpile for 20 years.

Now weapons will remain there longer, and more importantly, many will soon reach an age that exceeds our operating experience. At the same time, substantive reductions in the size and redundancy of the nuclear weapon complex are occurring. These substantial changes throughout the complex led to the need to integrate support for sustaining all weapon types in the stockpile. The Stockpile Life Extension Program meets this need by integrating programs and activities across the DOE complex.

The W87 life extension program, begun in September 1994, works to enhance and refurbish the structural integrity of the warhead to extend its lifetime. In 1995, with the DoD, LLNL conducted a successful flight test of a W87 test unit on a Peacekeeper missile launched from Vandenburg Air Force Base. Livermore also conducted ground tests to evaluate the performance of refurbished design options when exposed to environmental extremes. Physics analysis of the refurbished design options is continuing, and information has been transferred to Los Alamos for their independent technical review.

Enhancing Stockpile Surveillance

Surveillance and evaluation of the safety and reliability of U.S. nuclear weapons have been essential Lawrence Livermore responsibilities ever since the first LLNL-designed weapon entered the stockpile. A major current focus for LLNL weapon scientists is on surveillance responsibilities for the B83 bomb, the W84 cruise missile warhead, and the W62 and W87 ICBM warheads. Livermore weapon experts are developing comprehensive plans to extend the life of these systems through an expanded program of surveillance, maintenance, and refurbishment.

LLNL experts are working to increase knowledge in the science of surveillance to better understand and predict the effects of age on metals, high explosives, polymers, and other materials under realistic service environments. The program is developing new surveillance technologies, such as new sensors that will allow extensive self-diagnosis of weapon components.

Other nondestructive evaluation and imaging techniques involve tools like scanning tunneling microscopes to examine, on an atomic level, the effects of corrosion on critical weapon parts.

Enhanced stockpile surveillance requires more detailed computer models of materials, from the atomic level to the systems level. Advanced models will help experts anticipate the onset of potential safety or reliability problems as well as reveal the likely effects of substituting different materials or manufacturing processes. This ambitious modeling effort, one of the keys to stockpile stewardship success, involves researchers in Livermore's Chemistry and Materials Science, Physics and Space Technology, and Engineering Directorates, as well as colleagues at several universities (see the [June 1996 S&TR](#), pp.6-13).

Assessing with Dual Revalidation

Resolving stockpile issues without nuclear testing requires a much better understanding of the physical processes that determine the safety, reliability, and performance of weapon systems. Part of the SSMP will include dual revalidation, in which two independent teams will assess a weapon system to revalidate its ability to meet its current military characteristics and stockpile-to-target-sequence requirements. The two independent teams, working with the coordination of the DoD/DOE Project

Officers Group, are the original design team (made up of the weapons laboratories that were involved with the original weapon development) and the independent review team (laboratories not involved with original development).

The assessments will include analysis of historical development and nuclear and high explosives test data, surveillance data, and recent test data. Where new experimental and computational capabilities have become available since development, they will be applied to the weapon system being evaluated. The first weapon system to undergo such an assessment will be the W76, a Los Alamos system. Because the W76 is deployed on both the C4 and the D5 missiles, it will be assessed for both delivery systems.

Flexible, Affordable Manufacturing

An allied effort is providing the flexible, affordable manufacturing capabilities needed to replace and refurbish aging and defective weapon components. This streamlined manufacturing capability will use modern commercial methods whenever possible to build a systematic refurbishment and preventive maintenance program for stockpile weapons. Much of this work is being done as part of the DOE-wide Advanced Design and Production Technologies (ADaPT) program aimed at developing innovative manufacturing processes that reduce cost and waste, improve efficiency, and are environmentally friendly.

LLNL researchers are testing several new fabrication technologies that generate less hazardous waste and are less costly than previous methods. One example is precision casting of plutonium, which requires little or no subsequent machining and thus significantly reduces cost, waste, and

personnel exposure to radiation. Another innovative concept is reusing certain old components that already contain plutonium, instead of manufacturing new parts.

Lawrence Livermore experts are developing precision casting, spinforming, and machining techniques to replace the current methods of rebuilding uranium parts destroyed in the surveillance program. For example, a project is under way to demonstrate the feasibility of using lasers to cut uranium parts with very little waste and almost no damage to the remaining material. The process uses laser expertise developed in LLNL's Inertial Confinement Fusion program and Atomic Vapor Laser Isotope Separation program.

Remanufacturing of critical parts requires a process of recertification, based on detailed tracking of the remanufacturing process as well as experimental and computational tools.

Lawrence Livermore computational scientists are using three massively parallel supercomputers—two Meiko CS-2s (one is pictured here) and a Cray T3D—to develop codes that will represent three-dimensional simulations of nonlinear high-explosive and plasma-physics phenomena present in a nuclear detonation. However, in the future, the equivalent of thousands of these machines will be required.



Even more important, recertification requires expert judgment to provide confidence that the remanufactured component or weapon will perform as designed. Such judgment is essential because it is impossible to exactly duplicate past processes and practices. Researchers must reconsider how to remanufacture many of the old components and weapons because they are considered unacceptable today for environmental, safety, and health reasons.

High-Explosives Tests Critical

High-explosives testing is the only currently available way of experimentally testing part of the operation of a nuclear weapon's primary stage. In the test units, the nuclear materials are replaced by inert, surrogate materials. LLNL's Flash X-Ray (FXR) facility, located at Site 300, is a part of the most capable high-explosives test facility in the world. The facility uses powerful x rays to penetrate deeply into dense materials and record the configuration of these materials at a chosen time during the operation of the test device.

A three-year upgrade of FXR is in progress. The upgrade is expected to increase x-ray output by 50% and decrease x-ray spot size by 50%, allowing examination of implosion phenomena in much greater detail. The replacement of film by a digital gamma-ray camera has also provided images of greater resolution. The camera paves the way for an upgrade that will provide two images of an imploding device a few millionths of a second apart during a high-explosives test.

An addition to the FXR, the Contained Firing Facility, will permit fully contained high-explosives tests with up to 60 kilograms of energetic

explosives. This facility is desirable in light of increasingly restrictive environmental regulations.

Lawrence Livermore researchers also are working with colleagues from other national labs, Bechtel Nevada, and Britain's nuclear weapon community to develop plans for an Advanced Hydrotest Facility, which would yield three-dimensional movies and data of the interior of an imploding device. (The site of this new facility is not yet determined, but it is not expected to be at Lawrence Livermore.)

NIF for Critical Physics Data

When operational in 2002, the NIF will permit experiments with conditions of pressure, temperature, and density closer to those that occur during the detonation of a nuclear weapon. By addressing the high-energy-density and fusion aspects of stockpile weapons, researchers will obtain critical, fundamental physics data that are essential for refining advanced computer simulation codes. We will need these codes to assess potential stockpile problems, certify fixes to stockpile systems, and continue certifying LLNL-designed warheads. Also, by using NIF-heated targets, scientists will sharpen their ability to predict the effects of radiation on weapon components.

Last year LLNL began the detailed design work for the NIF, identified by DOE's Reis as "the most important new facility" in the Defense Programs' budget request for Fiscal Year 1996. Lawrence Livermore has been designated the preferred site for this \$1-billion project because of resident technical expertise and infrastructure.

Until the NIF comes on line, Lawrence Livermore's Nova laser will provide essential data on many aspects

of weapon physics. In 1995, more than 200 ICF experiments were conducted with Nova by weapon scientists from Livermore and Los Alamos. (See *Dec. 1994 Energy & Technology Review*, pp. 23–32 for an in-depth look at the national security aspects of research using NIF.)

Moving to New Supercomputers

Lawrence Livermore weapon scientists emphasize that greatly enhanced modeling and simulation capabilities are critical to their ability to assess the status of nuclear stockpile weapons, predict weapon performance, analyze refurbishment options, and evaluate potential accident scenarios. Major improvements are needed in the fineness of detail, especially in three-dimensional calculations and in the physics incorporated into the codes. These codes must replicate existing nuclear test data before we can confidently use them for assessing stockpile problems.

Meeting these challenges requires computers with thousands of processors working together to rapidly solve a single problem. At Livermore, there are three of these so-called massively parallel supercomputers—two Meiko CS-2s and a Cray T3D. In these efforts, LLNL experts are using these computers to develop three-dimensional simulations that include the wide range of nonlinear high-explosive, nuclear, and plasma-physics phenomena present in a nuclear detonation. These efforts also require development of new numerical algorithms and programming techniques.

At the same time, Livermore computational experts are incorporating improved data from non-nuclear tests, developing a secure high-speed network to interconnect Livermore and

Los Alamos supercomputer resources, and collaborating with universities and supercomputer companies to hasten the arrival of new generations of machines.

"Sustaining confidence in the stockpile in the post-Cold War world will be extremely difficult," says Associate Director Anastasio. "It's going to require us to adapt our skills to different approaches and different teaming across the Laboratory and throughout the DOE complex. That's the changing culture we face. There is plenty for everyone to do. We need the whole Laboratory working together to help pull it off. But this is something the Laboratory is very good at."

Key Words: Accelerated Strategic Computing Initiative (ASCI), Advanced Design and Production Technologies (ADaPT), Advanced Hydrotest Facility (AHF), Comprehensive Test Ban Treaty, (CTBT), flash x-ray (FXR), National Ignition Facility (NIF), Nova, Stockpile Stewardship and Management Program (SSMP), stockpile surveillance.

For further information contact Carol T. Alonso (510) 422-4776 (alonsoct@llnl.gov).

Molten Salt Takes the Bang Out of High Explosives

WITH the dismantlement of thousands of nuclear weapons and the demilitarization of millions of conventional munitions, the Departments of Energy and Defense face the problem of disposing of large quantities of energetic materials, including high explosives, propellants, and pyrotechnics. Some energetic materials can be recycled and reused, but others must be destroyed. Open burning, open detonation, and incineration have been the most commonly used destruction methods. Although in some cases the traditional methods are still the best, the trend today is toward alternative destruction processes.

A team at Lawrence Livermore National Laboratory, led by Ravi Upadhye, recently completed development of an environmentally friendly method for destroying these energetic materials from conventional and nuclear weapons. The process involves a crucible of molten salt in which the high explosives and propellants are reduced to carbon dioxide, nitrogen, and water. Depending upon the material being destroyed and the environmental regulations under which the user is operating, the gas by-product, or "off-gas," from the molten salt process may be sent through a cold trap or filter to remove small quantities of salt carried in the off-gas before it is released to the atmosphere. (See the photo next page and the diagram at right.)

Livermore scientists have received two patents for their process and have two more patent applications pending. In 1995, the Northern California Section of the American Institute of Chemical Engineers named the team's molten salt destruction process their Project of the Year.

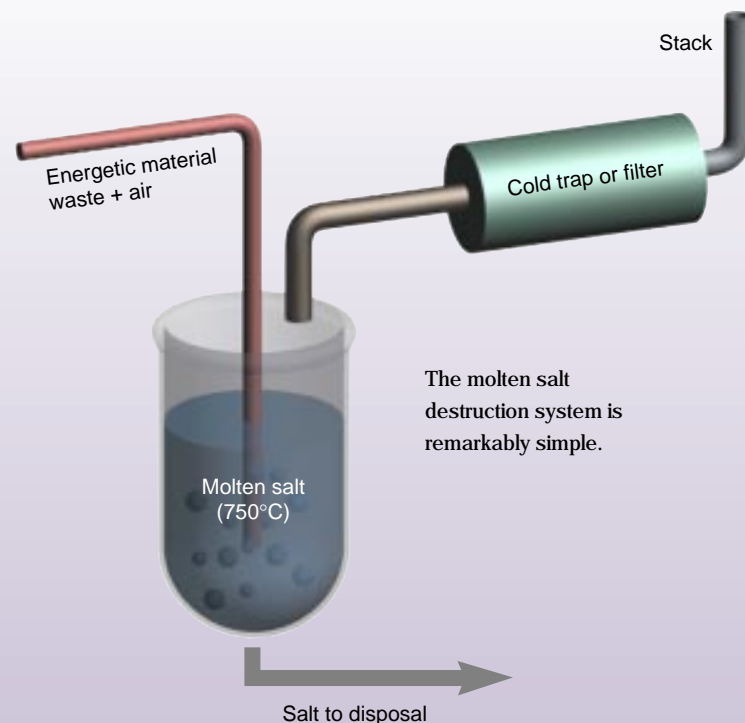
The Molten Salt Process

Energetic material waste is mixed with water to form a slurry that is introduced with air into a crucible. Inside the crucible are equal parts of sodium, potassium, and lithium carbonates. The temperature of these salts can be between 400° and 900°C, but 750°C is the temperature of choice for destroying the wastes. The melting point of the salt is about 400°C.

The organic components of the waste react with oxygen in air to produce carbon dioxide, nitrogen, and steam. The

inorganic components, in the form of ash, are captured in the molten salt bed as a result of wetting and dissolution. During the pyrolysis and oxidation processes, halogenated hydrocarbons in the waste generate acid gases, which are scrubbed by the alkaline carbonate component of the salt, producing carbon dioxide and the corresponding salt. (For example, hydrogen chloride produces sodium chloride, which is table salt.)

Bottles for sampling off-gas are attached to the crucible's exhaust line. After steady state has been achieved, infrared and mass spectrometers are used for real-time analysis of nitrogen oxides, carbon monoxide, nitrogen, carbon dioxide, argon, and hydrocarbons in the off-gases. As discussed above, the off-gas may be sent through a cold trap if necessary before being released to the atmosphere. Emissions from the process include no acid gases, such as hydrogen chloride or hydrogen fluoride. Furthermore, the



A view of the molten salt crucible and associated piping from above. The slurry of waste and air enters the top of the crucible, and off-gases exit through the larger pipe on the right.

quantities of nitrogen oxides are significantly lower than those produced during incineration.

At the end of the processing cycle, the salt can be separated into carbonates, noncarbonates, and ash. The carbonates can be recycled back to the process, and the neutral salts (such as sodium chloride) and ash are disposed of appropriately.

Livermore's latest molten salt unit has a capacity of 5 kilograms per hour (the equivalent of 60,000 pounds per year). It has a chimney-shaped, stainless steel crucible 2.2 meters tall, with a 40-centimeter nominal diameter at the top half and 20-centimeter diameter at the bottom. This design minimizes the amount of liquid salt droplets carried in the escaping off-gas. Waste is injected into the crucible through the top.

The whole assembly is placed inside an explosion-proof cell designed to contain a detonation of up to 10 kilograms of explosive. A remotely operated television monitor allows scientists to check on activity without entering the cell. All the mechanisms controlling the sample and feed sequences are operated remotely, and data are logged continuously by computer.

Upadhye noted, "Nitric oxide emissions from molten salt destruction of XM-46, a U.S. Army liquid gun propellant, were 100 times lower than those from incineration. The molten salt process also has the advantages over incineration of not having an open flame and of operating at lower temperatures. The team also compared it to a new method called supercritical water oxidation, which produced much more waste than the molten salt method. An added plus for the molten salt method is that it can be used to destroy chemical warfare agents."

From R&D to Field Use

The concept of using molten salt to destroy high explosives has been around for more than 20 years, but it took the end of the Cold War to prompt development of a usable system. In 1991, building on decades of experience with high explosives, Lawrence Livermore scientists began to do the chemical engineering necessary to take the molten salt method from theory to reality. They had at their disposal Livermore's state-of-the-art High-Explosives Applications Facility.

Livermore's initial laboratory-scale unit, with a capacity of 1 kilogram per hour (12,000 pounds per year), had a small side feeder and was used at first to destroy pure explosive powders. Then, a larger-diameter top injector was installed for feeding in real-world waste simulants such as machine shavings and sump sludge, including rust, metal parts, string, wood, sand, and floor sweepings. In every case, the waste simulants ran through the peristaltic pumps without clogging, and explosives were completely destroyed.

The 5-kilogram-per-hour unit was built in 1995 and has successfully completed a "shakedown run." In late 1996, it is scheduled to be dismantled and installed at Eglin Air Force Base in Florida for field demonstrations. Once the unit at Eglin is in full operation, it will be the first molten salt destruction system in the world that has proceeded past R&D and into field use.

Upadhye also noted, "Our process is safe, effective, and easy to use. We have built process controls and safety equipment into the system so that the unit can be operated after just minimal training." Ease of use is important because there is a huge job ahead—the Departments of Energy and Defense alone have hundreds of millions of pounds of energetic wastes to recycle or destroy.

Key Words: dismantlement, high explosives, incineration, molten salt destruction, open burning, open detonation.

For further information contact
Ravi Upadhye (510) 423-1299
(upadhye1@llnl.gov).

Security Clearances Meet the Electronic Age

EMPLOYEES throughout the Department of Energy complex will soon be filling out security clearance and reinvestigation forms on their desktop computers, thanks to a system developed at Lawrence Livermore that applies the latest computer and communication technologies to DOE's personnel security program. The new system, developed by LLNL's Fission Energy and Systems Safety Program (FESSP), promises to transform the traditionally slow—and costly—paper-based data collection systems to the Electronic Age, resulting in significant savings in time and money, as well as increased productivity and improved user satisfaction and attitudes about paperwork.

The modernization of the personnel security elements of DOE's Integrated Safeguards and Security System (DISS) is expected to shave at least a month off the average clearance process and save the DOE complex nearly \$30 million annually. The project, nearly completed, is essentially reinventing how DOE and the federal Office of Personnel Management (OPM) in Boyers, Pennsylvania, process some 30,000 security clearances and reinvestigations annually and how the agencies maintain and communicate their voluminous personnel data.

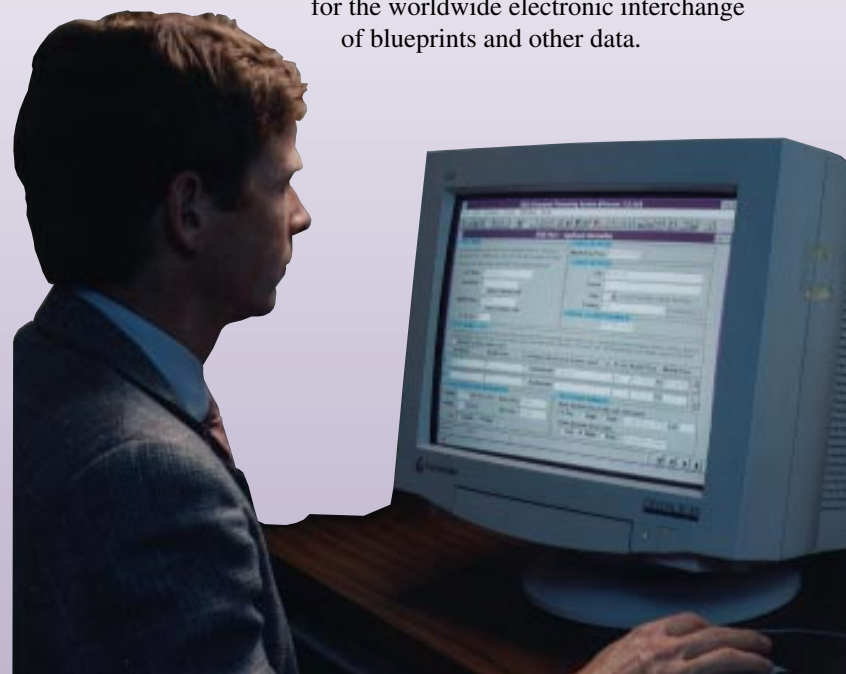
The \$12-million effort, begun in July 1993, taps the talents of some 25 people drawn from FESSP and the Laboratory's Computation and Engineering directorates who are expert in large computer systems integration and electronic commerce. Project leaders expect to have the new system deployed at 11 DOE operations offices, more than 30 maintenance and operations contractors, DOE Headquarters, and the OPM by the end of Fiscal Year 1996. DOE's Oakland Operations Office, which worked closely with FESSP during a December 1994 pilot evaluation, will be first to go online, followed by LLNL and Sandia National Laboratories, Livermore.

Scott Strait uses interactive software developed by the Laboratory's Fission Energy and Systems Safety Program (FESSP) to fill out personnel security forms. This modernization of DOE's Integrated Safeguards and Security System (DISS) will soon be used by DOE complex-wide to save time and money in the security clearance application, investigation, and renewal processes.

FESSP, along with its nuclear safety work, has long supported the federal government in meeting its security needs for facilities, personnel, and computer data. FESSP experts conducted a security vulnerability assessment of the U.S. Senate computer network and helped to produce an interactive version of the Vice President's "Reinventing Government" report for the Internet.

FESSP also cooperated in the design of Argus, an interconnected, computer-based system for access control, intrusion detection, and command and control that serves LLNL's Livermore and Site 300 facilities. Argus is saving the Laboratory some \$20 million annually, and DOE has selected the system as the standard automated electronic security technology for the entire complex. Presently FESSP is overseeing installations of Argus high-security systems at DOE's Pantex Plant in Amarillo, Texas, and at the Idaho National Engineering Laboratory.

The FESSP projects are part of a growing Lawrence Livermore expertise in aiding government and industry to do business more effectively by integrating the latest computer and hardware advances. The Computation Directorate's Technology Information Systems Program, for example, has automated procurement practices for the Air Force's Wright Patterson Air Force Base and the Veterans Administration in Long Beach, California; enabled the Laboratory (and soon other DOE sites) to authorize payment to suppliers using the Internet; and helped establish new standards for the worldwide electronic interchange of blueprints and other data.



Filing Prodigious Amounts of Paper

DISS program leader Scott Strait notes that DOE's personnel clearance activities, like those of most government departments, involve processing and filing prodigious amounts of paper, resulting in slow transmission of information and labor-intensive procedures. All applicant data, for example, are sent from DOE sites to the OPM as paper forms, where they are typed twice into a computer. Several operations offices maintain independent databases of applicant data, and each runs on different software. These systems are not tied electronically to DOE's central mainframe databases, requiring duplicate entry in local and Headquarters' systems.

The job facing FESSP experts was the creation of an integrated electronic system that could be implemented uniformly across the DOE complex with common—and secure—communications, databases, and user interfaces. In short, the Laboratory's team was asked to create a seamless, integrated system among DOE sites, operations offices, Headquarters, and the OPM where an authorized user could gain access to personnel information, no matter where it is stored in the DOE complex.

The overall goals included a reduction in the time to process security clearance requests; improved tracking and monitoring of the clearance process; improved data accessibility, timeliness, and quality; and greater productivity for DOE and contractors. A potential savings from the reduction in clearance time also may be fewer requests for clearances once managers realize how quickly individuals can be cleared.

FESSP people standardized procedures across the DOE complex to eliminate the inefficiencies from maintaining different processes in every operations office. They also standardized the local databases so that the operations offices no longer need to maintain their own software separately. These databases will now store in consistent form all applicant data entry, contractor and DOE additions, notes, current status, scanned documents, fingerprint images, secure e-mail messages, and the database access audit trail. Livermore developers also designed DOE's main personnel security databases to share common data with each other and the operations offices nationwide.

The new system is being linked to DOE's Visitor Access Database to provide the necessary information to interact with automated access control systems at DOE sites and for ensuring DOE badge accountability. This link eliminates the need to re-badge DOE and DOE-contractor visitors from off-site who need entry through automated access control systems and who hold the proper clearance. At LLNL, this change will reduce the number of visitor badges issued annually by about 16,000.

In creating the electronic forms for clearance applicants to enter their data, FESSP people incorporated the latest advances in electronic commerce and interactive technologies and data security features. As an example, they developed a system-wide infrastructure of secure "digital signatures" (a series of numbers unique to an individual) to assure the authenticity of information. They also integrated specialized software that permits the electronic transfer of fingerprints.

The developers had to keep in mind the large amounts of required data, geographically dispersed DOE contractor population, and the wide range of applicant computer skills and hardware. To ensure that an application is complete, for example, they added internal checks to the computer fields, so that warnings pop up if a field is left blank.

Filling Out Forms on a PC

Indeed, the project's biggest impact on most employees will be the opportunity to complete their personnel security forms on their own desktop computers. With interactive software developed by FESSP, applicants will know before they transmit clearance forms to their on-site security office whether their data meet OPM requirements. The data will then be relayed electronically to the DOE Field Office, which in turn will advance it to the OPM.

One of the developers' most important tasks was to assure the privacy of data. FESSP experts developed numerous "firewalls" against intruders and eavesdroppers. In addition, database security features will assure that only those with a "need to know" will have access to personnel data. Finally, all information will be sent over DOEBN, DOE's specialized communication network, and will be automatically encrypted.

Strait says that one of the biggest benefits from the modernization project will be an improvement in a factor hard to quantify—morale. Reduction in clearance processing time, he says, should improve attitudes of DOE and contractor employees awaiting a clearance or a clearance upgrade. And with reduced difficulties in accessing sites throughout the complex, the attitudes of visitors are sure to improve as well.

Key Words: DOE's Integrated Safeguards and Security System (DISS), electronic security clearances.

For further information contact
Scott Strait (510) 423-6681
(strait1@llnl.gov).

Exploring Oil Fields with Crosshole Electromagnetic Induction

WHEN Lawrence Livermore researchers developed a means to detect tunnels in Korea in the early 1970s, they had no idea that American oil and gas companies in the late 1990s might turn to a derivative of that technology to gain a more informative underground picture of their oil fields.

Yet crosshole electromagnetic (EM) induction technology, developed jointly by Lawrence Livermore and Lawrence Berkeley researchers with scientists at Schlumberger (an international provider of oil production services), may hold the key to significant increases in the extraction of oil and gas from existing reservoirs. What's more, the technology also may prove to be a cost-effective means for environmental site characterization and remediation monitoring.

"It is becoming increasingly difficult and expensive to locate new petroleum deposits, particularly in the U.S., so we must devise ways to get more oil out of existing fields," says Michael Wilt, a geophysicist and leader of the Laboratory's crosshole EM induction technology development effort. "Improved reservoir characterization is the key to extracting more oil and gas from oil fields. Producers are missing large pockets of oil because existing exploration methods, such as surface seismic reflection, sample too coarsely, and borehole logging techniques only measure rocks and fluids in the immediate vicinity of wells."

Wilt explains that crosshole EM induction technology is designed to provide high-resolution images of oil, gas, and water-bearing rock layers between existing wells up to 1,000 meters apart. A series of such images over time can also provide insight to changes in the field caused by oil production or by steam or water injection, which is used for enhanced oil recovery.

Determining the Electrical Resistivity

The electrical resistivity (resistance to the flow of electrical current) of rock formations can be determined from EM

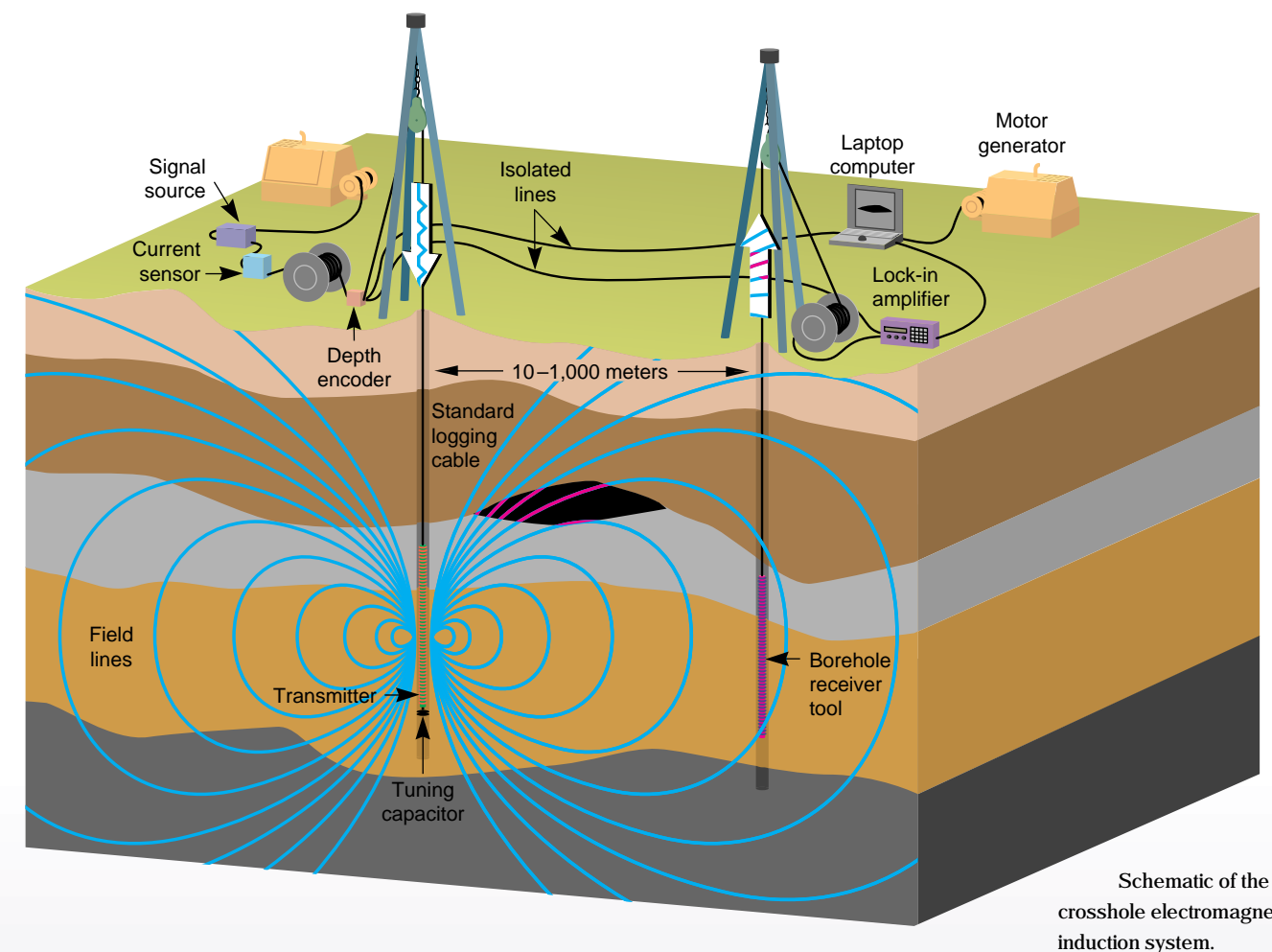


Laboratory scientist Michael Wilt sets up a field trial of crosshole electromagnetic induction technology at the University of California's Richmond Field Station. He is placing the receiver sensor in the borehole; in the background, Hung-Wen Tseng, an associate, is installing the transmitter coil.

induction measurements. Rock formations containing salt water, clay, or metallic minerals conduct current readily and therefore have low resistivity, while rocks containing fluids such as oil or gas have high resistivity. These resistivity differences can be used to distinguish between oil- and water-saturated sands, for example.

Measuring the electrical resistivity near a borehole has long been used to determine production zones in oil and gas fields and to map sand and shale layers. These measurements are usually made with an EM induction logging device that determines the resistivity within a meter or so around the borehole. Crosshole EM induction offers the ability for the first time to map subsurface resistivity between wells, on a reservoir scale (some 100 times greater an area than before), thereby locating bypassed concentrations of oil and gas.

The technology is an outgrowth of radar experiments conducted by Laboratory researchers in the early 1970s. The idea was to transmit high-frequency radio waves (greater than 20 megahertz) through the ground to detect tunnels in Korea. Although the technique proved effective for hard rock, the high-frequency signals could not propagate for more than a few meters in soft rock environments such as oil fields.



However, it was discovered that at frequencies in the kilohertz range, it is possible to propagate signals up to a kilometer through a typical oil field. The penalty is that at low frequencies, the signals are dispersive—i.e., they get smoother as they propagate—making them impossible to image with traditional techniques. Recently, new tools were developed at the University of California at Berkeley and Schlumberger that can determine the resistivity between boreholes from these crosshole EM measurements.

The crosshole system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well (see above figure). The transmitter uses a vertical-axis coil wrapped with 100 to 300 turns of wire tuned to broadcast a single low-frequency sinusoidal signal that induces currents to flow in surrounding rocks.

The optimum operating frequency depends on borehole separation and background resistivity, but generally the frequency ranges between 40 hertz and 100 kilohertz. A frequency that is too low limits the resolution, while one too high limits the range of the measurement.

At the receiver borehole, a custom-designed coil detects the total magnetic field, consisting of the magnetic field from the induced currents as well as the primary magnetic field generated by the transmitter. The receiver section consists of a magnetic field sensor and a commercial lock-in amplifier located at the surface. The lock-in amplifier operates like a radio by measuring only those signals that are coherent with the transmitted signal while rejecting incoherent background noise.

By positioning both the transmitter and receiver tools at various levels above, below, and within the zone of interest, researchers can create an image of the resistivity distribution between the wells. The EM data are interpreted by computer modeling in which the rock between the wells is divided into thousands of small, two-dimensional, square blocks 1 to 5 meters on a side. Each block is assigned an electrical resistivity value, estimated from the borehole resistivity log (if available). The computer then modifies the resistivity of these blocks until the calculated and measured data agree to

within the measurement error. This process usually requires 10 to 12 hours per data set on a 50-megahertz workstation to produce a detailed image of the underground strata.

Application in Oil Fields

After two years of development, a series of tests was conducted at Mobil Oil leases at Lost Hills in Central California in 1993 and 1994. The experiments were made to demonstrate the technology for characterizing oil reservoirs and monitoring steam floods. Two fiberglass-cased boreholes were drilled about 55 meters apart near a steam injector in shallow, heavy oil sands. Steam was injected at depths of 65, 90, and 120 meters, corresponding to upper, middle, and lower layers of the target Tulare formation.

The resulting crosshole EM induction images in the figure below, collected before steaming and 6 months and 11 months

after (a, b, and c), clearly show the distribution of the high resistivity oil sands (blue and green) and the intervening shale layers (red). (The arrows indicate points of steam injection.) The image in (a) indicates that the upper oil sand is a thick unit dipping gently eastward. The middle and lower sands are thinner and more discontinuous between the wells. The images shown in (b) and (c) are visibly different only at depths below 70 meters, where the resistivity has decreased significantly due to the steam injection. In all other parts of the image, the before and after resistivity values are unchanged. The resistivity decline is caused by the temperature increase and the replacement of oil by water and steam.

Images (d) and (e) are "difference" images made by subtracting the baseline image (a) from the other two images (b) and (c), respectively to show the percentage of change in resistivity. These images highlight the parts of the section

that have changed during the steam flooding. Images (d) and (e) show that the resistivity has decreased dramatically in the middle and lower oil sands, indicating the presence of substantial steam there. The images also indicate that almost no steam has gone into the upper oil sand. The steam also seems to preferentially flow to the west in the middle sand but to the east in the lower unit.

The steam is clearly not as successful in moving the very thick upper layer of oil. The technology showed the steam flood to be much less uniform than the operator anticipated, providing valuable information on the progress of the flood and the parts of the reservoir affected by the steaming.

Future Developments

For the past three years, the focus of R&D work centered on a recently concluded Cooperative Research and Development Agreement with Schlumberger. During the developmental work, Schlumberger developed an advanced computer code for imaging the data, and the Laboratory refined the hardware. The end result was a complete prototype system designed for application in deep oil field environments. This system, which is a significant upgrade over existing equipment, will be tested in the fall of 1996.

In addition to the cooperative work with Schlumberger, EM induction research is also proceeding at other national laboratories (Lawrence Berkeley and Sandia) and at other

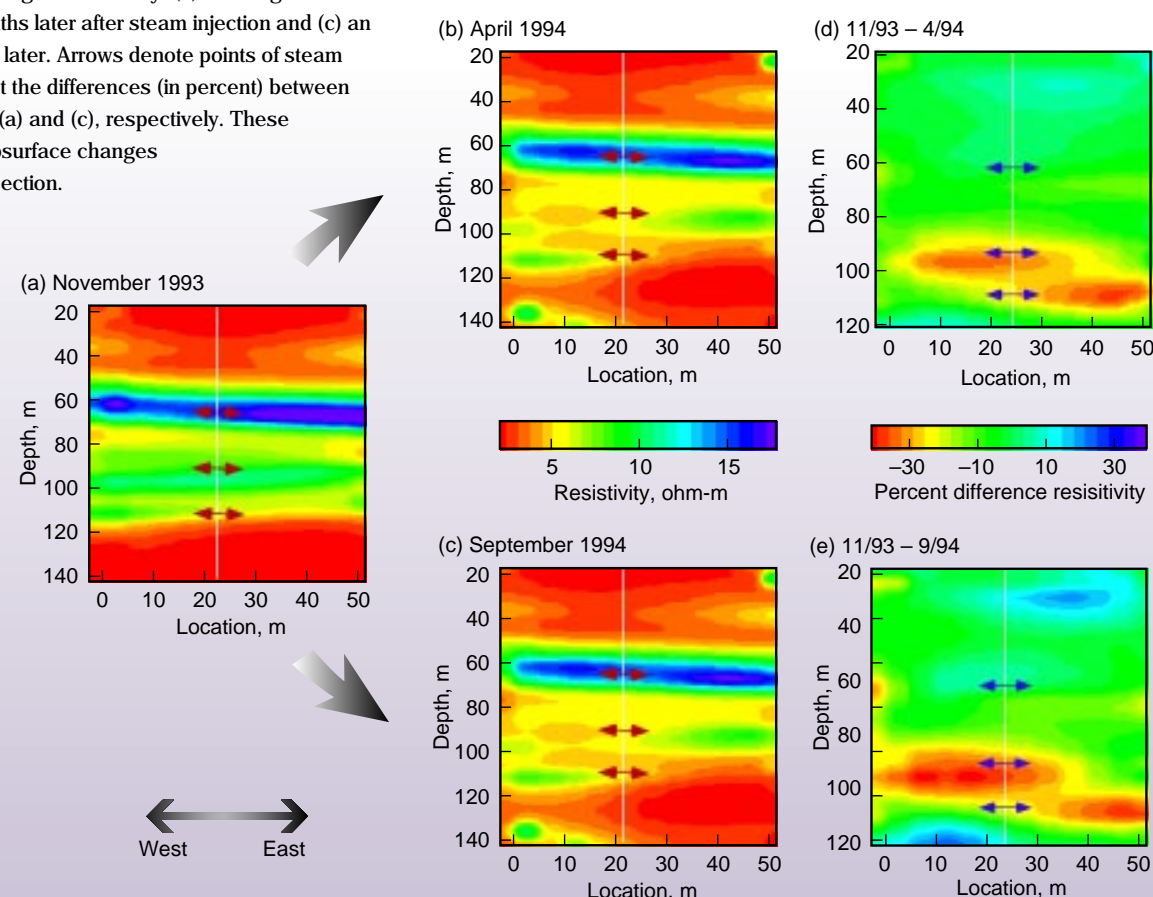
companies (Western Atlas and Oyo Corporation) to improve the quality of field data and to sharpen the image resolution. Among the most pressing problems is the application of the technology through steel well-casing. Although the steel casing dramatically attenuates EM signals, recent field measurements have shown that the subsurface resistivity may still be obtained under the right conditions. Steel-cased wells make up the vast majority of oil field drillholes, so this improvement in the technology could have dramatic effects on its widespread application.

EM induction technology has also been applied to environmental site characterization with good success. It is presently included in the Laboratory's arsenal of geophysical tools for site cleanup and monitoring. Research is also in the early stages for applying the technology to the exploration for mineral deposits.

Key Words: crosshole electromagnetic (EM) induction, electrical resistivity, oil-field imaging.

For further information contact
Michael Wilt (510) 422-3152
(mjwilt@lbl.gov).

(a) A baseline resistivity image of an oil field in Central California. Blue indicates high resistivity, low conductivity; red indicates low resistivity, high conductivity. (b) An image of the same area taken 6 months later after steam injection and (c) an image taken 11 months later. Arrows denote points of steam injection. (d) and (e) plot the differences (in percent) between images (a) and (b) and (a) and (c), respectively. These differences indicate subsurface changes caused by the steam injection.



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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Robert J. Deri Frank Patterson	Polarization-Independent Optical Wavelength Filter for Channel Dropping Applications U.S. Patent 5,515,461 May 7, 1996	The elimination of polarization dependence of optical wavelength filters by using waveguide directional couplers. Material birefringence is used to compensate for the waveguide birefringence, the original cause of the polarization dependence, and is introduced in a controllable fashion by replacing bulk waveguide layers by finely layered composites, such as multiple quantum wells using III-V semiconductor materials.
Joseph C. Farmer Francis T. Wang Robert G. Hickman Patricia R. Lewis	Mediated Electrochemical Oxidation of Organic Wastes without Electrode Separator U.S. Patent 5,516,972 May 14, 1996	An electrochemical cell/electrolyte/mediator combination for the efficient destruction of organic contaminants using cobalt salt mediators in a sulfuric acid electrolyte. Electrodes and mediator are chosen so that hydrogen gas is produced at the cathode and Co(II) is oxidized at the anode to produce Co(III), which converts the organics to CO ₂ . No electrode separator is required, so simple, inexpensive large-scale systems can be built.
Thomas E. McEwan	Ultra-Wideband Directional Sampler U.S. Patent 5,517,198 May 14, 1996	A four-port device that combines the function of a directional coupler with a high-speed sampler. Two of the four ports operate at a high sub-nanosecond speed in real time, and the other two operate at a slow millisecond-speed, in "equivalent time." A signal flowing to either of the high-speed ports is sampled and coupled, in equivalent time, to the adjacent equivalent-time port while being isolated from the opposite port.
Christopher D. Marshall Stephen A. Payne William F. Krupke	Optically Pumped Cerium-Doped LiSrAlF₆ and LiCaAlF₆ U.S. Patent 5,517,516 May 14, 1996	System in which cerium-doped laser crystals are pumped by ultraviolet light, which is polarized along the c axis of the crystals to effectively energize the laser. The crystals have the formula XYZF ₆ where X is Li, Na, K, or Rb; Y is Mg, Ca, Sr, Ba, or Cd; and Z is Al, Ga, or Sc. The p-polarized pump source reduces polarization-dependent excited-state absorption by the laser crystal.
Thomas E. McEwan	Transient Digitizer with Displacement Current Samplers U.S. Patent 5,519,342 May 21, 1996	A digitizer architecture using high-speed sample gates that is economical, easy to manufacture, and very fast. The digitizer has a sample transmission line, strobe transmission line, and samplers connected to the sample transmission line at a plurality of positions. The samplers with a two-diode sampling bridge are connected to a meandered sample transmission line.

Awards

Former Associate Director for what is now the Biology and Biotechnology Research Program, **Mort Mendelsohn** recently received Japan's prestigious Third Order of the Sacred Treasure, the country's highest civilian honor, for his work in studying the health effects of the Hiroshima and Nagasaki bombings. He also has just been named an honorary fellow of the international Society of Analytical Cytology, which he founded in the late 1970s.

For his outstanding contributions in model-based acoustic signal processing, **James Candy** was recently named a Fellow of the Acoustical Society of America. Candy is director of the Laboratory's Center for Advanced Signal and Image Sciences in the Laser Programs Directorate. His 20-year career at LLNL includes work in signal and image processing, sound propagation, and laser ultrasonics. Recently his work has concentrated on acoustic sound, such as in ocean acoustics and prosthetic heart valve classification.

Former Laboratory Director **John H. Nuckolls** was recently honored as recipient of the 1996 Distinguished Career Award from Fusion Power Associates. The award recognizes Nuckolls for "pioneering work in inertial confinement fusion, support of the fusion program during his tenure as director of LLNL, his visionary papers and speeches relating to fusion development, and his incisive technical challenges to the fusion development program." Given annually since 1987, the award is presented to individuals who, in the judgment of the FPA board of directors, have made distinguished lifelong career contributions that have benefited fusion development.

Electrical engineer **Kent McCammon** is a recipient of the California State Polytechnic University (San Luis Obispo) 1996 Medallion Award. It is one of seven awards given out each year to alumni of the university's Engineering Department for furthering the education of students. McCammon was honored for his contributions to the engineering profession and for his efforts to assist students on campus. Manager of the Cal Poly Graduate Internship Program between the Lab and the University, McCammon follows in the footsteps of the program's founder, **Jim McQuaid**, also a Cal Poly graduate and the first manager of the internship program, which is now 10 years old.

For his work in molten-salt destruction for high explosives, **Ravi Upadhye** has been named this year's recipient of the Professional Progress Award from the Northern California section of the American Institute of Chemical Engineers.

A 1996 Federal Laboratory Consortium (FLC) award for excellence in technology transfer was recently presented to **Ronald G. Musket** and **Jeffrey D. Morse** for their work in large-area, flat-panel displays. This unique field-emission technology has the potential to greatly change the computer and TV display markets.

Erratum: In June, we mistakenly reported 1994 awards from the FLC as having just been presented. Please accept our apology.

Keeping the Nuclear Stockpile Safe, Secure, and Reliable

The Department of Energy has launched a far-reaching plan to ensure that the nation's nuclear force remains safe, secure, and reliable without the use of underground nuclear testing. The plan, formally called the Stockpile Stewardship and Management Program, is the result of close collaboration among the Department of Energy and scientists from Lawrence Livermore, Los Alamos, and Sandia National Laboratories. The program will use enhanced computational and experimental capabilities to predict, detect, evaluate, and correct problems affecting nuclear weapons in the national arsenal without nuclear testing.

For Lawrence Livermore, the program represents a fundamental change from its historic mission of nuclear weapons development, testing, and surveillance. Stockpile Stewardship work at LLNL centers on five major efforts: the National Ignition Facility, the Accelerated Strategic Computing Initiative, hydrodynamic experiments, enhanced surveillance, and life-extension programs for Livermore-designed weapons.

■ Contact:

Carol T. Alonso (510) 422-4776 (alonsoct@llnl.gov).

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