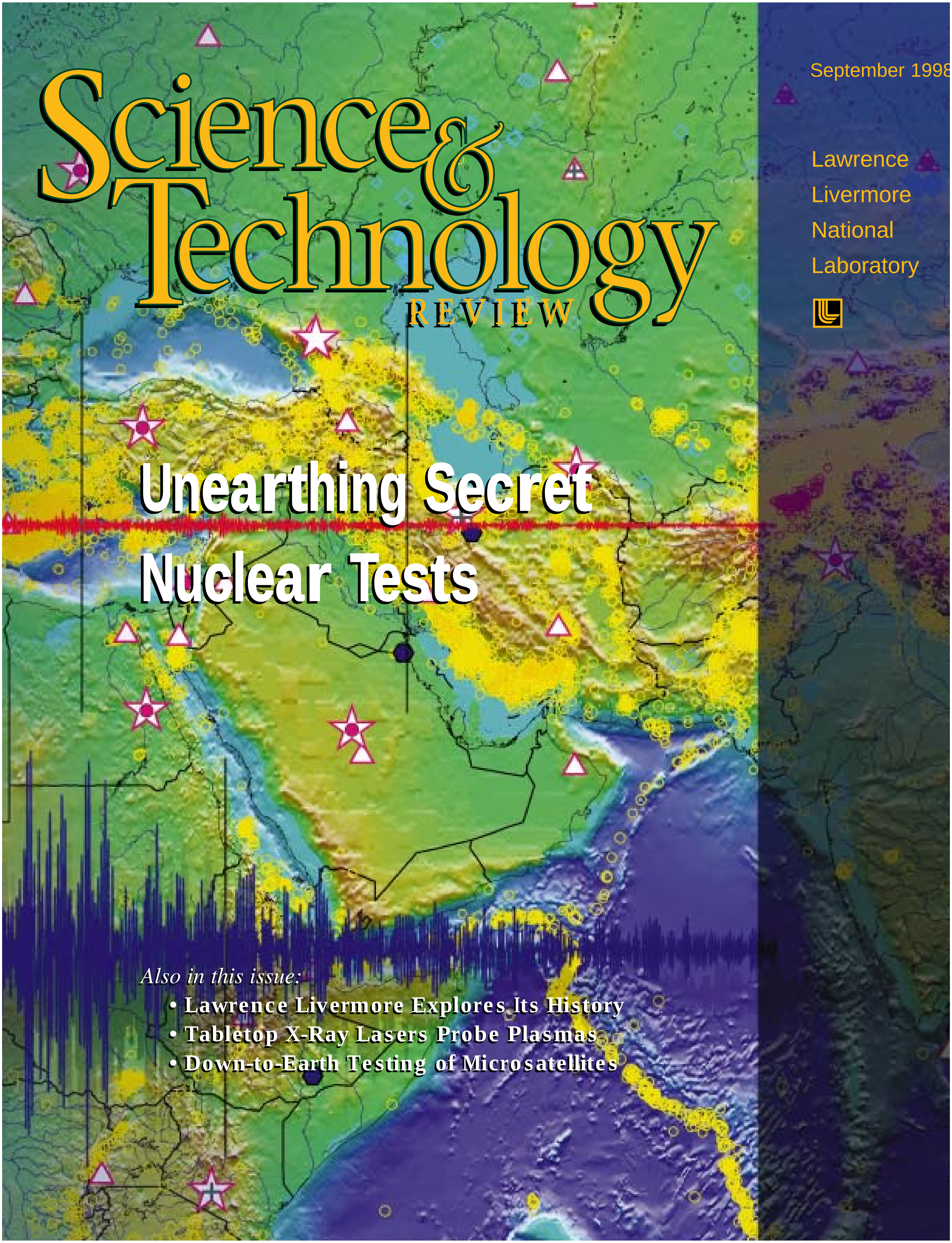
September 1998

Science & Technology Review

Lawrence Livermore National Laboratory



Unearthing Secret Nuclear Tests

Also in this issue:

- **Lawrence Livermore Explores Its History**
- **Tabletop X-Ray Lasers Probe Plasmas**
- **Down-to-Earth Testing of Microsatellites**

About the Cover

This month's cover story focuses on Lawrence Livermore's monitoring research in support of a future Comprehensive Test Ban Treaty. The images on the cover tell part of that story—a map of North Africa and the Middle East where Laboratory scientists are concentrating their monitoring efforts to distinguish clandestine nuclear tests (red seismogram) from earthquakes (blue seismogram) or other seismic events. For details about the Laboratory's contributions to national and international monitoring in support of the CTBT, turn to p. 4.

Cover design: George Kitrinos

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten 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.

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 (925) 422-8961. Our electronic mail address is *str-mail@llnl.gov*.

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S&TR Staff

Scientific Editor
J. Smart

Managing Editor
Sam Hunter

Publication Editor
Dean Wheatcraft

Writers
Bart Hacker, Arnie Heller, Katie Walter, and Gloria Wilt

Art Director
Ray Marazzi

Designers
George Kitrinos and Ray Marazzi

Internet Designer
Kitty Tinsley

Compositor
Louisa Cardoza

Proofreaders
Carolin Middleton and Al Miguel

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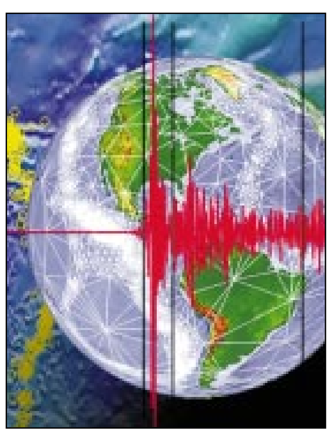

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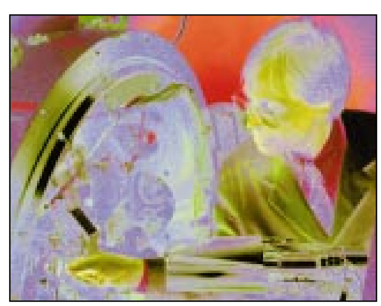

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Livermore is big R&D 100 Award winner

For the second year in a row, Lawrence Livermore scientists and engineers brought home seven R&D 100 Awards. Since 1978, the Laboratory has won 75 of these prestigious awards.

Each year, *R&D Magazine* presents awards to the top 100 industrial, high-technology inventions submitted to its competition for outstanding achievement in research and development. This year, Livermore tied with the Department of Energy's Pacific Northwest National Laboratories for the most awards won by a research institution. In all, DOE laboratories won 30 awards, with other major winners being Los Alamos (four awards) and Sandia (three awards).

The awards will be presented September 24 at a banquet and ceremony at the Chicago Museum of Science & Industry. *S&TR* will devote its October issue to detailed reports on Lawrence Livermore's award-winning inventions and the teams that created them.

And the Laboratory's winners are:

- HERMES (High-Performance Electromagnetic Roadway Mapping and Evaluation System), a high-resolution, radar-based mobile inspection system for detecting and mapping defects in bridge decks.
- A Lasershot^{sm} peening system that installs deep compressive stress in metals and is expected to extend the lifetime of major airplane components.
- The Light Lock optical security system, a reprogrammable, laser locking system that provides both the code to activate the locking device and the power to move the mechanical lock.
- An optical dental imaging system to noninvasively image internal tooth and soft tissue microstructure for dental applications.
- A two-color fiber-optic infrared sensor for measuring temperature and emissions for medical and industrial applications.
- The INDUCT95 computer simulation code that helps equipment designers optimize tools used in plasma-aided manufacturing of semiconductor devices.
- The OptiPro-AED (acoustic emission detector) grinding wheel proximity sensor, a real-time feedback product used to substantially improve the efficiency of precision optics manufacturing by sensing the separation between fine abrasive grinding tools and optical glass parts.

Contact: Karena McKinley, director of the Industrial Partnerships and Commercialization office at Livermore, (925) 423-9353 (mckinley3@llnl.gov).

Davis to head new DOD agency

Challenged to build a new organization to counter the threat posed by weapons of mass destruction, Jay Davis is off to Washington, D.C., where he will head the new Defense Threat Reduction Agency in the Department of Defense.

On leave as the Associate Director for Earth and Environmental Sciences at Livermore, Davis will be responsible for integrating nuclear, chemical, and biological functions and for consolidating the On-Site Inspection Agency, Defense Special Weapons Agency, and Defense Special Technology Security Administration. The new agency's primary function will be to understand nuclear, chemical, and biological warfare threats and minimize them worldwide

"This will be the lead DOD agency for countering weapons of mass destruction," Davis said.

Davis came to the Laboratory in 1971 as a physicist, with bachelor's and master's degrees from the University of Texas and a Ph.D. in nuclear physics from the University of Wisconsin. He has been the director of Livermore's Center for Accelerator Mass Spectrometry, which he helped found, and is a Fellow of the American Physical Society. In 1991, Davis participated as a member of the United Nations team that inspected Iraqi installations for possible nuclear weapons or technology that could produce nuclear weapons.

Livermore contributes to DOE climate study

President Clinton challenged the U.S. to reduce greenhouse gas emissions and spur economic growth. To meet the challenge, 11 Department of Energy laboratory directors, including Bruce Tarter of Livermore, reported to the Secretary of Energy some 47 technologies that could eliminate hundreds of millions of tons of carbon emissions each year. Technologies cited in the report include: electric hybrid vehicles, high-efficiency lighting, superinsulating windows, fuel cells, microturbines, and hydrogen fuel systems.

Partially finished before the Kyoto environmental summit in October 1997, the report now identifies and prioritizes the pathways to major technology opportunities. The report addresses three major issues: energy efficiency, clean energy, and carbon sequestration (removing carbon from emissions and enhancing carbon storage). The directors of the laboratories conclude that "success will require pursuit of multiple technology pathways to provide choices and flexibility for reducing greenhouse gas emissions." The report is available on the Internet at *http://www.ornl.gov/climate_change*.

Meeting the Monitoring Challenges of the Comprehensive Test Ban Treaty

ALTHOUGH political tensions have eased significantly between the West and the former Soviet Union, nuclear proliferation remains a grave concern worldwide. Recent events underscore this concern. In the months following the Gulf War, United Nations investigators were surprised to discover the progress Iraq had secretly made toward developing a nuclear arsenal. Just this spring, the nuclear tests by India and Pakistan raised the frightening specter of unfriendly neighbors acquiring their own nuclear missile forces and triggered urgent appeals for all nations to sign and ratify promptly the Comprehensive Test Ban Treaty (CTBT).

This ban on "any nuclear weapon test explosion or any other nuclear explosion"* is the latest step in a decades-long quest to halt nuclear proliferation. The treaty calls for an international system of several hundred monitoring stations transmitting data continuously to an international data center in Vienna, which in turn distributes the data and summary reports to national data centers, including the U.S. National Data Center in Florida.

As the article beginning on p. 4 points out, the treaty presents an unprecedented monitoring challenge: namely, detecting low-yield, clandestine nuclear tests among thousands of seismically similar events, such as small earthquakes and routine mining explosions, that will be reported daily by the monitoring stations arrayed around the globe.

The Department of Energy is drawing on the expertise and technical strengths of its national laboratories to devise tools and techniques for monitoring this most restrictive of all test bans. For its part, Livermore is home to expertise in nuclear-test-related seismology, geology, engineering, chemistry, instrumentation, and computer science. During the nation's earlier nuclear testing program, Livermore seismologists, geologists, and engineers, many of them now a part of the Earth and Environmental Sciences Directorate, played a critical role in ensuring the containment of the underground tests at the Nevada Test Site. In addition, our seismologists have a long history of treaty monitoring research and, along with other Livermore experts, have provided technical support and advice to U.S. policymakers and treaty negotiators for all of the treaties limiting underground nuclear testing.

During CTBT negotiations in Geneva a few years ago, Livermore made major contributions to the selection of international monitoring station sites, the definition of on-site inspection procedures, and even the adoption of national monitoring concepts undergirding the treaty. For the past few years, Livermore researchers have been working on several projects to help the U.S. National Data Center prepare for a CTBT. One vital effort focuses on determining how the regional geology in key parts of the world, such as the Middle East, will affect seismic signals as they travel underground from explosions, earthquakes, and other sources to the international monitoring stations. As the article describes, fulfilling this task has taken Livermore people to remote corners of the world and even teamed them with colleagues in Russia to calibrate seismic wave propagation in areas of the former Soviet Union.

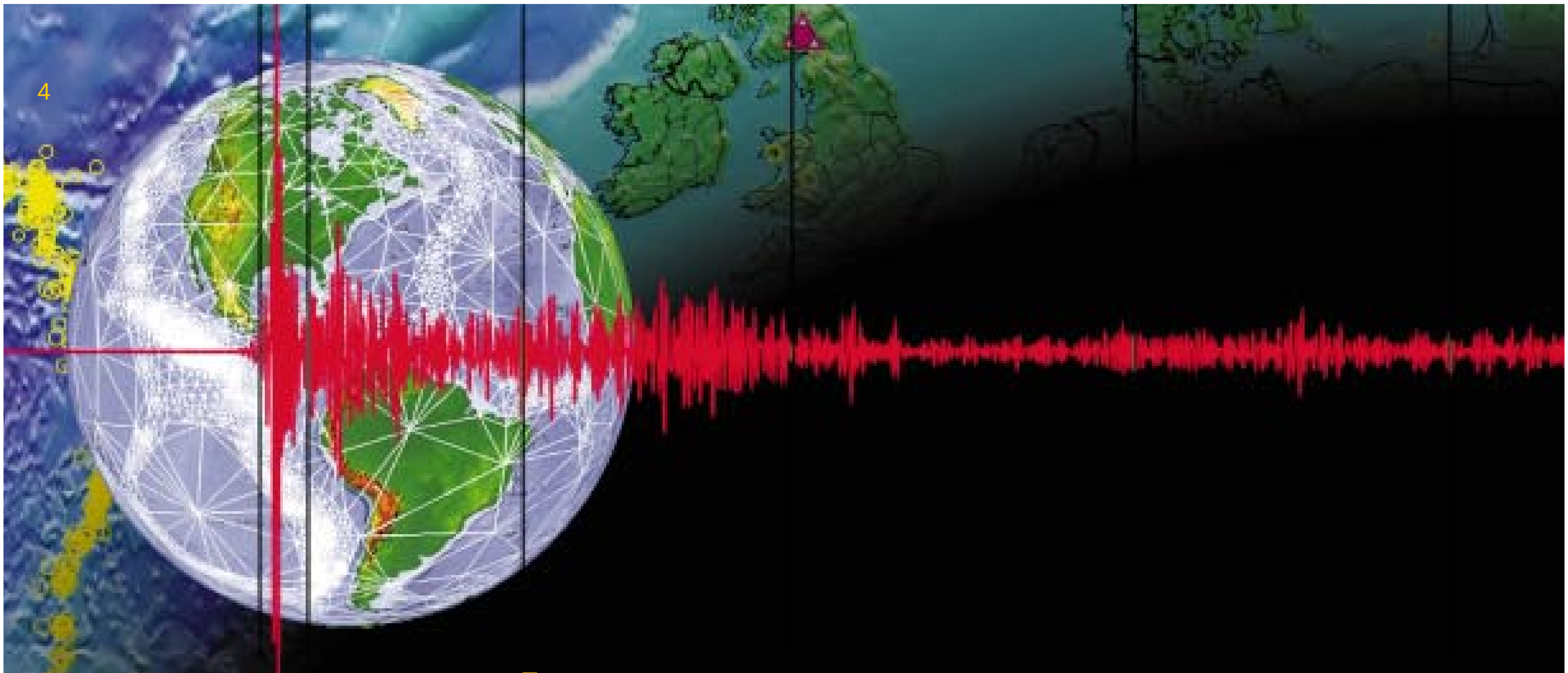
The research team's work supports Livermore's Nonproliferation, Arms Control, and International Security Directorate—in particular, its Proliferation Prevention and Arms Control Program. Among this program's responsibilities are conducting analyses in support of DOE nuclear arms control policies and guiding the development of treaty verification technologies. Indeed, the directorate was created in part to use Livermore's core strengths in nuclear science and advanced sensors and instrumentation to help this nation prevent the spread of nuclear weapons and supporting technology.

Livermore and the other DOE national security laboratories have an essential role to play in providing the analyses and technologies needed to monitor compliance with arms control treaties. This role, as never before, demands technological inventiveness from experts representing a host of mutually supporting disciplines, with the overriding goal of enhancing national and global security.

*From the text of the CTBT, which can be viewed at *http://www.acda.gov/treaties/ctbt.htm*.

■ Wayne Shotts is Associate Director, Nonproliferation, Arms Control, and International Security.

■ Lee Younker is acting Associate Director, Earth and Environmental Sciences.



Forensic Seismology Supports the Comprehensive Test Ban Treaty

Some 53 years after the first nuclear explosion, a team of Livermore researchers is helping the nation prepare for the Comprehensive Test Ban Treaty by developing methods to detect clandestine nuclear tests.

THE nearly worldwide condemnation of India’s and Pakistan’s unexpected nuclear tests in May was a telling indicator of the determination of nearly all nations to put an end to nuclear testing. That determination is embodied in the Comprehensive Test Ban Treaty (CTBT), signed in 1996 following a half-century of passionate discussions, various proposals, and international research to ensure that attempts to evade the treaty would be detected.

The CTBT forbids all nuclear tests, including those intended for peaceful purposes, and creates an international monitoring network to search for evidence of clandestine nuclear explosions. The agreement—signed by President Clinton but still to be ratified by the U.S. Senate—is of profound interest to dozens of scientists at Lawrence Livermore. They have worked over the past several years to support American diplomats in achieving this international agreement backed by sound monitoring and verification measures. Lawrence Livermore scientists have developed monitoring technologies in support of nuclear treaties and have outstanding credentials in providing technological support to treaty negotiations and verification. (See the box on p. 7.)

The CTBT’s International Monitoring System will consist of a

network of automated scientific instrumentation stations, secure communications links, and the International Data Center based in Vienna, Austria. The monitoring stations (many of which already exist) will consist of 170 seismic stations to record underground pressure waves, 60 infrasound stations to record low-frequency sound waves in the air, 11 hydroacoustic stations to record underwater sound waves, and 80 radionuclide stations to record airborne radioactive gases or particles (Figure 1).

Each day, these stations will transmit enormous amounts of data via satellite to the International Data Center in Vienna, which in turn distributes it to national data centers around the world. Computers at the international center will process the raw data, associate segments of the data stream with specific events, and estimate the location of those events. Analysts will then review the processed data and send a daily bulletin to all parties to the treaty.

In turn, national data centers will have the responsibility to make judgments about the true nature of any suspect events. These national centers will have access to all raw data available at the international center. They will also have the right to use their own computer analyses, informational databases, and data gathered by their own technical resources. Most importantly, each nation will apply its own criteria for distinguishing between compliance and noncompliance.

The U.S. National Data Center at Patrick Air Force Base in Florida is the facility responsible for American monitoring of the treaty. The U.S. Department of Energy, in light of its extensive experience in making seismic and other measurements of nuclear tests, is providing data analysis, algorithms, and technology needed for the national center to reach the low monitoring thresholds required to meet the U.S. goals. DOE's research program focuses on advances in methods to precisely detect, locate, and characterize events in key areas of interest. The program draws upon the strengths of major universities, private contractors, and DOE laboratories such as Lawrence Livermore, Los Alamos, Sandia, Environmental Measurements, and Pacific Northwest.

At Lawrence Livermore, a team of about 30 researchers has been helping to prepare the National Data Center for monitoring compliance with the future CTBT. Most team members are geologists, geophysicists, and seismologists from the Earth and Environmental Sciences Directorate, while others are from the Computation, Engineering, and Chemistry and

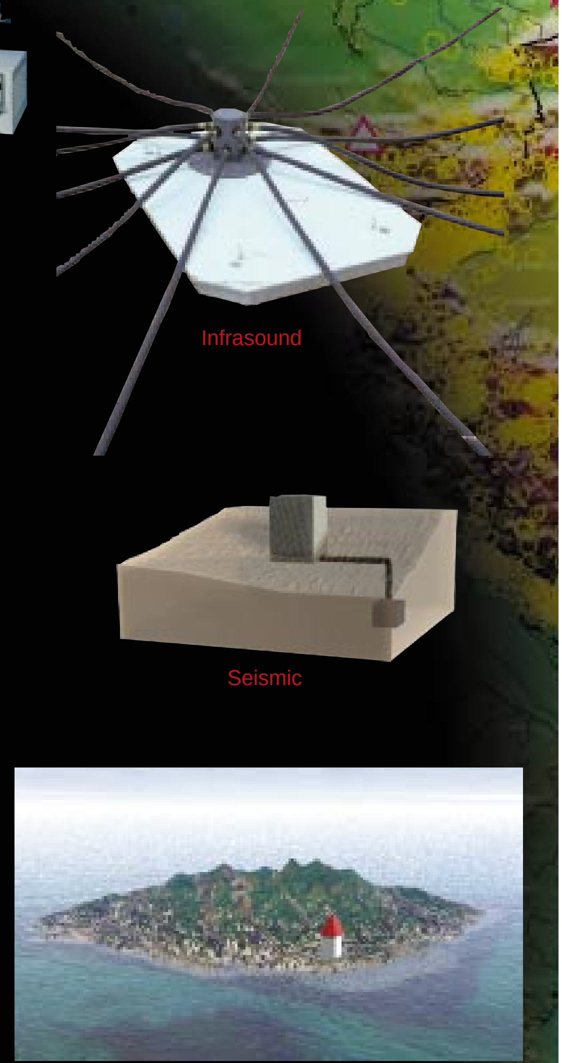


Figure 1. The CTBT's International Monitoring System will consist of automated radionuclide, infrasound, seismic, and hydroacoustic stations. Together, they will monitor for evidence of clandestine nuclear explosions.

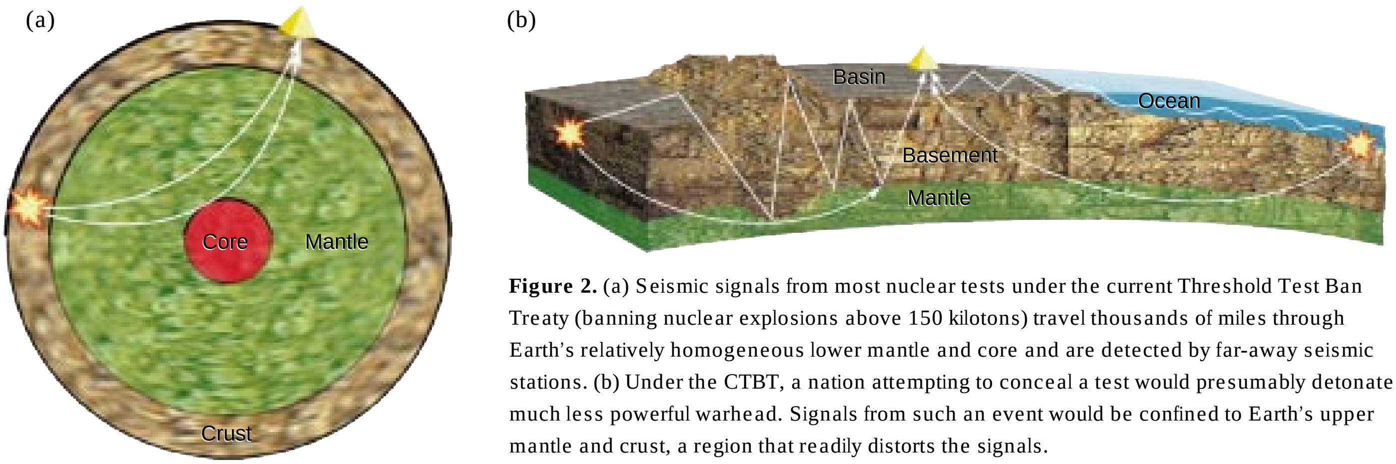


Figure 2. (a) Seismic signals from most nuclear tests under the current Threshold Test Ban Treaty (banning nuclear explosions above 150 kilotons) travel thousands of miles through Earth's relatively homogeneous lower mantle and core and are detected by far-away seismic stations. (b) Under the CTBT, a nation attempting to conceal a test would presumably detonate a much less powerful warhead. Signals from such an event would be confined to Earth's upper mantle and crust, a region that readily distorts the signals.

Materials Science directorates. The team's work supports the Laboratory's Nonproliferation, Arms Control, and International Security Directorate, which helps prevent the proliferation of weapons of mass destruction and assists in U.S. arms control matters.

For the CTBT, Livermore is carrying out field experiments, at sites ranging from the deserts of Jordan to the former Soviet nuclear test site in Kazakhstan, to document how regional geology affects the transmission of seismic signals. At the same time, Livermore specialists are developing powerful computer algorithms that calculate the degree to which measurements collected by seismic and hydroacoustic stations are altered by regional geology and how they compare with previous data from, say, regional earthquakes and mining operations (activities that can mimic small nuclear explosions). Finally, Livermore experts provide technical advice and expertise to U.S. negotiators and developed methods for international teams to use for on-site inspections. (See the box on p. 10.)

"Our goal is to achieve a very high level of confidence in the nation's ability to detect any clandestine nuclear explosion," says Livermore program leader Jay Zucca, a seismologist. Zucca notes that while DOE is the sponsor of this work, the primary user for the Livermore research program is the U.S. National Data Center. Livermore is also working closely with representatives of the Provisional Technical Secretariat (the international organization created by the treaty for its implementation) in Vienna in establishing the International Monitoring System and data center.

Meeting Monitoring Challenges

Zucca points out that under the current Threshold Test Ban Treaty (banning explosions exceeding 150 kilotons), determining accurate explosive yield is the critical issue. Most nuclear tests near the threshold treaty's limit generate seismic magnitudes of about 6 or greater on the Richter scale. Seismic signals from these tests travel thousands of miles through Earth's relatively homogeneous core and mantle and are readily picked up by far-away seismic stations for relatively straightforward characterization (Figure 2a).

Under the CTBT, however, the critical issues will be to determine that a nuclear explosion—no matter its size—took place and to pinpoint its location accurately. A nation attempting to conceal a test could attempt to minimize the seismic signals. Such signals from a small nuclear test could be well below magnitude 4, with resulting measurable signals traveling 1,000 miles or less. What's more, the signals would likely be confined to Earth's upper mantle and crust, an extremely heterogeneous environment that distorts, and even blocks, parts of the signals (Figure 2b).

Accurately locating and characterizing signals at these so-called regional distances pose a significant challenge, says seismologist Bill Walter. "It's a much harder job because we can't use global models of Earth. We have to calibrate region by region, seismic station by seismic station." Successfully meeting the regional distance challenge, says seismologist Marv Denny, has been the most difficult aspect of the Livermore effort over the past several years.

Denny says that complicating the task is the huge number of events that, at first cut, can resemble a small nuclear detonation. Stations will be recording a constant stream of background noise that includes earthquakes, lightning, meteors, sonic booms, navy armament testing, mining explosions, construction activities and other industrial operations, nuclear reactor operations and accidents, natural radioactivity, and even strong wind and ocean waves.

"As we consider the possibility of smaller and smaller clandestine tests, the

The Road to a Comprehensive Test Ban Treaty

Awed by the destructive power of nuclear weapons, scientists and others began discussing banning further weapons tests shortly after Trinity, the first test of a nuclear explosive in 1945. Since then, a succession of treaties has slowly narrowed the lawful testing environments. For example, the Limited Test Ban Treaty, ratified in 1963, banned nuclear explosions in the air, oceans, and space, while the Threshold Test Ban Treaty, ratified in 1988, limited underground nuclear weapon tests to 150 kilotons.

The Comprehensive Test Ban Treaty was signed by President Clinton and other heads of state on September 24, 1996, at the United Nations, following two years of international negotiations. In signing the treaty, President Clinton used the same pen President John F. Kennedy used to sign the Limited Test Ban Treaty. Following the signing ceremony, the President told the United Nations General Assembly that the treaty “points us toward a century in which the roles and risks of nuclear weapons can be even further reduced—and eventually eliminated.”

As of mid-1998, the treaty has been signed by 149 nations and ratified by 13 nations. The treaty will not enter into force until ratified by the 44 nations named in the treaty that possess nuclear reactors. The U.S. has signed but not ratified the treaty; three other named nations—India, Pakistan, and North Korea—have neither signed nor ratified the treaty.

Under the treaty, each nation undertakes “not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.” Each party also undertakes “to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear weapons test explosion or any other nuclear explosion.”

Other articles of the treaty describe the international monitoring system, on-site inspections, confidence-building measures, organization of the treaty’s executive council and the technical secretariat, and measures to redress violations. (The main text of the treaty may be viewed at *http://www.acda.gov/treaties/ctbt.htm*.)

An international organization, the Preparatory Commission in Vienna, Austria, was established in November 1996 to create the international monitoring and verification regime.

number of background events, both natural and human made, becomes immense,” says Walter. For example, more than 200,000 earthquakes similar in seismic magnitude to a small nuclear explosion occur in the world every year. Many of these background events can be disregarded because of their depth or similarity to other events known to be nonnuclear. However, many will not be identified so readily. As a result, the National Data Center will require a set of tools, largely data-processing software, modeling capability, and reference databases, to perform what Walter terms “forensic seismology” to separate a weak potential nuclear test from background noise.

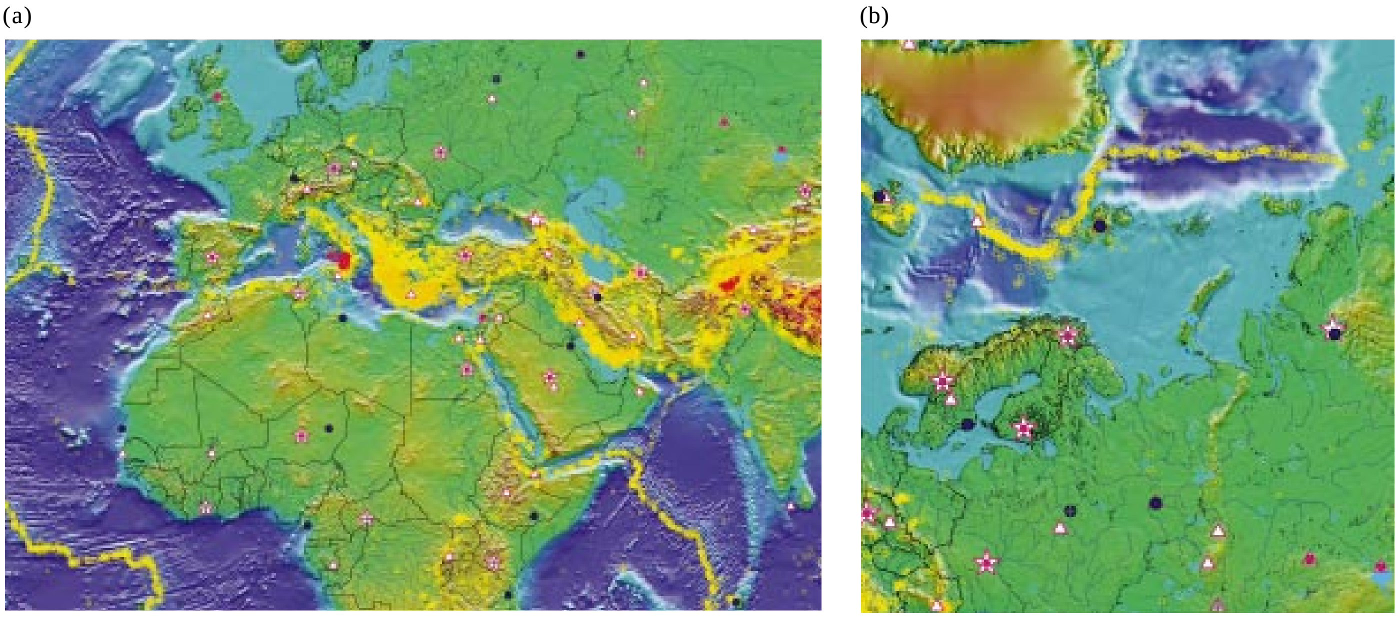
One essential tool will be a comprehensive database that includes seismic patterns and the location of mines and seismically active regions. This database must also include information on how Earth’s crust and mantle affect the travel time and amplitude of seismic signals as they make their way to international stations. “We want to be sure that data relayed by individual stations are interpreted in light of their regional settings so that the location and nature of an event are properly determined,” says Zucca.

Building the Knowledge Base

The DOE is assembling such a database, called the Knowledge Base, to manage, store, and retrieve vital information about major areas of the world. “A key Livermore product for the National Data Center is our contribution to the Knowledge Base,” says Zucca. While the Knowledge Base includes information from all four sensor technologies, it is dominated by hydroacoustic and seismic data, considered the most essential for interpreting events in their regional context.

The Livermore team has been assigned by DOE to focus largely on the Middle East and North Africa (called MENA) and the western part of the former Soviet Union, which includes the former Soviet test site at Novaya Zemlya, near the Arctic Sea (Figure 3). The work has entailed collecting and organizing large quantities of geological, geophysical, seismological, and human-activities data within these areas. The task is complicated by the geological diversity of MENA and by the lack of “ground truth,” that is, seismic data from well-documented earthquakes, mine explosions, or explosions carried out for seismic calibration purposes.

Obtaining needed ground truth has prompted several avenues of research. Geologist Jerry Sweeney, for example, is researching published literature for reports of earthquake aftershock studies from Iran, Algeria, and Armenia. Other researchers have deployed temporary stations in areas awaiting the construction of permanent international stations to record background seismic activity so that they can determine how the regional geology affects the seismic readings. Last April, engineer and seismologist Dave Harris traveled to Jordan to set up two temporary seismic stations in cooperation



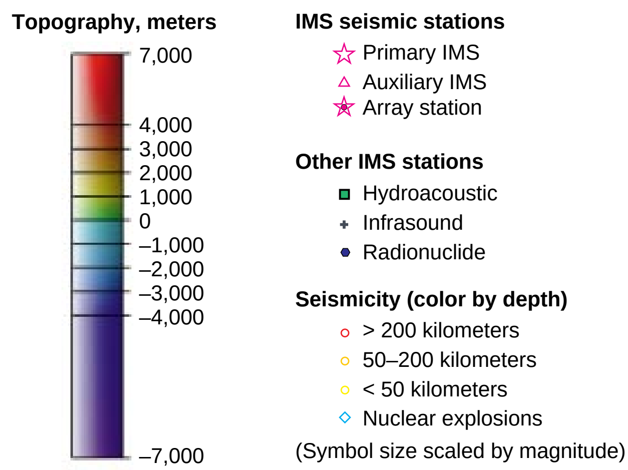
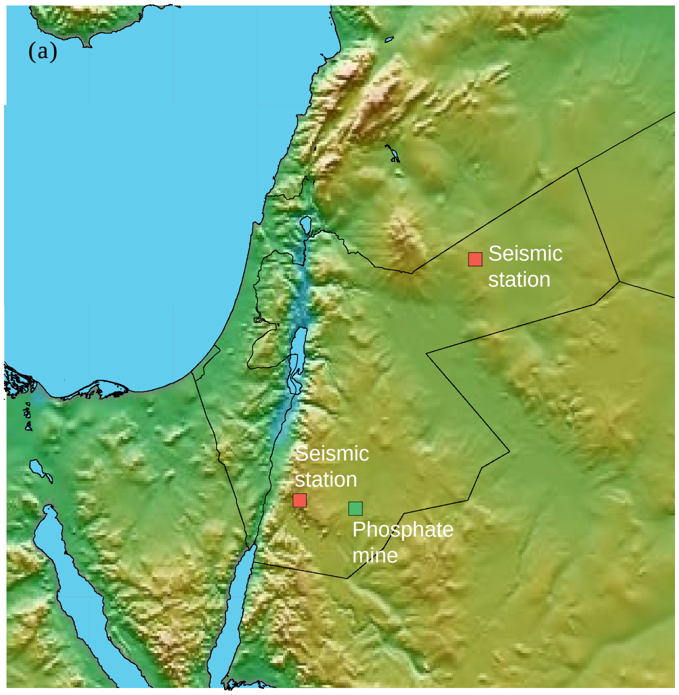


Figure 3. Livermore researchers are focusing on (a) the Middle East and North Africa and (b) the western part of the former Soviet Union, which includes the former Soviet nuclear test site at Novaya Zemlya. The locations of seismic, hydroacoustic, infrasound, and radionuclide monitoring stations for the International Monitoring System (IMS) are shown for both areas. The historic seismic record is plotted using a scale determined by the depth of the seismic signal. Past nuclear explosions (many of them for peaceful purposes) are denoted by blue diamonds. (Maps created by Livermore scientist Bill Walter.)

with the Jordanian Natural Resources Authority to record the seismic signatures of earthquake activity and nearby phosphate mining operations (Figure 4). “These extra stations provide additional constraint on the locations of earthquakes in the region and provide us with higher quality ground truth,” explains Harris.

Aiding the MENA effort is an ongoing Livermore study of earthquakes and underground explosions around the Nevada Test Site. Livermore researchers are comparing seismograms of underground nuclear tests conducted in 1992 (the last year of American nuclear testing) with several moderate local earthquakes in the same year. They also participated in a DOE test at the site in 1993 (called the Non-Proliferation Experiment) involving a kiloton of chemical explosive. The test revealed that seismic signals from an underground chemical blast closely mimic the signals that would be expected from an underground nuclear test.

Zucca notes that potential treaty violators might be tempted to detonate a nuclear device in the center of a large underground cavity, a technique called decoupling. The seismic signal from such a test is reduced by a factor of up to 70 through a muffling effect that reduces the amplitude of the signal. A 1-kiloton nuclear explosion, for example, would produce a magnitude in the range of approximately 2.5 to 3 on the Richter scale when tested in a large underground cavity. Seismic signals of the lower magnitude are produced frequently in a large number of mine explosions worldwide, and many thousands of earthquakes are in this range.



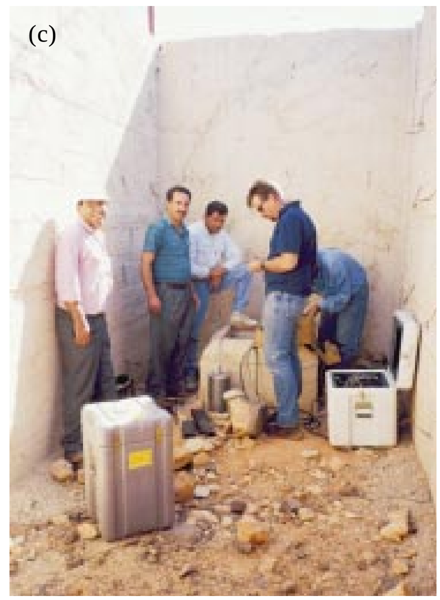


Figure 4. Livermore and Jordanian researchers recently established two temporary seismic stations in Jordan to record the seismic signatures of background earthquake activity and of explosions from phosphate mining activities from operations at the Eshidiyah phosphate mine. (a) Map of the area showing the location of the phosphate mine and seismic stations. (b) Outside view of the seismic station nearest the mine. (c) Inside view of the seismic station.

Livermore scientists have investigated the signal effects possible with blasts conducted in cavities formed from different rock types. Researchers have also attempted to gain a more complete understanding of the seismic signals caused by routine mining operations. They have joined with colleagues from the U.S. Geological Survey and Russian scientists to calibrate seismic wave propagation in regions of the former Soviet Union. Livermore scientists have also monitored different types of seismic signals from operations in mines located in Wyoming, Colorado, and Nevada.

Determining Underwater Events

While seismic network research is progressing along many fronts, several Livermore specialists have devoted their energies to advancing hydroacoustic monitoring technology. They have combined fundamental research on detecting the propagation of underwater sound waves with contributions to the Knowledge Base's storehouse of underwater signals from earthquakes, volcanoes, shipping activity, and chemical explosions from military testing. "A lot of background underwater events have to be taken into account," says seismologist Phil Harben, although he notes that they are not as pervasive as land activities such as mining.

Aiding Livermore's understanding of ocean signals is an automated data-acquisition facility on San Nicolas Island off southern California. Data from this station permit researchers to check computer models and conduct research on the sensitivities of island seismic stations and offshore hydrophones to water-borne signals.

The database of nuclear explosions at sea is limited to a few tests carried out years ago by the agencies preceding the DOE. Because data are so limited, Livermore scientists have developed a calculational capability to predict the effects of underwater nuclear explosions. They used this capability to provide diplomats with options for hydroacoustic networks. They also provided analyses showing the economic advantages of fixed hydroacoustic stations (connected by cable to recording sites on land) over unmoored, floating buoys. On the basis of this work, a network of six hydrophones and five island seismometers was chosen as the international system to detect and locate underwater explosions and, in some cases, explosions in the low atmosphere.

The network takes advantage of the fact that underwater explosions generate acoustic waves (in the frequency range of 1 to 100 hertz) that can travel completely across an ocean basin—in some cases, more than

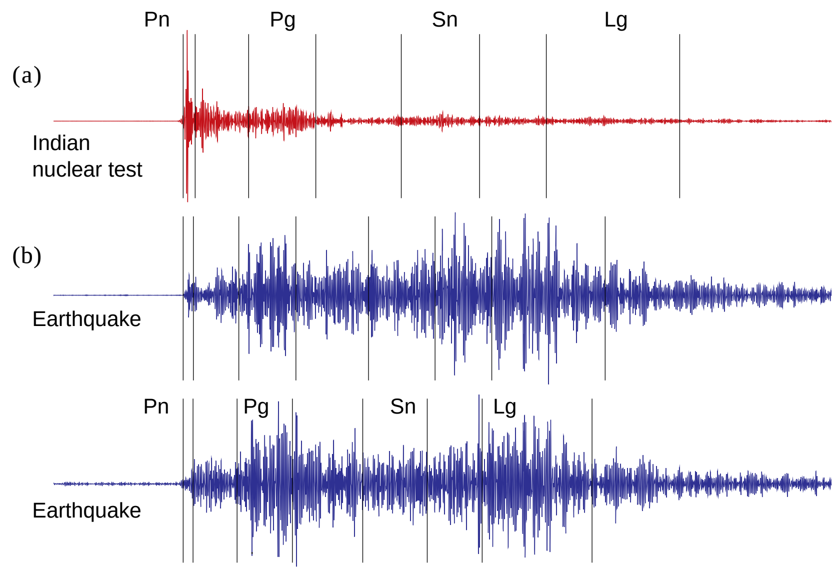


Figure 5. An international monitoring station in Pakistan detected the Indian nuclear test of May 11, 1998, about 740 kilometers away. (a) Analysis of the seismogram showed a P-wave-to-S-wave ratio strongly indicative of an explosion and not (b) nearby earthquakes.

When Monitoring Stations Aren't Enough

Under the terms of the Comprehensive Test Ban Treaty, a nation suspecting another of conducting a nuclear test may request that the treaty's 51-member Executive Council conduct an on-site inspection to determine the nature of the suspect event. The requesting nation may introduce evidence acquired on its own to strengthen its case to the organization. On-site inspections must be approved within 96 hours of receiving an inspection request because of the need to observe short-lived nuclear phenomena that are produced by a nuclear test.

Over the past decade, Lawrence Livermore experts have led the U.S. development of on-site inspection technologies and procedures; many of these procedures were eventually incorporated into the text of the treaty. Livermore seismologist Jay Zucca serves as the U.S. point of contact for the On-Site Inspection Experts Group that meets regularly in Vienna.

Zucca explains that a clandestine explosion may not necessarily form a telltale crater. In such a case, an inspection team will search for other evidence. For example, the team may deploy portable seismic equipment to detect very small aftershocks, collect samples of soil gases and water to look for radioactive materials, or search for an underground explosion cavity or rubble.

Livermore researchers have shown that low-frequency aftershocks associated with nuclear explosions may also be caused by mining operations. They compared aftershocks from the 1993 Non-Proliferation Experiment at the Nevada Test Site (in which 1 kiloton of chemical explosive was fired in an underground cavity) with those from routine operations at the Henderson Mine in Colorado. Although the events from both sources are similar, there are subtle differences in the aftershock signals. They were interested in the Henderson Mine because the caving operation is similar to the chimney formation following an underground nuclear event.

Also as part of the Non-Proliferation Experiment, Livermore experts found that very small amounts of rare radioactive gases such as xenon-133 and argon-37 generated in underground nuclear detonations can migrate toward the surface along natural fault lines and earth fissures in a time frame consistent with an on-site inspection. The technology used in these tests can be an extremely sensitive way to detect nearby underground nuclear explosions that do not fracture the surface. (See January/February 1997 *S&TR*, pp. 24–26.)

10,000 miles. The acoustic waves travel along the SOFAR (sound fixing and ranging) channel, described by Harben as "a wave guide for ocean acoustic energy that depends on temperature, density, and depth." However, waves traveling in this channel can be blocked or weakened by land masses and regions of shallow or cold water. Livermore modeling of the properties of this channel during CTBT negotiations was important in determining the global distribution of hydroacoustic stations.

Refining Algorithms

A major effort of the National Data Center will be the automated analysis of data obtained from the international center, supplemented by data provided by other U.S. resources. Final reviews will be provided by analysts working with Knowledge Base data such as reference seismograms from historic nuclear events conducted in the area of a suspect event. Key to the automated process will be several algorithms for determining the location and nature of an event. Livermore experts are using data gathered for the Knowledge Base—for example, underground signal travel times to each international station—to refine the algorithms.

As part of their algorithm work, an interlaboratory team headed by Livermore seismologist Craig Schultz made a fundamental advance in the field of kriging, a geostatistical estimating process. The advance enables the team to develop estimates of the level of confidence in the regional seismic properties derived from a few geographically isolated observations. Zucca describes the work as one of the key breakthroughs for the functioning of the Knowledge Base. It is likely, he says, that the approach taken by Schultz's team for the algorithms will be adopted by seismologists everywhere for their own applications.

Key algorithms provide discriminants, characteristic features of a waveform (peak-to-peak distance, height, width, or some ratio). A particularly useful discriminant, for example, is the ratio of P-wave amplitude to S-wave amplitude. The P (or primary) wave is a compressional wave that is the first to arrive at a station. The S wave or shear wave has a slower propagation speed and arrives behind the P wave. The seismogram from the Indian nuclear test of May 11, 1998, as recorded by an international monitoring system station in Pakistan about 740 kilometers away, showed a P-to-S ratio strongly characteristic of an explosion and not an earthquake (Figure 5).

Zucca points out that the Indian test successfully demonstrated the capability of the international network. Based on Livermore's work at other sites and current examination of events in this area, he is confident a potential nuclear explosion in key areas of interest can be detected and identified down to much smaller magnitudes. In other words, says Zucca, the world will soon have strong international monitoring and analysis capabilities to help determine international compliance with the Comprehensive Test Ban Treaty.

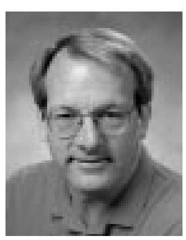
—Arnie Heller

Key Words: Comprehensive Test Ban Treaty (CTBT), discriminants, International Data Center, Knowledge Base, MENA (Middle East and North Africa) region, National Data Center, Nevada Test Site, SOFAR (sound fixing and ranging) channel, Threshold Test Ban Treaty (TTBT).

Editor's Note: On p. 4, the image of the globe is courtesy of Sandia National Laboratories, the image of the radionuclide monitoring devices was provided by Pacific Northwest National Laboratories, and the image of the infrasound monitor was created at Los Alamos National Laboratory.

For more information contact Jay Zucca (925) 422-4895 (zucca2@llnl.gov). Information on DOE's overall CTBT program may be found at **www.ctbt.rnd.doe.gov**.

About the Scientist



JOHN J. (JAY) ZUCCA, leader of Livermore's Comprehensive Test Ban Treaty Program, joined the Laboratory in 1984. He has worked primarily for the Laboratory's Treaty Verification Program, concentrating on seismic instrumentation development, on-site inspection, and regional seismology. He was a member of the U.S. delegation to the Nuclear Testing Talks (Threshold Test Ban Treaty) and a member of the U.S. delegation to the Conference on Disarmament for the Comprehensive Test Ban Treaty. He is currently a member of the U.S delegation to the Preparatory Commission for the CTBT. Zucca received his B.S. from the University of California at Berkeley and his Ph.D. from Stanford University. He completed postdoctoral positions at the U.S. Geological Survey in Menlo Park and the University of Karlsruhe in Germany.

A Short History of the Laboratory at Livermore

On the fortieth anniversary of E. O. Lawrence's death, S&TR explores the history of the laboratory he founded at Livermore.

THE institution now known as Lawrence Livermore National Laboratory formally opened its doors in 1952 as a branch of the University of California Radiation Laboratory (now the Ernest Orlando Lawrence Berkeley National Laboratory). Managed by the University of California under contract with the Atomic Energy Commission (AEC), the new laboratory would soon become what the well-established laboratory at Los Alamos, New Mexico, and home of the World War II Manhattan Project already was: a premier nuclear weapons design laboratory for the United States.

The laboratory lies on a tract of more than one square mile in Livermore, California, about 40 miles southeast of the university's Berkeley campus and its parent laboratory. Although still managed by the university under government contract, it has long since outgrown its origins as a branch laboratory. Today, it serves as a national resource in a broad range of science and engineering research, with national security remaining its core mission.

Creating the Laboratory, 1949–52

Establishing the laboratory at Livermore was a process spanning several years on either side of the formal opening in 1952. Essentially, it began in August 1949, when the Soviet Union tested its first nuclear weapon. Edward Teller, a gifted and sometimes controversial physical scientist highly regarded by his peers and by the AEC, promptly redoubled his efforts to push work on the "Super," a thermonuclear weapon that derived its energy mainly from the fusion of deuterium, an isotope of hydrogen.

So-called hydrogen bombs, or H-bombs, were potentially far more powerful than fission bombs, which drew their energy from splitting atoms

of the heavy elements uranium or plutonium. Fission bombs (atomic bombs, or A-bombs) were developed at Los Alamos during the Manhattan Project. At wartime Los Alamos, Teller had been the chief advocate of thermonuclear weapons development, and he had continued to press his case from a postwar position at the University of Chicago, although without much success. The Soviet A-bomb changed everything.

To Teller (and many others), an American H-bomb seemed the best response to the new Soviet threat. Convinced that not enough was being done, he vigorously lobbied a reluctant AEC for a second nuclear weapons laboratory to compete with the existing Los Alamos laboratory. He also sought other allies. When the Air Force in late 1951 supported a second laboratory, the AEC's resistance began to crumble.

By spring 1952, the AEC had reversed its position, a change greatly furthered by the emergence in California of a viable prospect for a second laboratory. Earlier that year, Ernest Orlando Lawrence—cyclotron inventor, Radiation Laboratory founder, and Nobel Prize winner—had proposed to the AEC establishing a branch of the Radiation Laboratory in Livermore. Acting in response to news of the 1949 Soviet test, Lawrence had secured the former Livermore Naval Air Station for AEC work.

The main project at Livermore was a giant linear accelerator called MTA (ostensibly for Materials Testing Accelerator, a meaningless code name) intended to produce then-scarce plutonium. Figure 1 shows the full-scale working model of the machine's front end under construction. A team from Lawrence's laboratory also used the roomy Livermore site to develop a diagnostic experiment for the 1951 George event in Operation Greenhouse, the first Los Alamos test of thermonuclear principles. In short, Lawrence could back his proposal by pointing to ongoing operations at a proven site. Such arguments coming from a widely admired scientist with other large projects to his credit allayed most AEC doubts.

Figure 1. The first big project at the Livermore site began in 1951, before the laboratory itself was approved. This photo shows the prototype vacuum chamber for the so-called Materials Testing Accelerator under construction. Once development was completed, the full mile-long linear accelerator was constructed near St. Louis.

When Teller accepted a position at Livermore, the last piece fell into place. The AEC and the Regents of the University of California quickly agreed to what would become the second nuclear weapons laboratory. That Lawrence himself would remain in Berkeley and have little part in day-to-day operations scarcely lessened his pervasive influence. His former student and fellow faculty member, Herbert York, largely organized the branch laboratory and became its first on-site director.

Organizationally, York reported to Lawrence and clearly modeled the new laboratory on what he had learned from Lawrence about running big science programs at Berkeley. Teller, a daily presence at the Livermore Laboratory, played a quite distinct but no less significant role. His imprint was, and remained, especially strong on the laboratory's choice of programs to pursue. The creation and subsequent shaping of the branch laboratory at Livermore and its programs owed much to all three men (Figure 2).

The Formative Years, 1952–58

Like its parent laboratory in Berkeley and future sister laboratory at Los Alamos, the Livermore branch laboratory became an AEC facility under University of California management. Initially, the scope of Project Whitney, the code name assigned to work at Livermore, was quite modest. At the official branch opening on September 2, 1952, the entire staff numbered only 123, many still working in Berkeley, with a projected first-year budget of $600,000. Broadly speaking, Livermore was expected to support Los Alamos with work on aspects of designing and testing thermonuclear weapons.

Weapons, however, never exclusively preoccupied Livermore. Research in controlled fusion soon began. From its first days, Livermore studied such related areas as magnetic fusion. Under the auspices of the AEC's Project Sherwood, several other laboratories were also looking for practical methods of confining a fusion reaction to produce useful energy. Livermore chose to pursue the so-called magnetic mirror approach: magnetic fields would confine ionized gas or plasma within an open-ended cylindrical cavity. Livermore also began its long fascination with high-powered electronic computing and hands-on experimentation: the first UNIVAC arrived in 1953, and the Site 300 high-explosive test facility was opened in mid-1955.

Weapons research nonetheless held center stage, although the first efforts of Livermore's novice bomb designers proved disappointing. Concepts tested during 1953 in Nevada and 1954 at Bikini had yields so far below expectation as to prompt some jeering observers to label them "fizzles" (Figure 3). Disappointed but undismayed, the young scientists and engineers quickly broadened their design approaches and soon turned things around. The breakthrough for fission designs came in 1955 during Operation Teapot at the Nevada Test Site and for thermonuclear designs during Operation Redwing at the Pacific Proving Ground. Satisfactory test results at last allowed the Livermore team to stake a plausible claim as weapon designers, if not yet to quiet all doubts.

Livermore's first weapon assignment, developing the warhead for the Navy's Regulus II missile, came in 1955. Although Regulus II went nowhere, the laboratory's warhead design became part of a gravity bomb for carrier-based aircraft. Livermore also joined forces with the Army to develop nuclear artillery shells. Notwithstanding such modest successes, Livermore remained a relatively marginal player in the nuclear weapon field through the mid-1950s.

Then in June 1957, the Navy decided to entrust the design and development of warheads for its new Polaris missiles to the second laboratory. Meeting the Polaris challenge has often been described as Livermore's coming of age. Two other large development projects also began officially in 1957. One was Project Pluto, an Air Force–backed effort to develop nuclear ramjets for unmanned aircraft. The other was Project Plowshare, aimed at using peaceful nuclear explosions for civil engineering purposes. Livermore clearly had turned the corner.

On March 31, 1958, Herbert York resigned as director of the Livermore laboratory, leaving for Washington to become the first Director of Defense Research and

Figure 2. This 1957 photograph shows the three men most responsible for organizing and shaping the new laboratory at Livermore earlier in the decade—from left to right, Ernest Lawrence, Edward Teller, and Herbert York.

Figure 3. Livermore bomb designers failed their first test. At the Nevada Test Site in 1953, a risky design fizzled, yielding this widely displayed photo of a bent tower.

Engineering. Five months later, on August 27, E. O. Lawrence died. His flourishing laboratory at Berkeley became the Lawrence Radiation Laboratory (LRL) on November 7. Livermore's status as a branch laboratory remained unchanged, although it too flourished. Under the leadership of Lawrence, Teller, and York, it had grown to 3,000 employees with an annual budget of $55 million. Edward Teller, the only one of the original founders who remained at Livermore, succeeded York as director.

Moratorium, 1958–61

A moratorium on nuclear weapons testing went into effect on November 1, 1958. It lasted almost three years, until September 1961, during which LRL Livermore saw three directors in rapid succession: Edward Teller (April 1958–June 1960), Harold Brown (July 1960–May 1961), and John Foster (June 1961–September 1965). Despite questions raised about the future of the laboratory—no one could be certain that nuclear testing would ever resume—Livermore continued its rapid growth. Employment increased by a thousand and the annual budget swelled to $78 million by fiscal year 1961.

Although the moratorium barred further testing of the Polaris warhead, deployment proceeded. In July 1960, the Navy accepted delivery of the first 16 warheads, and four months later, USS *George Washington*, the first Polaris submarine, went to sea on its first patrol with 16 armed missiles aboard. After the moratorium, the Polaris missile system provided the only full-scale operational test from launch through detonation ever conducted for a U.S. nuclear missile. On May 6, 1962, a submerged Polaris submarine launched a stockpile Polaris missile to explode a thousand miles away over the open ocean. Figure 4 shows a Polaris missile launch.

Polaris designers trusted their work despite changes from the designs field-tested before the moratorium and the implementation of substantial warhead upgrades. A major factor in promoting this trust was computer modeling of the extremely complex physical phenomena involved in nuclear explosions. Stimulated by their concern to understand the physics, bomb designers devised increasingly complex computer codes to model the physical behavior of nuclear weapons. That required state-of-the-art computers—the more powerful the better—one reason that Livermore has consistently pioneered the use of large, high-speed computers.

Computers also played a major role in hydrodynamic experiments at Site 300. Located 15 miles from Livermore across a low range of hills in a rough and thinly peopled corner of the San Joaquin Valley, the new test facility would become a center for nonnuclear experimentation to study warhead safety and reliability. Widening efforts to understand complex phenomena through experiment and computer modeling became a laboratory hallmark.

When the moratorium sharply curtailed nuclear weapons work, Project Pluto assumed a larger place in the Livermore laboratory's activities. It had begun in the mid-1950s as a joint project between the AEC and the Air Force to develop a nuclear ramjet

Figure 4. Polaris missile launched from a submerged submarine. Livermore came of age with its successful development of the warhead for the Polaris missile.

engine. Livermore designed and built two Pluto test reactors—Tory II-A to demonstrate feasibility and Tory II-C as a realistic flight-engine prototype. The first model breezed through its 1961 trials at the Nevada Test Site. Three years later, the prototype engine passed its first tests with flying colors (Figure 5). But the Department of Defense concluded that it had no need for nuclear ramjets and canceled Project Pluto one week later.

Expansion and Change, 1961–71

Events of the 1960s contributed to reshaping Livermore's environment. The public became increasingly concerned about what President Eisenhower in his 1961 farewell address named the military–industrial complex; the 1963 Limited Nuclear Test Ban Treaty ended atmospheric testing; and later in the decade, protests against the war in Vietnam increased dramatically. As the decade progressed, the laboratory became the object of growing criticism from the University of California community and from outside as well. It was also the scene of active demonstrations. Livermore nonetheless sustained its steady growth under the directorships of John Foster and Michael May (October 1965–August 1971), adding another thousand to the workforce and $50 million to the budget.

During the 1960s, Livermore's nuclear weapons design work focused on strategic missiles. To improve the Navy's submarine-launched ballistic missile systems, the laboratory developed warheads for the second-generation Polaris and its successor, Poseidon. While the Air Force continued to rely heavily on Los Alamos for developing bombs and some missile warheads, it increasing assigned warhead development for its intercontinental ballistic missiles, notably Minuteman, to Livermore. By the end of the decade, most warheads in the nation's strategic nuclear weapons stockpile were Livermore designs.

Plowshare and the quest for peaceful nuclear explosions became one of Livermore's major programs in the 1960s. Initially, the program focused on large-scale earth-moving, or nuclear excavation, with the long-term goal of using nuclear explosions to excavate a new Atlantic–Pacific canal through Central America (Figure 6). Development problems, the 1963 test ban treaty, and growing doubts about the economic advantages of nuclear

Figure 5. Project Pluto aimed at developing a ramjet engine for the Air Force. Tory II-C, depicted here, was a prototype flight engine tested successfully in 1964.

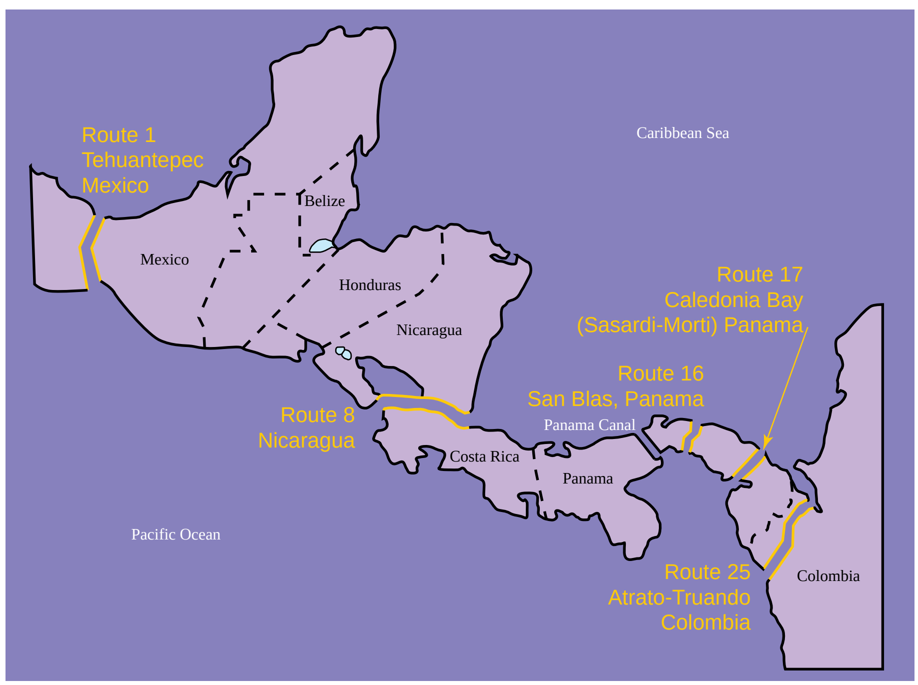


Figure 6. Project Plowshare sought to use peaceful nuclear explosions for civil engineering purposes. One proposal envisioned the nuclear excavation of a new Atlantic–Pacific canal in Central America. Some of the routes considered are shown in this map.

over conventional explosives as well as the lack of public acceptance of such work stifled that plan by the end of the decade.

A reoriented Plowshare program centered on underground engineering, using nuclear explosions to stimulate the flow of natural gas from tight rock formations. Ambiguous experimental results and the environmental legislation of the late 1960s proved obstacles too great to overcome. Like nuclear excavation, underground engineering began to look more costly than it was worth, and Plowshare faded away in the early 1970s.

One of Plowshare's major legacies was Livermore's biomedical research program, created largely in response to concerns about fallout and other radioactive hazards. Fallout had become a major public issue in the mid-1950s with the advent of thermonuclear weapons testing. Plowshare focused interest in the subject because nuclear explosions in populated areas for a variety of routine engineering tasks seemed to pose much more direct threats. The Biomedical Division was established in 1963 to investigate the effects of radionuclides on living systems. Ironically, it became itself a center of controversy when its first director, John Gofman, differed publicly with the AEC on the hazards of radioactive fallout.

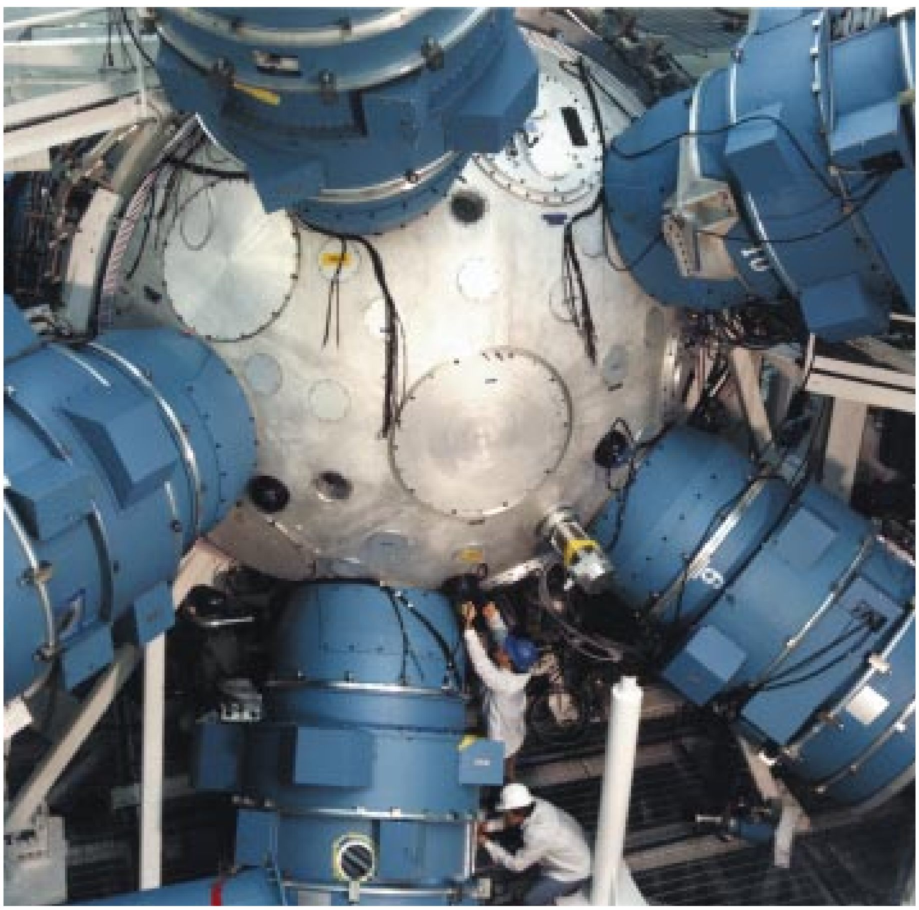


Figure 7. For a decade and a half, the Nova laser has allowed scientists at Livermore to conduct laboratory experiments on laser fusion and weapon physics. This photo shows an external view of the Nova target chamber, a 15-foot-diameter sphere where the system's 10 laser beams converge to heat the tiny experimental package in the center.

The Mature Laboratory, 1971–88

In June 1971, Livermore and Berkeley parted company. Responding in part to campus protest, the Lawrence Radiation Laboratory divided into the Lawrence Berkeley Laboratory and the Lawrence Livermore Laboratory. In December, Roger Batzel became the Laboratory's sixth director, beginning a tenure of unprecedented length and extraordinary growth. From 1971 until 1988, when Batzel retired from the directorship, the Laboratory's budget rose steadily, from $129 million to $896 million, while its workforce climbed from 5,300 to 8,200.

Meanwhile, the Laboratory's federal patron underwent metamorphosis. The AEC split into the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA) in January 1975. ERDA proved short-lived, becoming within three years part of a new Department of Energy. Livermore's management remained with the University of California, and the Laboratory's growing status received validation of a sort in the 1980 congressional decision to make it a national laboratory. Henceforth, it would be known as Lawrence Livermore National Laboratory.

During the 1970s, Livermore weapons designers lost their near-monopoly on warheads for intercontinental ballistic missiles. Although Livermore was assigned the Air Force's MX/Peacekeeper missile warhead, Los Alamos was designated to develop the warhead for Trident, the third generation of submarine-launched ballistic missiles. By the 1960s, the Army was becoming LLNL's most consistent client, often for politically controversial systems. In 1968, work on the warhead for the Spartan missile embroiled Livermore in the heated debate over antiballistic missile systems. Work in the late 1970s and into the 1980s on the ground-launched cruise missile and enhanced radiation warheads for such tactical weapon systems as the Lance missile and nuclear artillery raised questions about nuclear war fighting and policy.

Livermore entered still more controversial waters in the 1980s, when Laboratory studies suggested the feasibility of nuclear-powered x-ray lasers. Theoretically, such lasers could destroy ballistic missiles in flight and might thus become the backbone of a reliable defense, as Edward Teller and others vigorously argued. In 1983, President Reagan launched his so-called Star Wars program, the Strategic Defense Initiative, that committed the United States to developing the technology for such a defensive system. Although only one of many institutions studying directed-energy weapons and other potential antimissile and antisatellite weaponry under the program's aegis, Livermore remained closely identified with Star Wars, even after the end of the Cold War.

Magnetic fusion research at Livermore began to produce results by the mid-1970s. An experimental magnetic mirror machine (2XII-B) created a stably confined plasma at temperatures, densities, and times approximating those a power plant might need. Although not the most favored approach in the fusion research community, the magnetic mirror then stood second only to the tokamak concept of power generation through fusion. The AEC approved a large-scale scientific feasibility test of the magnetic mirror approach, the so-called Mirror Fusion Test Facility, but changing priorities scuttled the $350-million experiment, canceled in 1987 before ever operating and sold for scrap a decade later.

The invention of the laser offered another avenue toward the goal of controlled fusion. Beginning in the early 1970s, the Laboratory developed a series of neodymium-glass lasers, each more powerful than its predecessor, culminating in 1984 with the Nova system. For a decade and a half, Nova has provided unrivaled facilities to pursue the goal of practical laser fusion. For Livermore, high-power lasers had an additional advantage: the thermonuclear microexplosions they could generate allowed scientists to study weapon physics in the laboratory under controlled conditions (Figure 7). Nova's successor, the National Ignition Facility now under construction, promises to greatly expand both areas of research.

Lasers also offered a powerful new tool for isotope separation. Precisely tuned light can ionize a specific isotope in a mixture of vaporized isotopes, allowing it to be easily separated from the rest. Livermore's development of the process for atomic vapor laser isotope separation, more commonly known by its acronym, AVLIS, promised to provide a safe, cost-effective, and environmentally responsible means of producing uranium-235. The AVLIS process is currently undergoing commercialization.

Biomedical research at Livermore expanded greatly during the 1970s and 1980s. Carcinogenic and mutagenic chemicals were included with radionuclides as subjects of study, and the research program increasingly focused on understanding basic biological processes at every level from cell to organism. Livermore-devised instruments, notably the flow cytometer, made the Laboratory a world center for analytic cytology (Figure 8). When the Department of Energy, the AEC's successor, decided to support a massive effort to map the human genome and establish the sequence of every gene on human chromosomes, Livermore was well placed to develop the automated techniques that would make the project feasible.

Environmental research complemented biological studies. Precise sampling techniques and sophisticated computer modeling have allowed Livermore to play a growing role in environmental assessment, while other research has contributed to make cleanup techniques more effective.

Project Plowshare had included studies of several techniques for using nuclear explosions to extract oil or minerals from underground deposits too costly to reach by other means.

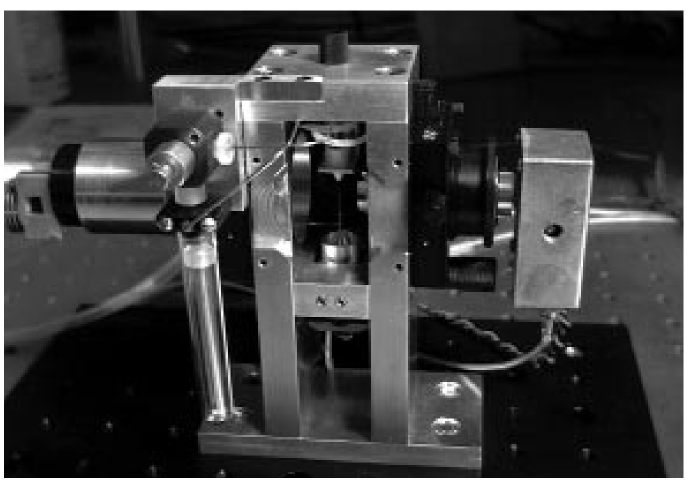


Figure 8. A demonstration model of Livermore's miniature flow cytometer. The pattern created by laser light reflected from a cell passing through the laser beam of this instrument reveals the cell's size and internal structure.

Although merely paper studies, they assumed new importance when the oil embargo of the early 1970s generated public concerns about the nation's dependence on foreign sources of energy. Nonnuclear energy became a major subject of Livermore study. In situ retorting of oil shale and coal gasification assumed a prominent part in Livermore's newly initiated and wide-ranging energy research program. Once again, however, changing national priorities brought the efforts to a standstill.

Era of Transition, 1988–Present

As an institution created to sustain and promote American science and technology for the Cold War, Lawrence Livermore faced a new world when the Cold War ended. Few foresaw that end as imminent when John Nuckolls became Livermore's seventh director in 1988. Average annual employment hovered around 8,000 into the early 1990s. The budget Nuckolls inherited in 1988, just under $900 million, rose to over $1 billion in fiscal year 1991. Both budget and workforce had declined significantly from those peak levels by April 1994, when Bruce Tarter succeeded Nuckolls as director.

In the immediate post–Cold War world, Livermore confronted a congressionally mandated moratorium on nuclear weapons testing, a vanishing Strategic Defense Initiative, and shrinking Department of Defense and DOE budgets. In response to the changing nature of perceived threats to national security, the Laboratory formed a new multidisciplinary directorate in 1992—Nonproliferation, Arms Control, and International Security.

Dismantling retired nuclear weapons and ensuring the safety and reliability of the remaining U.S. nuclear stockpile without nuclear testing displaced designing new weapons as the major national need of applied weapons experience and expertise. Testing or not, the Laboratory was still obliged to help preserve a viable nuclear weapons stockpile. As a key participant (along with Los Alamos and Sandia) in DOE's Stockpile Stewardship Program, Livermore is making major investments in advanced computation and nonnuclear testing. It is part of the Accelerated Strategic Computing Initiative to increase massively parallel computational power for virtual analysis of the aging stockpile verified by past nuclear test data and nonnuclear experiments. The National Ignition Facility is a keystone experimental facility in the Stockpile Stewardship Program, offering a means to obtain vitally needed data, maintain competence in weapon physics, and pursue inertial confinement fusion. Groundbreaking for this advanced laser program took place in 1997 (Figure 9).

After a period of uncertainty and reevaluation, Livermore has reaffirmed its central role as "a premiere applied-science national security laboratory." As further stated in the Laboratory's recently published strategic plan, *Creating the Laboratory's Future*, the Livermore's "primary mission is to ensure that the nation's nuclear weapons remain safe, secure, and reliable and to prevent the spread and use of nuclear weapons worldwide."

—Bart Hacker

Figure 9. On May 29, 1997, Secretary of Energy Federico Peña (center) joined Laboratory Director Bruce Tarter and Congresswoman Ellen Tauscher in breaking ground for the National Ignition Facility.

For further information contact Bart Hacker (202) 357-2250 (Hacker@NMAH.SI.EDU).

Editor's Note: Bart Hacker recently left the staff of S&TR *to become the curator of Armed Forces History at the Smithsonian Institution in Washington, D.C. He did the research for this article while serving as Lawrence Livermore National Laboratory Historian, 1992–1996.*

The X-Ray Laser From Underground to Tabletop

Figure 1. Jim Dunn makes adjustments to the tabletop x-ray laser's target chamber.

THE concept for x-ray lasers goes back to the 1970s, when physicists realized that laser beams amplified with ions would have much higher energies than beams amplified using gases. Nuclear explosions were even envisioned as a power supply for these high-energy lasers. That vision became a reality at the time of the Strategic Defense Initiative of the 1980s, when x-ray laser beams initiated by nuclear explosives were generated underground at the Nevada Test Site. Livermore's Novette, the precursor of the Nova laser, was used for the first laboratory demonstration of an x-ray laser in 1984.

Since then, Nova, Livermore's largest laser, has set the standard for x-ray laser research and been the benchmark against which x-ray laser research has been measured. Nova uses a very-high-energy pulse of light about a nanosecond (a billionth of a second) long to cause lasing at x-ray frequencies. Because these high-energy pulses heat the system's glass amplifiers, Nova must be allowed to cool between shots. Nova can thus be fired only about six times a day.

In contrast, a team at Livermore has developed a small "tabletop" x-ray laser that can be fired every three or four minutes. By using two pulses—one of about a nanosecond and another in the trillionth-of-a-second (picosecond) range—their laser uses far less energy and does not require the cooling-off period.

Scientists had theorized for years that an x-ray laser beam could be created using an extremely short, picosecond pulse, which would require less energy. But very short pulses overheated the glass amplifiers, destroying them. Laser chirped-pulse amplification, developed in the late 1980s, gets around that problem by expanding a very short pulse before it travels through the amplifiers and then compressing it to its original duration before the laser beam is focused on a target.[1] If chirped-pulse amplification is combined with lower energies, the pulses do not overheat the glass amplifiers, so the system can be fired many times a day.

The development team for this new laser includes Jim Dunn, the experimentalist, and theoreticians Al Osterheld and Slava Shlyaptsev, a visiting scientist from Russia's Lebedev Institute. All are physicists in the Physics and Space Technology Directorate. Together, they have produced one of only a handful of tabletop x-ray lasers in the world (Figure 1).

X-ray lasers produce "soft" x rays, which is to say their wavelengths are a bit longer than those used in medical x rays. Soft x rays cannot penetrate a piece of paper, but they are ideal for probing and imaging high-energy-density ionized gases, known as plasmas. X-ray lasers are an invaluable tool for studying the expansion of high-density plasmas, particularly laser-produced plasmas, making them useful for Livermore's fusion and physics programs. Basic research using x-ray lasers as a diagnostic tool can fine-tune the equations of state of a variety of materials, including those used in nuclear weapons and under investigation by the Stockpile Stewardship Program. These lasers also have applications for the materials science community, both inside and outside the Laboratory, by supplying detailed information about the atomic structure of new and existing materials.

Notes Osterheld, "Plasmas do not behave nicely. To verify the modeling codes for plasmas, we need lots of experiments." With an experiment every three or four minutes on the tabletop x-ray laser, large quantities of data can be produced quickly. The team's goal is to refine the process and reduce the size and cost of the equipment so that someday an x-ray laser might be a routine piece of equipment in plasma physics research laboratories.

Achieving a Stable Lasing Plasma

In x-ray lasers, a pulse of light strikes a target, stripping its atoms of electrons to form ions and pumping energy into the ions ("exciting" or "amplifying" them). As each excited ion decays from the higher energy state, it emits a photon. Many millions of these photons at the same wavelength, amplified in step, create the x-ray laser beam. The highly ionized material in which excitation occurs is a plasma (which should not be confused with the plasma that the x-ray laser beam is later used to probe).

X-ray lasers are specifically designed to produce a lasing plasma with as high a fraction of usable ions as possible to maximize the stability and hence the output energy of the laser. If the target is made of titanium, which has 22 electrons, the ionization process strips off 12 electrons, leaving 10, which makes the ions like a neon atom in electron configuration. Neonlike ions in a plasma are very stable, closed-shell ions. They maintain their stability even when faced with temporal, spatial, and other changes. Dunn, Osterheld, and Shlyaptsev have also studied palladium targets. When palladium atoms are stripped of 18 electrons, their ions become like a nickel atom, which is also closed-shell and stable.

A One-Two Punch

In Livermore's Nova laser, a high-energy, kilojoule pulse lasting a nanosecond or slightly less must accomplish three things: produce an initial line-focus plasma, ionize it, and excite the ions. Because the excitation, or heating, is happening relatively slowly compared to other plasma behavior, this process is called quasi-steady-state excitation.

The tabletop x-ray laser is configured differently from Nova (Figure 2). It uses the compact multipulse terawatt (COMET) laser driver to produce two pulses. First, a low-energy, nanosecond pulse of only 5 joules strikes a polished palladium or titanium target to produce the plasma and ionize it. The pulse must accomplish less than the Nova pulse, so less energy is needed.

Then a 5-joule, picosecond pulse, created by chirped-pulse amplification, arrives at the target a split second later to excite the ions. Although the picosecond pulse uses 100 times less energy than a Nova pulse, its power is ten times higher

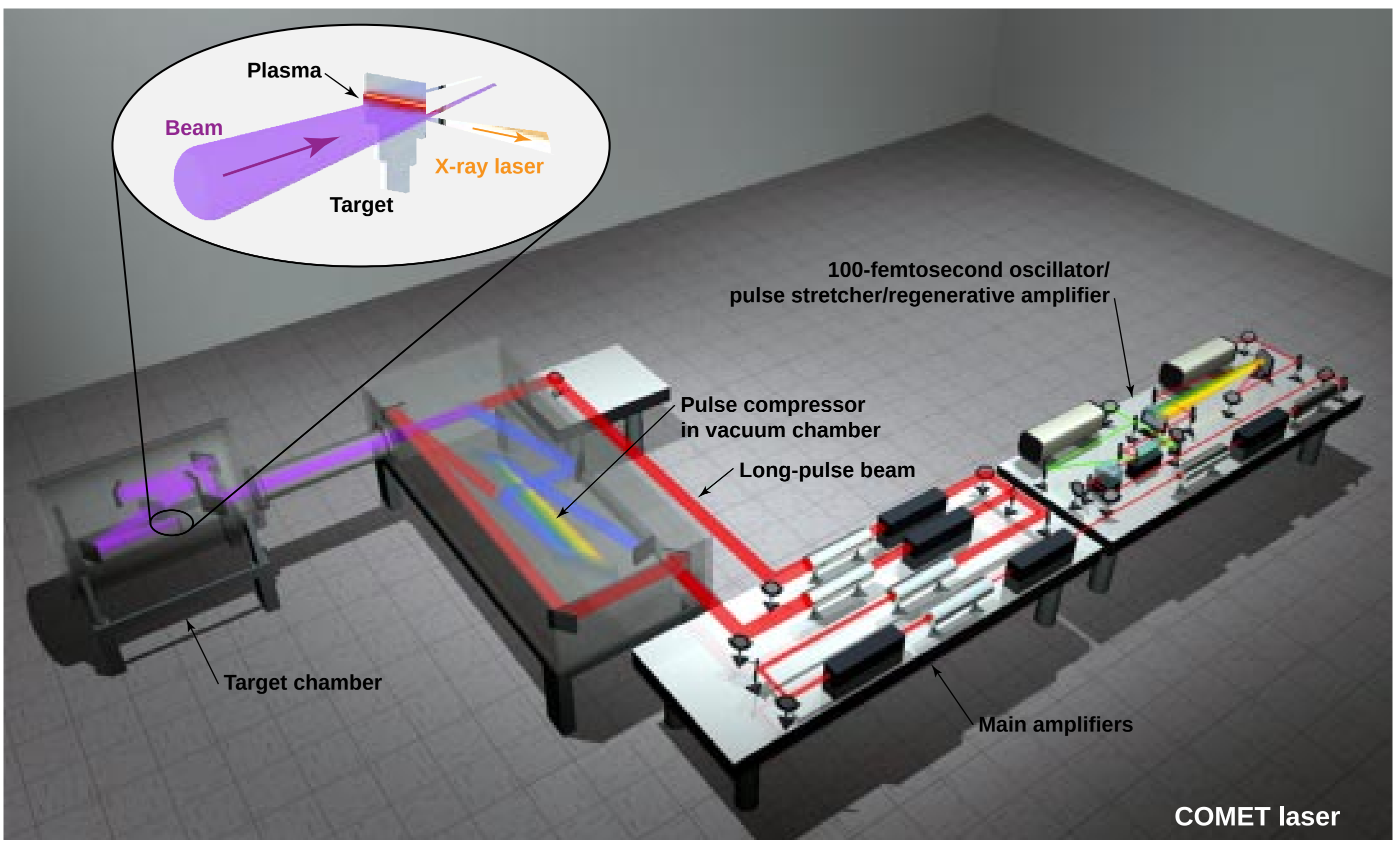


Figure 2. Rendering of Livermore's COMET (compact multipulse terawatt) tabletop x-ray laser showing the laser system and target chamber. The inset shows laser beams hitting the stepped target and producing a plasma, which in turn generates an x-ray laser beam.

because the pulse is one thousand times shorter. And its power density, which adds the length of the target to the power equation, is also very high.

The brief, picosecond, "transient" plasma excitation plays a major role in the laser's effectiveness. During the ionization process, the plasma expands rapidly. In the quasi-steady-state approach used with Nova, excitation occurs while the plasma is continuing to expand and be heated so that much of the deposited energy is lost from the lasing process. With the transient scheme, excitation happens so fast that more ions in the plasma can contribute to the lasing.

For plasma research purposes, the tabletop x-ray laser almost has it all—low energy requirements, high power, a repetition rate of a shot every four minutes, and a short wavelength. (Keep in mind that the shorter the wavelength of the laser, the more effectively it can penetrate high-density plasmas.)

Two Plasmas in One Chamber

To date, the Livermore team has studied neonlike titanium and nickel-like palladium transient schemes. It has produced the first transient-gain, nickel-like, x-ray lasing at 14.7 nanometers with a laser pump of less than 10 joules (Figure 3).[2] The team is looking at various ways to maximize the laser's output, including using different target designs and delaying the arrival of the picosecond pulse to match the propagation of the x-ray laser in the gain region.

Within the next year, the team plans to have a second plasma in the target chamber. The first one will be for lasing, while the second will be studied and probed. The very-short-pulse x-ray laser probe will act as a strobe to "freeze" the action of the second plasma, resulting in clearer images of plasmas than any yet produced. And with an experiment every three or four minutes, there can be lots of excellent images.

—Katie Walter

Key Words: chirped-pulse amplification, plasmas, soft x rays, tabletop x-ray laser.

References

1. For more information on chirped-pulse amplification, see *Science & Technology Review*, "Crossing the Petawatt Threshold," December 1996, pp. 4–11.
2. J. Dunn, A. L. Osterheld, R. Shepherd, W. E. White, V. N. Shlyaptsev, and R. E. Stewart, "Demonstration of X-Ray Amplification in Transient Gain Nickel-like Palladium Scheme," *Physical Review Letters* **80**(13), 2825–2828 (1998).

For further information contact Jim Dunn (925) 423-1557 (dunn6@llnl.gov) or Al Osterheld (925) 423-7432 (osterheld1@llnl.gov).

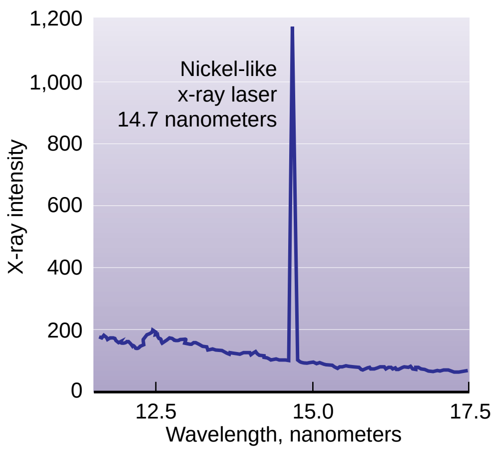


Figure 3. A line out of the emission spectrum from an x-ray laser experiment shows that the 14.7-nanometer x-ray laser line is orders of magnitude brighter than any other emission line.

Down-to-Earth Testing of Microsatellites

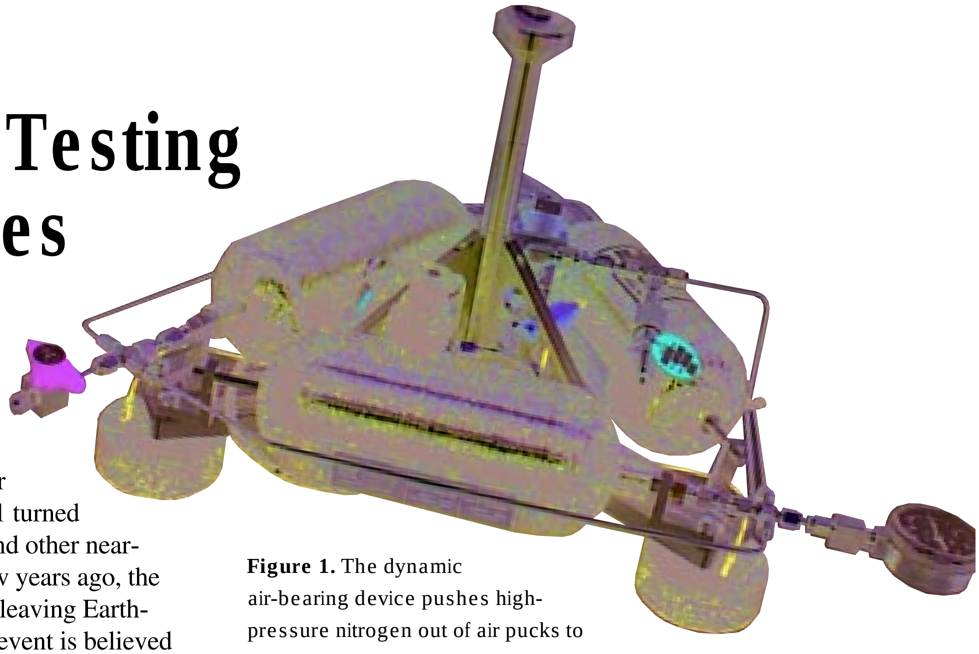


Figure 1. The dynamic air-bearing device pushes high-pressure nitrogen out of air pucks to create a gravity-free environment in which space vehicles can maneuver with five degrees of freedom.

ALTHOUGH the recent prediction of a near collision between Earth and asteroid XF11 turned out to be inaccurate, hazards from asteroids and other near-Earth objects are out there. After all, just a few years ago, the Shoemaker–Levy comet hurtled onto Jupiter, leaving Earth-sized scars on the planet's face, and a similar event is believed to have caused the extinction of the dinosaurs on Earth. The few nervous moments we Earthlings had over XF11 serve as a reality check on the hazards that await from space.

Scientists and engineers at Lawrence Livermore have been engineering small, agile satellites that can help deal with potential space calamities. Called microsatellites (microsats, for short), they are an outgrowth of research performed for the Laboratory's Clementine satellite program, which mapped the moon and then discovered the first evidence that water may exist there. The microsatellites are envisioned as operating autonomously in orbit to serve a variety of future space-exploration needs in addition to probing near-Earth asteroids. Microsatellites would be able to strike or probe the potentially hazardous objects that threaten Earth. In addition, they might be handy rescue vehicles used to inspect disabled satellites and relay observations about them to ground stations; they might also dock with and repair satellites. Microsatellites could also be part of a control system that protects and defends U.S. assets in space.

The capability for such uses will come through integrating a complex array of advanced technologies in the microsatellite vehicle. Sensors, guidance and navigation controls, avionics, and power and propulsion systems—all must perform precisely and in concert so the vehicles can find, track, lock onto, and rendezvous with their targets, even though those targets are also on the move. The rigorous ground testing of microsatellites' integrated technologies is essential; these tests produce data needed for effective flight testing.

The best ground-testing environment is one that mimics, as much as possible, the free-floating environment of a space flight. Finding a way to emulate such an environment was one of the important tasks facing microsatellite developers.

Inspired by a Game

Traditionally, space vehicles have been ground tested on a stationary hemispherical air bearing, a device that floats a test vehicle with high-pressure air. The air bearing provides the vehicle with three angular degrees of freedom. The stationary air bearing is useful for testing the stability of a space vehicle in orbit. But because microsats will be performing precision maneuvers in space that involve translation—that is, parallel, sideways motions—its testing must also account for linear dynamics.

Clementine II program leader Arno Ledebuhr, engineering group leader Larry Ng, and mechanical engineers Jeff Robinson and Bill Taylor came up with the idea for a dynamic air-bearing device that provides five degrees of freedom (three rotational, or angular, and two translational, or linear, motions). Their inspiration came from the game of air hockey, which uses air pushed out of a table to float hockey pucks. In the dynamic air bearing, this configuration is inverted—the air is pushed out of the pucks. Three such air pucks are used to support a traditional air bearing on a fixture that also includes an air supply—from high-pressure nitrogen tanks (Figure 1). As the air pucks release the high-pressure air, the whole device is lifted off the surface on which it has been sitting. Because the three air pucks, equally distributed on a 19-centimeter-radius circle, can support a total weight of more than 150 kilograms, it capably floats itself (5 kilograms) and a microsat test vehicle (25 kilograms). It thus allows the test vehicle to move linearly as if in a near-zero-gravity space environment.

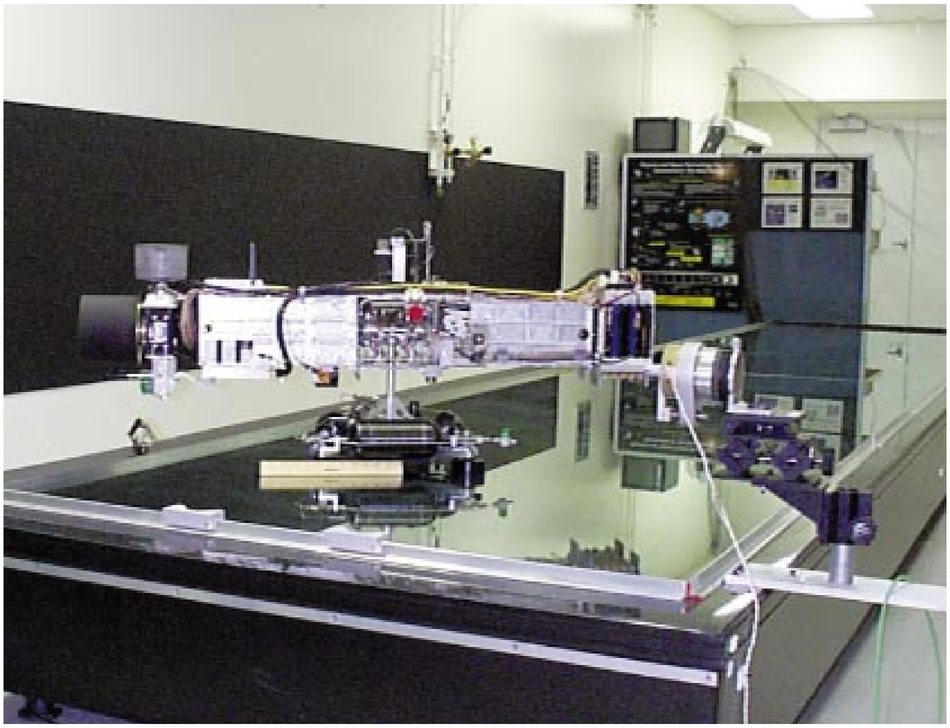


Figure 2. The dynamic air-bearing device floats a microsatellite above a glass surface to test the microsatellite's ability to accurately track and maneuver to its target.

Scaling Down Space Maneuvers

The Livermore team is using the dynamic air-bearing device in a series of experiments called AGILE, for air-table guided-intercept and line-of-sight experiments. These experiments will evaluate a vehicle's ability to "divert," that is, maneuver in space while keeping track of a moving target (such as an incoming asteroid) and then close in to intercept it. The objective of these experiments is to quantify the distances by which the microsats miss intercepting the target, thus allowing microsat developers to identify hardware and software deficiencies.

For a vehicle to accomplish an interception, its sensors and measurement, navigation, and control systems must work together to continually calculate vehicle speed and position in relation to the target. They must calculate the point at which the target can be intercepted and get the vehicle to that point at precisely the same time as the target. Because both the vehicle and target are moving, the line of sight to the target continually changes, and therefore, vehicle acceleration and position must be constantly adjusted. Further complicating these calculations are the many other factors that can affect maneuvering precision, such as changing vehicle mass due to fuel expenditure, vehicle acceleration capability, and minor misalignment of hardware components.

The interception experiments use a test vehicle that can move with five degrees of freedom. The vehicle sits on the dynamic air bearing, which in turn is borne on two large, smooth glass plates resting side by side on a table. The glass plates form a rectangular test table approximately 1.5 by 7.2 meters. A laser projects a target onto a wall-mounted target board parallel to the long side of the glass test table. A precision measurement system, consisting of a laser and a camera, accurately measures and records the test vehicle's position (Figure 2).

The intercept geometry, comprising the vehicle positions, target positions, and the changing line of sight between them, is scaled for the indoor table experiment to preserve the intercept geometry of an actual flight. For example, for a successful interception, the line-of-sight rate must approach zero; that is, the vehicle and target must both arrive at the same point at the same time. To preserve that line-of-sight requirement in the test, the test maneuvering distance is scaled down in relation to the target that is projected on the screen. The target location and interception point are predetermined, and these values, used in conjunction with the precise measurements of vehicle position (from the laser measurement system), allow experimenters to determine the ability of the onboard guidance and control software to maneuver the vehicle to the point of interception.

Taking Testing to the Next Steps

The current rectangular, indoor dynamic air-bearing test setup is useful for a variety of experiments. However, the short length of the current glass test surface limits maneuvering distance, thus prohibiting replication of the exact

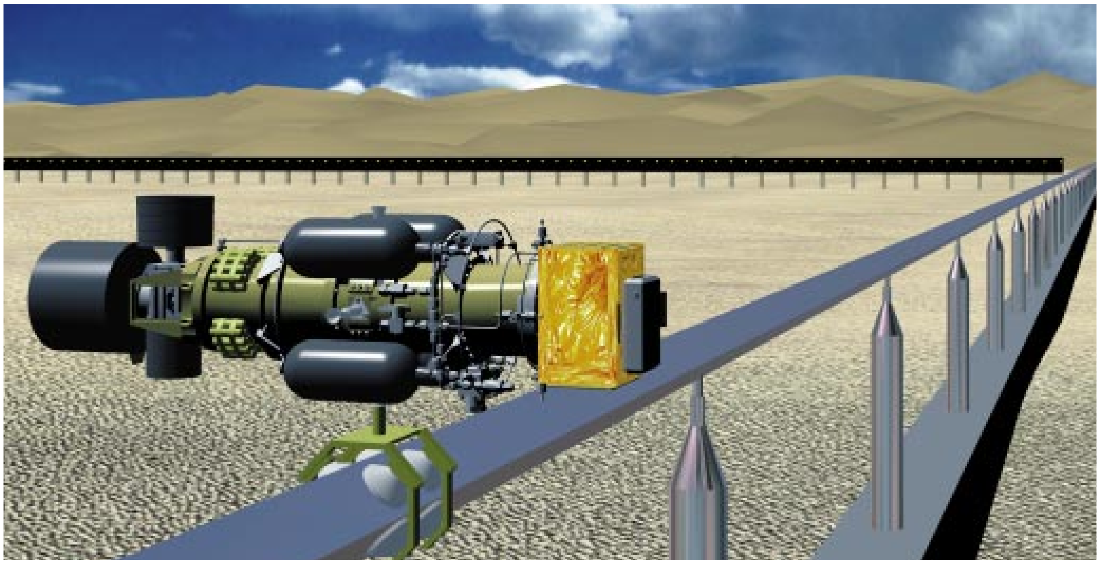


Figure 3. To improve replication of flight maneuvers and provide more accurate tracking of vehicle position, Livermore scientists are designing a large, outdoor version of the dynamic air bearing. The larger scale means more precise reconstruction of line-of-sight angles, which in turn means improved predictions of how to maneuver the test vehicle to meet with its target.

frequency and duration of engine acceleration in actual flight maneuvers. Making the test surface larger and square (10 meters by 10 meters) will enable the performance of a greater range of rendezvous and docking maneuvers, including practicing the circumnavigation of a satellite and determining its spin axis and rotation rate.

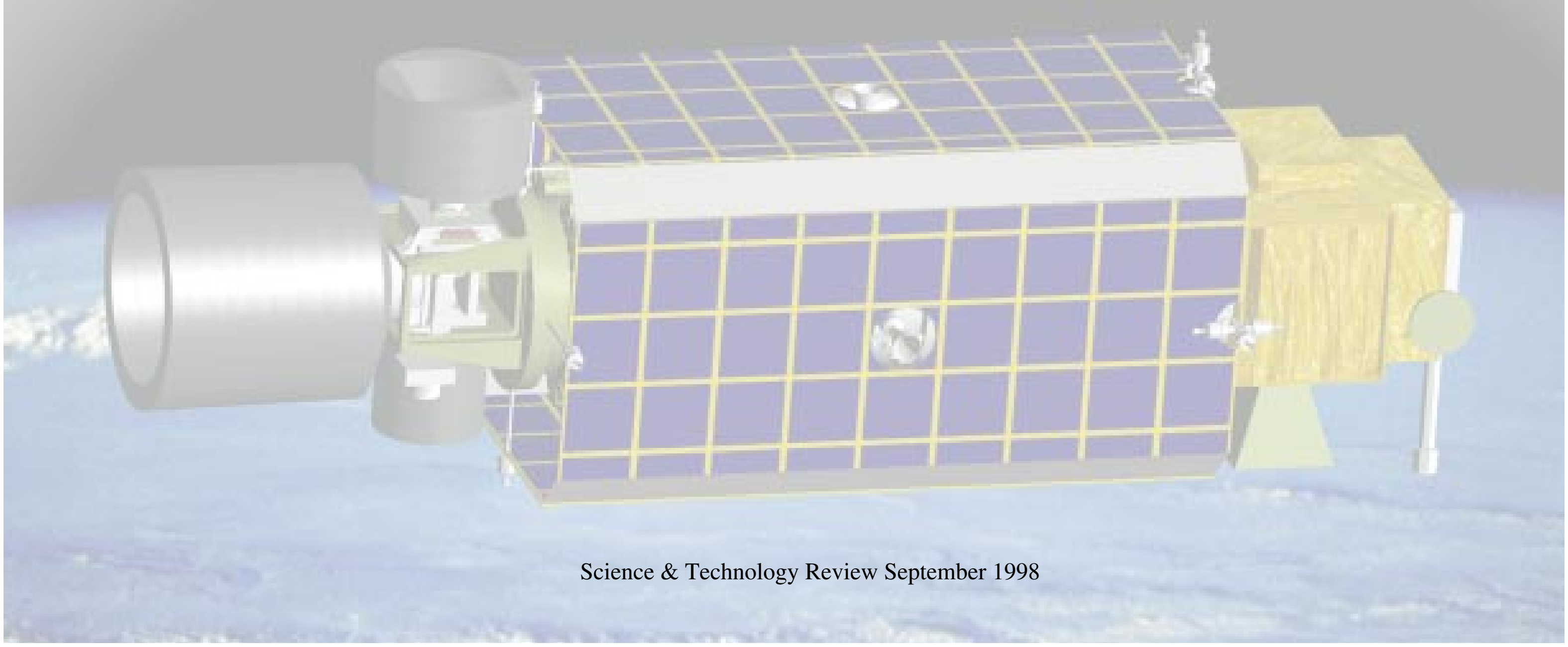
To eliminate some of the indoor setup's limitations, an outdoor version of the device is being developed. In this version, the test vehicle "floats" on a smooth rail 100 to 200 meters long and "views" a tilted board on which an incoming target is projected (Figure 3). The rail air-bearing system can move in only one linear direction, but because of its larger scale, it provides an improved replication of flight maneuvers and a more accurate tracking of vehicle position. Both improvements lead to a more precise reconstruction of line-of-sight angles, which is key to correctly predicting the point at which the microsat maneuvers to its target.

The air-bearing team's work on ground testing techniques continues. To date, a 17-meter-long rail has been used to "fly" the newest generation of the microsat vehicle. Longer range outdoor docking experiments that incorporate both an onboard Star Tracker camera, which uses stars to calculate the orientation of the microsats, and a global positioning system receiver are in the planning stages.

—Gloria Wilt

Key Words: AGILE (air-table guided-intercept and line-of-sight experiments), dynamic air-bearing table, dynamic air-bearing rail, ground testing, microsat, microsatellite, spacecraft interceptor, space vehicle.

For further information contact Arno Ledebuhr (925) 423-1184 (ledebuhr1@llnl.gov).



Patents and Awards

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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Simon J. Cohen Lynn G. Seppala	**Critical Illumination Condenser for X-Ray Lithography** U.S. Patent 5,737,137 April 7, 1998	A critical illumination condenser system, adapted for use in extreme ultraviolet (EUV) projection lithography based on a ring field imaging system and a laser-produced plasma source. The system uses three spherical mirrors and is capable of illuminating the extent of the mask plane by scanning the primary mirror or the laser plasma source. The angles of radiation incident upon each mirror of the critical illumination condenser vary by less than 8 degrees. For example, the imaging system in which the critical illumination condenser is used has a 200-micrometer source and requires a magnification of 26.
Troy W. Barbee, Jr. Gary W. Johnson	**Nanostructure Multilayer Dielectric Materials for Capacitors and Insulators** U.S. Patent 5,742,471 April 21, 1998	A capacitor formed of at least two metal conductors having a multilayer dielectric and opposite dielectric–conductor interface layers in between. The multilayer dielectric includes many alternating layers of amorphous zirconium oxide (ZrO_2) and alumina (Al_2O_3). The dielectric–conductor interface layers are engineered for increased voltage breakdown and extended service life. The local interfacial work function is increased to reduce charge injection and thus increase breakdown voltage.
Richard W. Pekala	**Organic Carbon Aerogels from the Sol-Gel Polymerization of Phenolic-Furfural Mixtures** U.S. Patent 5,744,510 April 28, 1998	A high-surface-area foam made from sol-gel polymerization of a phenolic-furfural mixture in dilute solution leading to a highly cross-linked network that is supercritically dried. These porous materials have cell/pore sizes less than or equal to 1,000 angstroms. The phenolic-furfural aerogel can be pyrolyzed in an inert atmosphere at 1,050°C to produce carbon aerogels. This new aerogel may be used for thermal insulation, chromatographic packing, water filtration, ion exchange, and carbon electrodes for energy storage devices, such as batteries and double-layer capacitors.
Jim J. Chang Ernest P. Dragon Bruce E. Warner	**Apparatus for Precision Micromachining with Lasers** U.S. Patent 5,744,780 April 28, 1998	A new material-processing apparatus using a short-pulse, high-repetition-rate visible laser for precision micromachining. It uses a near-diffraction-limited laser; a high-speed, precision two-axis tilt-mirror for steering the laser beam; an optical system for either focusing or imaging the laser beam on the part; and a part holder. The system is useful for precision drilling, cutting, milling, and polishing of metals and ceramics and has broad application in manufacturing precision components.
Joseph W. Balch Anthony V. Carrano James C. Davidson Jackson C. Koo	**Hybrid Slab-microchannel Gel Electrophoresis System** U.S. Patent 5,746,901 May 5, 1998	A system that permits the fabrication of isolated microchannels for biomolecule separations without imposing the constraint of a totally sealed system. It incorporates a microslab portion of the separation medium above the microchannels, thus substantially reducing the possibility of nonuniform field distribution and breakdown due to uncontrollable leakage. The microslab of the sieving matrix is built into the system by using plastic spacer materials and is used to uniformly couple the top plate with the bottom microchannel plate.
William McLean II Mehdi Balooch Wigbert J. Siekhaus	**Laser Ablated Hard Coating for Microtools** U.S. Patent 5,747,120 May 5, 1998	A method for depositing wear-resistant coatings composed of laser-ablated hard-carbon films by pulsed laser ablation using visible light on instruments such as microscope tips and microsurgical tools. Hard carbon (known as diamondlike carbon) films produced in this way enhance the abrasion resistance, wear characteristics, and lifetimes of microtools without affecting their sharpness or size.

(continued on page 28)

(continued from page 27)

Patents and Awards

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Robert T. Taylor Kenneth J. Jackson Alfred G. Duba Ching-I Chen	**In Situ Thermally Enhanced Biodegradation of Petroleum Fuel Hydrocarbons and Halogenated Organic Solvents** U.S. Patent 5,753,122 May 19, 1998	An in situ thermally enhanced microbial remediation strategy and method for biodegradation of toxic petroleum fuel hydrocarbon and halogenated organic solvent contaminants. It uses nonpathogenic, thermophilic bacteria for the thermal biodegradation of toxic and carcinogenic contaminants from fuel leaks and past solvent-cleaning practices. The method makes use of preexisting heated conditions and delivery/recovery wells created by thermal treatment approaches, such as dynamic underground steam–electrical heating.
Alan F. Jankowski Daniel M. Makowiecki Glenn D. Rambach Erik Randlich	**Hybrid Deposition of Thin Film Solid Oxide Fuel Cells and Electrolyzers** U.S. Patent 5,753,385 May 19, 1998	A method using vapor deposition techniques to synthesize the basic components of a solid-oxide fuel cell, namely, the electrolyte layer, the two electrodes, and the electrolyte–electrode interfaces, and thereby produce a thin-film solid-oxide fuel cell. Reactive deposition of any ion-conducting oxide forms the electrolyte. The electrolyte is formed by reactive deposition of any conducting oxide by planar magnetron sputtering. The electrodes are formed from ceramic powders sputter-coated with an appropriate metal and sintered to a porous compact. The electrolyte–electrode interface is formed by chemical vapor deposition of zirconia compounds onto the porous electrodes to provide a dense smooth surface on which to continue the growth of the defect-free electrolyte, whereby one or more multiple cells may be fabricated.
Thomas E. McEwan	**Ultra-wideband Horn Antenna with Abrupt Radiator** U.S. Patent 5,754,144 May 19, 1998	An ultrawideband horn antenna that transmits and receives impulse waveforms from short-range radars and impulse time-of-flight systems. The antenna reduces or eliminates various sources of close-in radar clutter, including pulse dispersion and ringing, sidelobe clutter, and feedline coupling into the antenna. Low-frequency cutoff associated with a horn is extended by configuring the radiator drive impedance to approach a short circuit at low frequencies.

Awards

Laboratory physicist **Ben Santer** is one of this year's winners of the **John D. and Catherine T. MacArthur Award**. An atmospheric scientist in the Laboratory's Program for Climate Model Diagnosis and Intercomparison, Santer received the fellowship in recognition of his "originality, creativity, self-direction, and capacity to contribute importantly to society, particularly in atmospheric sciences." The award, popularly called a Genius Award, is accompanied by a stipend of $270,000, paid over five years.

A Livermore employee since 1992, Santer was thrust into the public spotlight in 1995 as the lead author of one chapter of a United Nations report. The chapter's conclusion that "the balance of evidence suggests a discernible human influence on global climate" provoked considerable scientific and political debate. The focus of Santer's research is to understand the nature and causes of global climate change using sophisticated computer models.

Santer is also a recipient of a 1998 **Norbert Gerbier/MUMM Award** for a paper entitled "A Search for Human Influences on the Thermal Structure of the Atmosphere," which appeared in the July 1996 *Nature*. The award was presented to Santer and his 12 co-authors at a ceremony in Geneva, Switzerland, in late June 1998.

The Laboratory's **Molten Salt Oxidation** (MSO) demonstration project has received the Northern California Section of the American Institute of Chemical Engineers' **Project of the Year Award**. **Peter Hsu** and **Martyn Adamson** developed the process, which is being demonstrated in a pilot-scale recycle system that is part of Livermore's integrated MSO demonstration system. The award is for "an intelligently conceived and directed project or program of research in Northern California that offers to extend chemical engineering practice through the development of new theory or empirical knowledge."

Two groups of Laboratory researchers were recently honored with 1998 **Excellence in Technology Transfer** awards from the **Federal Laboratory Consortium**. A multidisciplinary team from the Laboratory's Center for Healthcare Technologies led by **J. Patrick Fitch** won for the development and transfer of an **opto-acoustic recanalization** technique for breaking up stroke-causing blood clots in the brain to EndoVasix, Inc., of Belmont, California, which will commercialize the system and complete the path from laboratory concept to patient care.

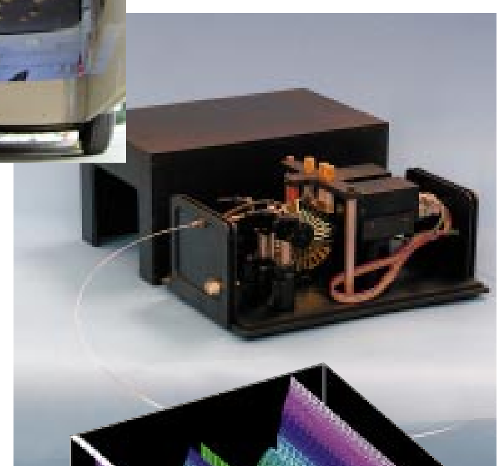
A second group, led by **Stephen Vernon**, won for developing and transferring to Veeco Instruments, Inc., of Plainview, New York, a new approach for fabricating low-defect-density, thin-film, multilayer coatings using an **ion-beam sputter deposition** process. This chip-coating technology has been incorporated in Veeco's IBD-350 machine, which produces advanced computer chips with a 300,000-fold reduction in defects compared to chips made with other commercial systems.

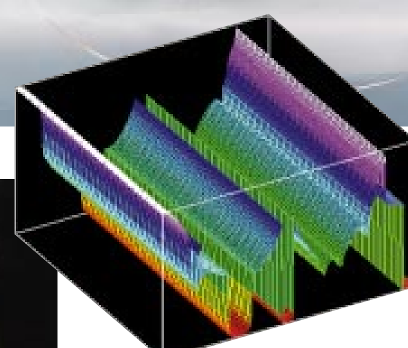
The FLC handed out 31 excellence awards, 9 of which went to DOE laboratories.

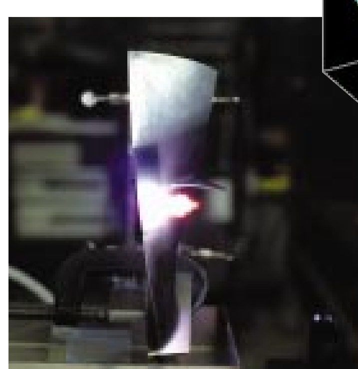
Coming Next Month

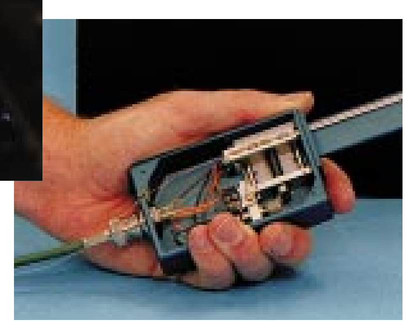
Livermore Wins Seven R&D 100 Awards

In October, *S&TR* will report the details about the winning inventions and the inventors.









Forensic Seismology Supports the Comprehensive Test Ban Treaty

A team of Lawrence Livermore scientists has worked to develop and refine monitoring technologies for the Comprehensive Test Ban Treaty (CTBT). The treaty, still to be ratified by the United States, forbids all nuclear tests (including those intended for peaceful purposes) and creates an international monitoring network to search for evidence of clandestine nuclear explosions. Livermore's efforts are part of a Department of Energy program focusing on advanced methods to precisely detect, locate, and characterize events in key areas of the world that could be clandestine nuclear tests. Livermore scientists have contributed significantly to the Knowledge Base, a database for managing, storing, and retrieving vital data—especially seismic, hydroacoustic, infrasound, and radionuclide information—from monitoring stations. Personnel at the U.S. National Data Center at Patrick Air Force Base in Florida, the nation's future test ban treaty monitoring facility, will use these data in cooperation with the CTBT's International Data Center in Vienna, Austria, to locate and identify possible CTBT violations.

Contact:
Jay Zucca (925) 422-4895 (zucca2@llnl.gov).

A Short History of the Laboratory at Livermore

What is today Lawrence Livermore National Laboratory opened officially in September 1952, less than six years before the death of its namesake Ernest Orlando Lawrence, inventor of the cyclotron and winner of a Nobel Prize. A branch of the University of California Radiation Laboratory in Berkeley, the laboratory at Livermore was founded by the Atomic Energy Commission at the urging of Lawrence (the Radiation Laboratory's founder), Edward Teller, and other top U.S. scientists in response to the first Soviet Union nuclear weapon test in August 1949. Its first mission was to join Los Alamos in the development of thermonuclear weapons.

The laboratory at Livermore separated from its Berkeley parent in 1971 and became a DOE national laboratory in 1980. Throughout its history, its national security mission has remained constant. That mission has grown to include a variety of basic and applied scientific research and development in the national interest. During its more than four decades of change and growth, Lawrence Livermore has remained true to its dedication to the finest scientific achievement for the security of the nation.

Contact:
Bart Hacker (202) 357-2250 (Hacker@NMAH.SI.EDU).

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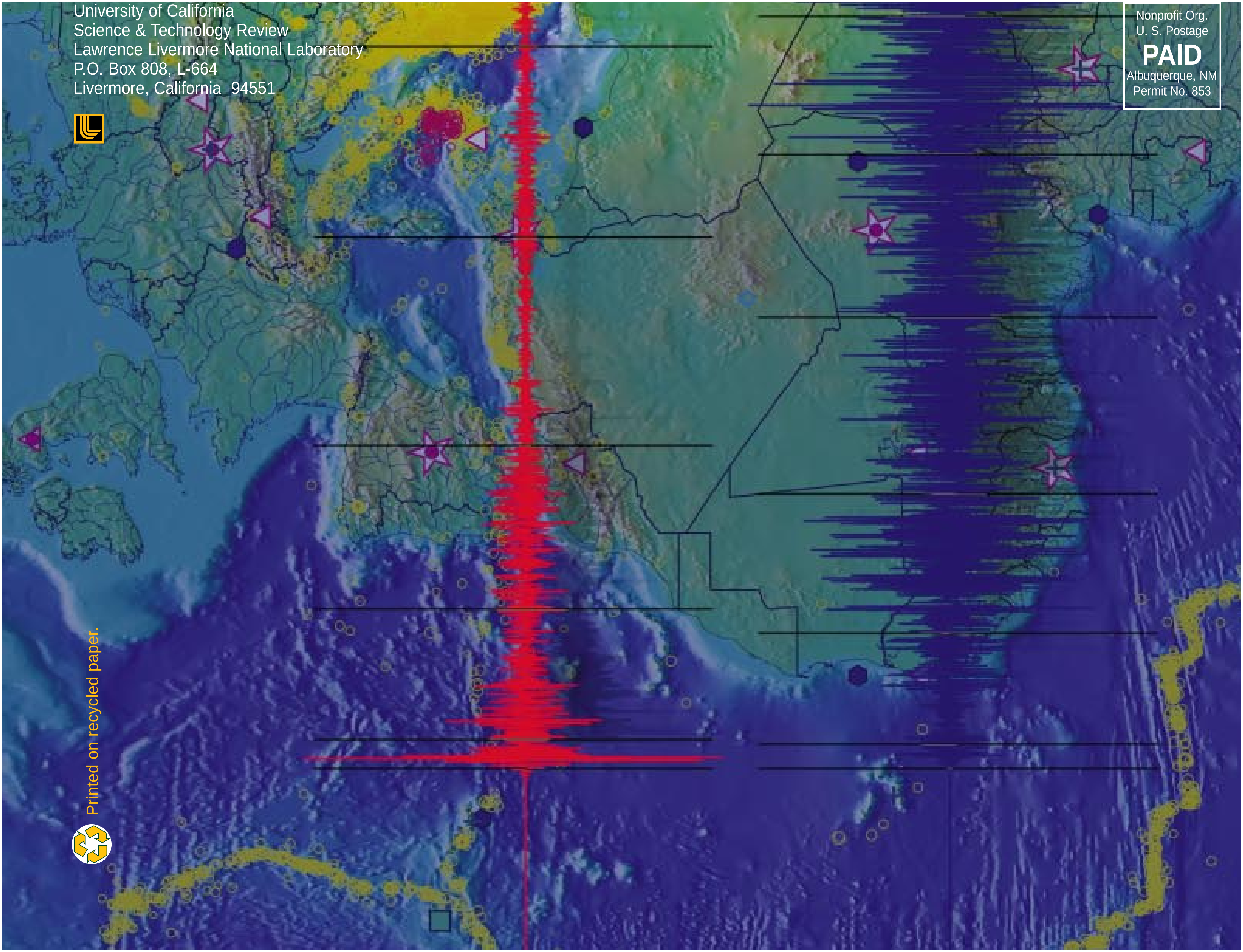

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