Science & Technology REVIEW

May 1999

U.S. Department of Energy's Lawrence Livermore National Laboratory

Science and Technology to Defend Our National Interests

Also in this issue:

- **Catching the Meaning of Acoustic Waves**
- **Lighting the Way to Faster Computers**

About the Cover

The DOE national laboratories have much to offer the Department of Defense. At Lawrence Livermore, a plethora of science and technology projects is supporting DOD missions (see the article beginning on p. 4). The cover is a composite illustration of several projects, including, from top to bottom, a fiber-composite sabot directing a projectile out of a weapon, a simulation of an electron beam heating a land mine, a shaped-charge warhead undergoing design evaluation by an optimization code, and a large explosive test used in developing models for evaluating missile propellant accidents.

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 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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
David Eimerl

Managing Editor
Sam Hunter

Publication Editor
Gloria Wilt

Writers
Arnie Heller, Ann Parker, Sue Stull, Dean Wheatcraft, and Gloria Wilt

Art Director and Designer
George Kitrinos

Internet Designer
Kitty Tinsley

Compositor
Louisa Cardoza

Proofreader
Carolin Middleton

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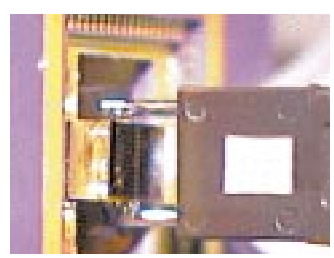

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Lab performance rated excellent in '98

The Department of Energy awarded Lawrence Livermore an overall performance rating of excellent for fiscal year 1998. The annual assessment includes appraisal of the Laboratory's performance in science and technology as well as administration and operations.

Laboratory science and technology programs received an overall rating of outstanding, DOE's highest rating, with an overall score of 90.6 percent, up slightly from last year's 90.1 percent. The programmatic assessment is based on Laboratory self-assessment, peer review, and validation by program managers at DOE headquarters.

"For administration and operations activities, the appraisal provides us with a valuable tool for measuring our progress in relation to the performance goals set out in the contract," says John Gilpin, head of the Office of Contract Management at Livermore. While these are areas where the Laboratory can continue to improve, great strides have been made in cutting administration and operations costs and improving efficiency since the results-oriented, performance-based contract with DOE went into effect in 1992, according to Gilpin. He also noted that improving productivity and performance ratings while reducing costs and organizational staffing "means a greater share of Lab dollars and resources are available for our core activities in science and technology."

Contact: John Gilpin (925) 423-1492 (gilpin1@llnl.gov).

DOE-ASML team to develop new chip technology

The Department of Energy recently announced an agreement with ASML, an international supplier of lithography tools based in the Netherlands, to participate as a licensee in a project led by the U.S. to develop a new technology for producing computer chips.

The technology, extreme-ultraviolet lithography (EUVL), has the potential to make desktop computer chips that are a hundred times more powerful and have a thousand times the memory of today's chips at feature sizes less than one-thousandth the width of a human hair. The pact with ASML is a major step toward realizing the commercial prospects and international acceptance of this new technology.

ASML joins U.S. lithography tool suppliers Silicon Valley Group and USAL in an ongoing cooperative research and development agreement (CRADA) between Extreme Ultraviolet Limited Liability Corporation—a consortium of U.S. computer chip makers Intel Corporation, Motorola, and Advanced Micro Devices—and DOE's Lawrence Livermore, Sandia, and Lawrence Berkeley national laboratories. The purpose of the CRADA is to demonstrate the feasibility of EUV lithography and establish a pathway to commercialization.

Contact: Gordon Yano (925) 423-3117 (yano1@llnl.gov).

Senate holds first field hearings at Lab

Members of the Senate's Armed Services Strategic Subcommittee traveled to Lawrence Livermore recently to hold budget hearings for the first time in the field rather than in Washington. Their purpose was to take testimony from DOE Assistant Secretary of Defense Programs Vic Reis, the directors of DOE's three national security laboratories, and the managers of the four DOE plants on the success of the Stockpile Stewardship Program.

At the hearing, Senator Robert Smith, the subcommittee chair, and Senator Mary Landrieu, the ranking minority member, questioned Reis and the laboratory managers on whether they believed the Stockpile Stewardship Program would work well enough to merit ratification of the Comprehensive Test Ban Treaty.

In written testimony, Livermore Director Bruce Tarter reported that stockpile stewardship in the absence of nuclear testing is working and that there is optimism that the program's long-term goals are achievable, given sustained support. Tarter, like Reis and the other DOE laboratory and plant managers, urged strong support of the fiscal year 2000 budget submission for DOE Defense Programs. Tarter detailed Lawrence Livermore's own involvement in maintaining a safe and reliable stockpile and provided updates on the National Ignition Facility and Livermore's role in the Accelerated Strategic Computing Initiative.

Tarter's complete testimony is available on the World Wide Web at *http://www.llnl.gov/PAO/cbt7-testimony/*.

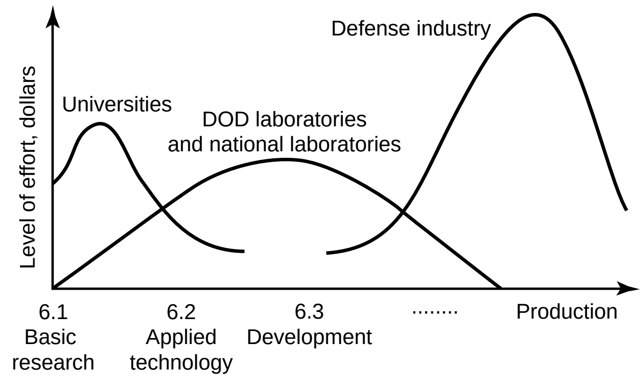
Sustained spheromak dedicated

Lawrence Livermore recently dedicated the Sustained Spheromak Physics Experiment (SSPX), giving a new lease on life to a magnetic fusion concept pioneered at Los Alamos National Laboratory. A reinterpretation of old results from Los Alamos fusion research by Livermore's Kenneth Fowler found them more promising than originally believed. The rejuvenated experiment involves a collaboration of Lawrence Livermore, Los Alamos, and Sandia national laboratories; General Atomics; the California Institute of Technology; the University of California at Berkeley and Davis; the University of Wisconsin; the University of Washington; and Swarthmore College.

The spheromak generates magnetic fields by internal dynamo motion caused by turbulence in the plasma, the hot ionized gas that serves as the reactor fuel. The objective of the SSPX is to better understand and, ultimately, control the physics of magnetic fusion, a potential source of abundant, inexpensive energy.

Contact: Keith Thomassen (925) 422-9815 (thomassen1@llnl.gov).

Supporting the DOD is Part of Livermore's National Security Role



THE major mission of Lawrence Livermore National Laboratory is national security, with a principal emphasis on providing a secure, safe, and reliable nuclear deterrent. We also contribute to national efforts to stem the proliferation of weapons of mass destruction. Our core competencies, developed because of our focus on the nuclear weapons program and our current responsibilities in the Department of Energy's Stockpile Stewardship Program, are acknowledged by the U.S. national defense leadership to be an important science and technology resource for the Department of Defense as well. Blue Ribbon panels, the Congress, and key defense managers historically have recognized the value in applying DOE's weapon technologies where they can advance conventional warfare capabilities. This is a mutually beneficial strategy. When Livermore weapons technology "spins off" to address a DOD requirement, in many cases there is also a return benefit ("spin-back") to DOE, wherein Livermore's core competencies have been enhanced.

Our DOD work is usually performed under Work for Others (WFO) programs, which are directly funded by the DOD, and sometimes under Memorandum of Understanding (MOU) programs where both DOE and DOD provide funds. In either case, DOD and DOE are mutually served. For example, Livermore develops sophisticated structural dynamics codes that can address the safety of nuclear weapons that are struck by fragments or projectiles. These are three-dimensional problems that require three-dimensional codes. These same codes were developed to enable DOD to address the lethality issues of hit-to-kill missiles used to intercept reentry vehicles. They also aid the design of three-dimensional, explosively formed projectiles (EFPs) used in flyover shoot-down munitions. In turn, DOE benefits from these applications. We couple the modeling and simulation efforts with experiments, which helps to establish benchmarks for the codes and often drives significant improvements and new code developments.

We at Livermore take the view that our role in the national security arena naturally includes working with DOD, in particular helping to fill an important gap for DOD in the weapon research, development, demonstration, and product implementation process. In general, universities, DOD laboratories, and not-for-profit research centers are depended upon to insert new science and technology into a pipeline that leads to production of warfare materials. DOD relies heavily on universities to provide fundamental basic research (designated as DOD 6.1 programs), and the DOD laboratories of the military services generally focus on early applied technology (DOD 6.2 programs, for example). Industry provides the output of the pipeline. DOD relies on defense industries for engineering development and production (DOD 6.3 and beyond) such as munitions, armored vehicles, planes, ships, and electronic systems.

The national laboratories help to fill the gap between basic research and manufacturing in the research-to-implementation cycle (see figure). We integrate basic research developments into focused, applied technology solutions, oftentimes by applying innovative, "out-of-the-box" concepts. Livermore's demonstrated role is to keep the flow going by filling in research as needed, integrating and applying science, maturing technologies, demonstrating proofs of concept, and teaming, where appropriate, with DOD entities and handing off to defense industry.

The full scope of our DOD activities naturally involves a wide spectrum of technologies and deliverables. We provide expertise in conflict simulation; codes for hydrodynamics, electromagnetics, and explosive response and performance; new explosives; sensors; laser technology; new materials; manufacturing technology; missile defense; and space technology and forensics, to name a partial list. The article beginning on p. 4 describes some of this work in detail, demonstrating some of the ways we leverage technologies for dual national security benefits. The projects represent a small portion of our DOD work, which is spread over almost all Laboratory directorates and involves multidisciplinary efforts.

■ Milton Finger is Deputy Director, DOD Programs.

Leveraging Science and Technology

The Department of Energy and the Department of Defense have historically shared Lawrence Livermore's wealth of national security resources. The results are more science and technology for the investment and better assurance that the nation's security and defense needs will be met.

THE three DOE national security laboratories—Lawrence Livermore, Los Alamos, and Sandia—have a technology base of interest to the Department of Defense. Their nuclear weapons technology can be leveraged to address the DOD nonnuclear security mission. Therefore, it's not surprising that DOE and DOD have a long history of collaboration at the three laboratories. At Lawrence Livermore, that collaboration dates at least as far back as February 1956, when Edward Teller made a bold pledge to deliver to DOD a smaller, lighter warhead for the Polaris missile and do so on an extremely short schedule. Lawrence Livermore scientists took up the challenge and made good on Teller's promise. It was one of many instances where scientists from DOE national security laboratories were to fulfill DOD requests.

Later, during the Cold War, a Navy Trident test missile blew up and extensively damaged the testing range. Lawrence Livermore, working with Los Alamos and two Navy laboratories, unraveled the cause of the explosion, which led to the development of a safer, high-energy propellant to put the Trident missile back on track. More recently, in Kuwait while the Persian Gulf War was being waged, Livermore's Atmospheric Release Advisory Capability tracked smoke plumes from torched oil wells so pilots could plan safe flight paths and environmental air monitors could estimate the plumes' health effects.

During war and in less turbulent times, the Laboratory delivers services and products to DOD. They range from a new missile warhead to a new direct, in-line detonator that provides a safe, reliable electronic fuse used to initiate explosives in munitions. Lawrence Livermore has also provided DOD with items such as the LX-14 explosive, currently found inside DOD's TOW, Hellfire, Javelin, and BAT antiarmor munitions.

A Two-Way Exchange

DOD has long recognized that Livermore—indeed, all the DOE national security laboratories—has unique capabilities that can be leveraged for DOD purposes. Traditionally, DOD has provided additional funding to the national laboratories to extend projects toward conventional weapons applications. In one instance, to maximize this leveraging, the funding arrangement was formalized in 1985 in a Memorandum of Understanding (MOU), which established a joint munitions program between the DOE national laboratories and DOD.

The MOU program at Livermore was managed for many years by chemist Milton Finger, now the Laboratory's Deputy Director for DOD Programs. He subsequently turned that responsibility to Al Holt, and currently Dennis Baum manages the program. Finger says that "the program provides a window through which Lawrence Livermore can be aware of DOD needs and DOD can be knowledgeable of the technologies available at Livermore. DOD can challenge Livermore to contribute innovative science and technology to attack pervasive problems and grand challenges in the defense arena. In addition, Livermore can focus its efforts more efficiently and productively to serve the dual interests of DOE and DOD."

Baum identifies the program's principal technical areas as high explosives, codes, nonnuclear weapons design, fuses, demilitarization, sensors, and advanced materials. Both Finger and Baum point to the program's efficient integration with Laboratory projects and priorities. Consequently, Livermore resources are being used more fully and productively, and DOD derives advantages from Livermore at the same time that Livermore core competencies are enhanced.

The projects described here, which are but a small portion of Livermore's DOD work, demonstrate some of the ways the Laboratory uses technologies for dual national security benefits.

Getting out of Tight Spots

One day, U.S. soldiers under attack in hostile, foreign terrain may find themselves depending on a device developed with the help of Lawrence Livermore. To put an insurmountable obstacle between themselves and the enemy, they pull out a weapon called a

in the National Interest

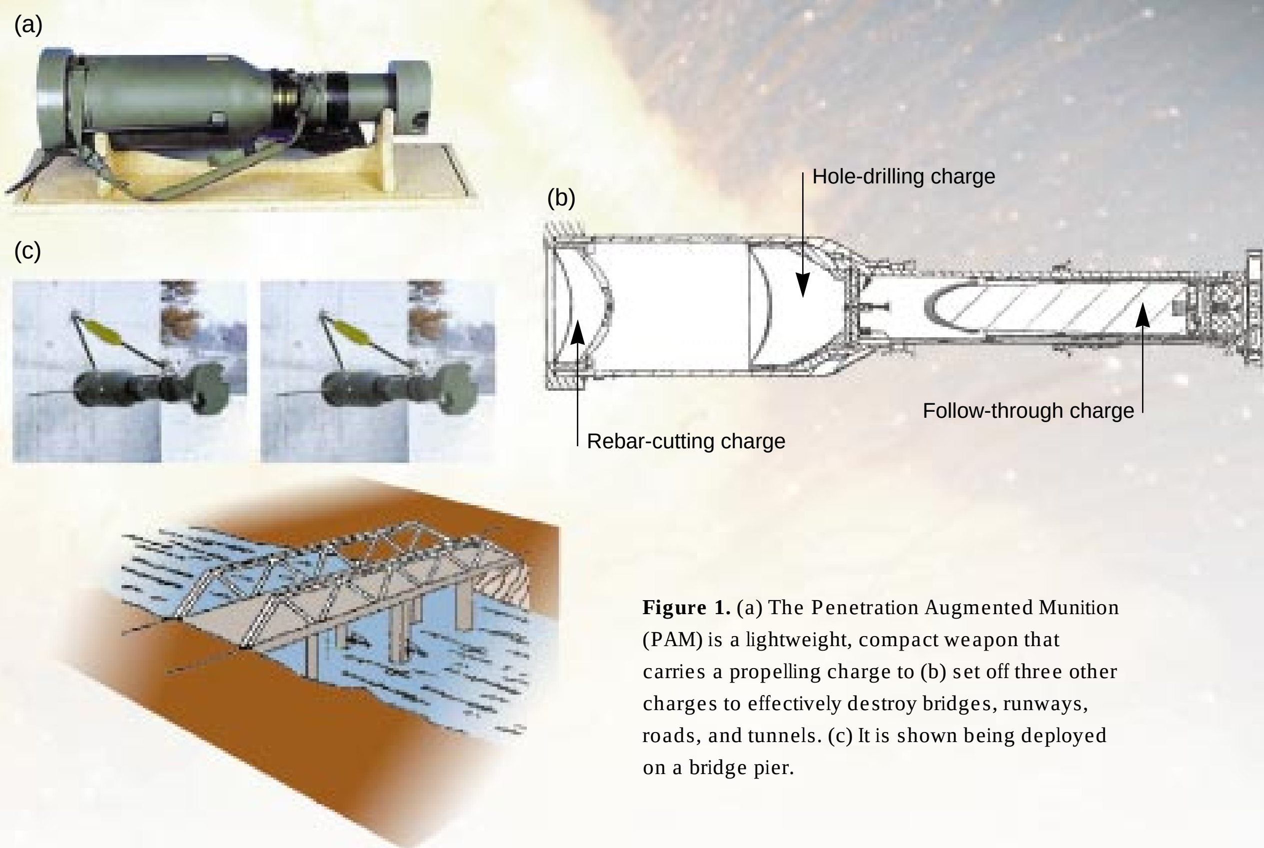


Figure 1. (a) The Penetration Augmented Munition (PAM) is a lightweight, compact weapon that carries a propelling charge to (b) set off three other charges to effectively destroy bridges, runways, roads, and tunnels. (c) It is shown being deployed on a bridge pier.

PAM, or Penetration Augmented Munition. Although compact and lightweight (approximately 35 pounds, 33 inches long), it contains the power of four explosive charges and when deployed, can effectively destroy bridges, runways, roads, and tunnels (Figure 1).

A typical demolition target for the soldiers is a bridge. To destroy it, they must detonate two PAM units simultaneously at the bridge pier. They trigger the PAMs' propelling charges and shoot the warheads directly into the structure. The motion of the propelling charge sets off each PAM's other three charges: one charge cuts through the bridge's concrete rebar, the second makes a deep, narrow hole in the bridge pier, and the third penetrates to the bottom of that hole and detonates. Objective accomplished. The soldiers have hindered enemy mobility.

The genesis of the multistage PAM can be traced to work during the 1980s on a two-stage munition system for the Air Force. Livermore scientists evolved a two-stage munition based on the work of a defense industry contractor into a warhead for a 2,000-pound laser-guided bomb. The Defense Advanced Research Projects Agency sponsored further development of a three-stage munition designed to crater airfield runways. The portable four-stage multicharge PAM—a demolition munition at once compact, light, and effective— was realized under the joint DOD/DOE MOU program.

During the fabrication and testing of the first PAM, the device would not work properly because the shock resulting from the rebar-destroying and hole-drilling charges caused the fuse in in the main penetrating charge to malfunction. Livermore scientists developed a fuse that could survive the explosive shocks and detonate the last charge at the appropriate time.

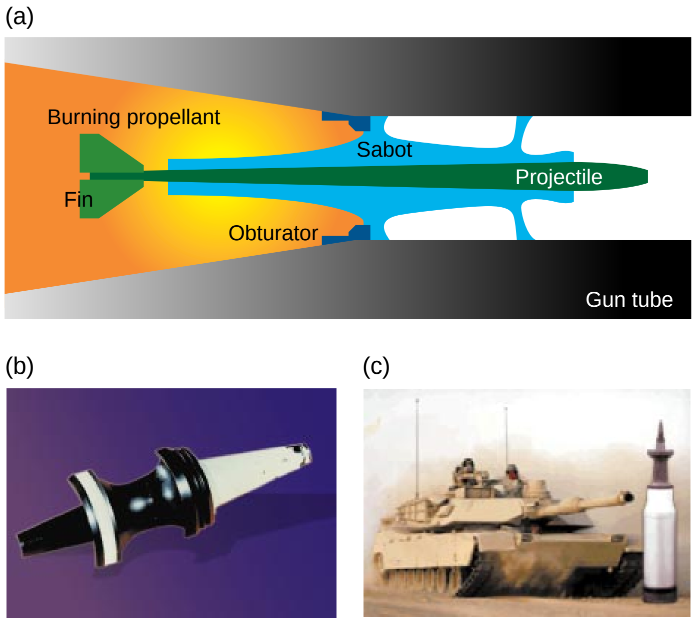


Figure 2. (a) A sabot transfers energy from the weapon propellant to its projectile. (b) Livermore's fiber-composite sabot is (c) part of the Army's weapon of choice for antitank warfare.

Michael J. Murphy, one of the developers of the device, says that the PAM has been designated by the Department of Defense as a "Type Classified Standard for Army Special Operational Forces Use," meaning that DOD has made a firm decision to produce and use it. It is now designated as the XM150. Engineering development, conducted at Alliant Techsystems and under U.S. Army sponsorship with Lawrence Livermore support, is complete.

Strong String and Glue

Engineers in Livermore's Mechanics of Materials Group, led by Steve DeTeresa, were part of a Lawrence Livermore–Army Research Laboratory team that developed a fiber-composite sabot for DOD use. A sabot is a lightweight carrier used both to position a missile or subcaliber projectile inside a gun tube and to transmit energy from the propellant to the projectile (Figure 2). DeTeresa says that the sabot works much like a person throwing a dart, where the thrower's arm movement acts as both the propellant-driving gas and the sabot's energy-gathering pusher (Figure 3).

In general, guns operate with a fixed mass to be propelled out of the gun's tube. The sabot is necessary to transfer propellant energy but is a parasitic weight in terms of projectile target performance. Reducing the sabot's weight allows greater projectile velocity. The weapons thus penetrate deeper, with more lethal results. But materials used to fabricate sabots can only be as lightweight as they are strong enough to withstand great pressures and loads during gun-tube acceleration. Previously, the lightest weight sabots were made of aluminum.

In the past, the search for lighter weight sabot materials focused on metal composites. But researchers were continually frustrated by failure—metal composites simply were too brittle. Attention then shifted toward polymer-based composites, which were being used extensively in thin structures for aerospace applications. Researchers began to consider fiber composites for complex shaped structures that needed to survive multidirectional stresses. Livermore material scientists were asked to help develop a new sabot based on these materials.

DeTeresa relates that some engineers refer whimsically to a fiber composite as "string and glue." It consists of high-strength carbon fibers, which must be laid down and oriented to yield maximal strength and handle maximal stress. Polymer is used to glue together layers of these fibers in a process similar to that used to manufacture plywood. When layers are glued together, the grains of adjacent layers are arranged either at right angles or at some wide angle to each other. Once a piece of the material has been fabricated, it can be machined into the required form. Fairly thick pieces that can withstand high three-dimensional stress are used for sabot material.

Although they have developed an effective, extremely lightweight sabot, development team members continue to investigate which material combinations and fiber architectures will provide ever-greater material strength. They are eager to understand the material's stress responses and failure modes completely, particularly because thin sheets of this material are used for safety-critical components in airplanes.

The team has developed models of fiber-composite materials and is simulating their performance using the Laboratory's DYNA and NIKE structural response codes. One of the models incorporates a misaligned fiber. By analyzing the effects of the imperfect fiber on material properties, the researchers can address how to prevent or minimize those effects. At the same time, they are investigating cheaper ways of producing fiber-composite material.

The Army, the largest consumer of advanced carbon fiber composites in the defense community, is using the fiber-composite sabot in the M829 A2 kinetic energy projectile, the weapon of choice for antitank warfare.

As a result of the sabot work, Livermore holds a patent on the fiber-composite sabot's structure and fabrication process. Livermore and the Army Research Laboratory have won an Army Service Award for developing the sabot. The Livermore engineers are the first non-DOD civilians to receive this award.

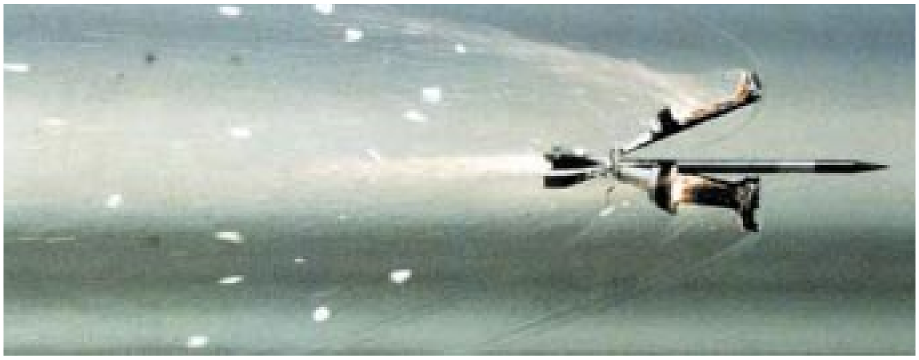


Figure 3. A sabot pushing the weapon projectile toward its target.

Code Optimizes Design

Computational modeling and simulation, already a key component of Livermore problem-solving capability, will become even more dominant as DOE's Accelerated Strategic Computing Initiative continues to increase computational speed and power. Not surprisingly, computer code development is flourishing at Livermore, and many scientists are wearing the dual hats of code developer and code user. Michael J. Murphy, who was involved in the design of the PAM, is one of them. He and Ernest Baker of the U.S. Army Armament Research, Development and Engineering Center have developed a code useful for optimizing warhead designs, including shaped charges (warheads encased in steel or aluminum and consisting of a metal cone, or liner, backed by high explosive). Murphy's code is called GLO (global local optimizer).

GLO directs physics code simulations to optimize the warhead design. It is a powerful tool that saves munitions designers time and produces robust results.

Two key steps are involved in GLO's work. First, it must incorporate a description of an optimum design, based on the kind and degree of damage that designers want the shaped charge to inflict. For example, the goal may be to create a hole of a specified size and depth in a certain target. GLO runs the physics codes and then compares the calculated hole profile with the desired hole profile. Figure 4 shows a simulation of the shaped-charge detonation, jet formation, and subsequent penetration into a target.

The second step optimizes the design using the results of the comparison from the first step. GLO is repeatedly linked to the physics codes and adjusts the shaped-charge design until it obtains as close a match as possible to the specified hole profile. Often, the code that GLO directs is the two-dimensional hydrodynamic code, CALE (C-language arbitrary Lagrangian–Eulerian), in which is embedded a number of parameters defining the overall size and geometry of the shaped charge. For each design considered, GLO specifies the values of the parameters that define the geometries of the shaped-charge explosive and metal cone. CALE calculates the mass and velocity distribution of the jet for each shaped-charge design. GLO's parameters change over the series of calculations to describe different configurations of the shaped charge.

The CALE calculations result in a definition of the geometry of the jet of metal formed when the cone of a particular shaped-charge configuration is compressed by the explosive charge. This definition is used by an analytic penetration code to calculate the jet penetration and the resulting target hole profile.

In a typical overnight optimization run, GLO can evaluate some 250 sets of parameters. The optimum design configuration is selected from these sets. Murphy says that GLO is a "very dedicated assistant working unceasingly to generate numerous iterations of shaped-charge configurations."

From TIGER to CHEETAH

Ron Atkins, head of Livermore's Energetic Materials Center, notes that it's usual for inventors to first try to make their inventions work and then to try to understand how they work. That is certainly the case with high-explosive detonations. Scientists have worked for over a century to understand the physics of detonation properties of explosives long in use. Atkins coordinates a group of projects attempting to expand that understanding further in order to design safer and more powerful explosives as well as to formulate new explosives with properties tailored to specific applications.

One ongoing project is a code that simulates detonations and predicts the results of detonating a specific mixture of chemical reactants. The code is CHEETAH, a fast, scientifically rigorous descendant of Livermore's TIGER and RUBY thermochemical codes. Chemist Laurence Fried and

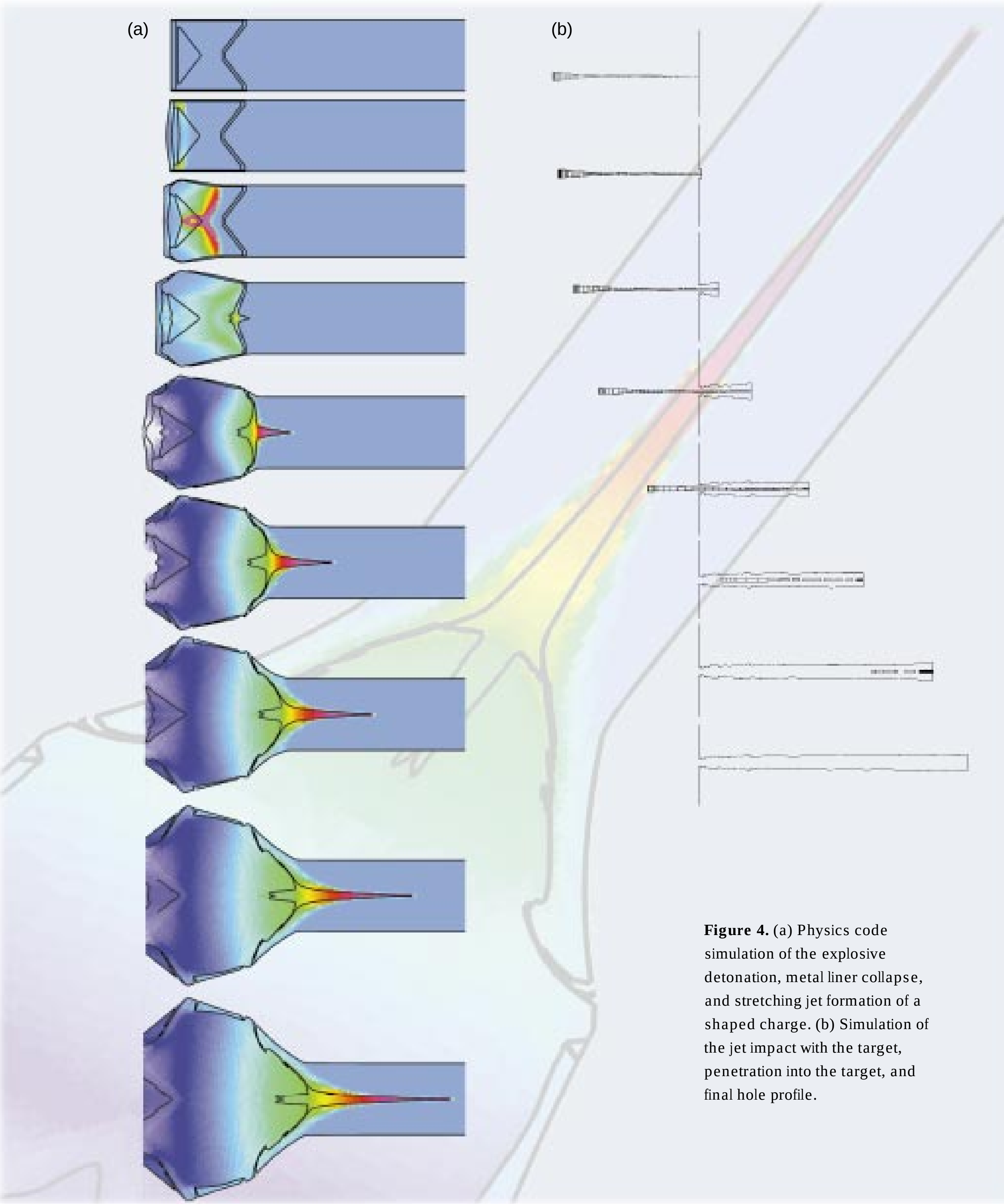


Figure 4. (a) Physics code simulation of the explosive detonation, metal liner collapse, and stretching jet formation of a shaped charge. (b) Simulation of the jet impact with the target, penetration into the target, and final hole profile.

colleagues designed CHEETAH to allow explosives formulators to predict different starting molecules and formulation performance and, hence, to design optimized explosives with specific characteristics.

The newest version of CHEETAH (described in *S&TR*, November 1997, pp. 21–23) is a particularly popular tool for explosives formulators in that it is more user friendly than earlier versions and includes a database of 200 chemical starting reactants and 1,000 possible products. This database saves a user the inconvenience of looking up thermodynamic constants for each chemical. More significantly, the new CHEETAH tracks chemical reactions down to the molecular level to obtain very accurate predictions of the velocity and energy of the detonation.

The earlier version of the code assumed that all reactions occur instantaneously, that all reaction ingredients are consumed completely, and that thermal equilibrium is reached at the same time. In reality, the chemistry of a detonation is much more varied and complicated. Many different molecules are involved, with some reacting more slowly than others, and those slow chemical reactions require a long time to achieve thermochemical equilibrium. Moreover, a variety of chemical reactions takes place during the explosive decomposition of mostly large, energetic-material molecules into small, simple product molecules. The explosive reaction products undergo material changes and occupy different states of pressure, density, and velocity. All these reactions must somehow be represented in the codes to obtain accurate predictions of detonation pressure, velocity, and energy of the detonation.

Fried implemented a kinetic detonation model, based on the Wood–Kirkwood detonation theory, which provides equations of state for complicated mixtures of detonation product molecules. This model accounts for the microscopic mechanical and thermal processes that occur in shock initiation and detonation, and it calculates chemical reaction rates at the molecular level. The calculational results showed CHEETAH effective for modeling many features of slowly reacting explosives.

Fried and his colleagues are continuing to improve CHEETAH by including the effects of high pressure and high temperature on chemical kinetics. They will thus be able to model more complex, slow detonation behavior such as shock initiation, hot-spot formations, and failure processes. They are also launching an effort to link CHEETAH to hydrodynamic codes so they can create even more complete models of high-explosive detonation. This effort will serve not only DOD explosives formulation work but also help Livermore fulfill its responsibilities to the DOE Stockpile Stewardship Program. In the case of CHEETAH, DOE resources that were leveraged to benefit DOD are in turn being leveraged to benefit DOE missions at Livermore.

Codes to Assess Safety

In addition to CHEETAH, other Livermore codes are proving useful for evaluating explosive performance and effects. For example, CALE is used in Laboratory projects to assess a variety of explosive and nonexplosive problems. Livermore scientists are using it for such applications as simulations to evaluate safety concerns at missile launch sites.

In April 1986, at 8.7 seconds into the launch of an Air Force Titan T34D-9 space vehicle from Vandenberg Air Force Base, one of the vehicle's solid rocket boosters failed. A portion of the booster came loose and fell back down from an altitude of 18,000 feet at a speed of 320 feet per second, hitting the ground sideways. That piece weighed an estimated 130,000 pounds, including 110,000 pounds of solid rocket propellant. At impact, it exploded and burned, releasing between 7 and 30 percent of the propellant energy and causing significant damage at Vandenberg.

This launch was representative of the one out of every 30 launches, on average, that ends in failure. Many of those failures result in explosions when unburned motor segments fall back to the ground. Launch safety officials need to know just how destructive and far-reaching such accidents can be. But until recently, they have had only intuition and sparse data to rely on for making their safety judgments.

The upgrade of the solid rocket motor of Titan IVB, which uses a new propellant and a new motor configuration with much longer and more massive booster segments, prompted the Air Force to initiate a project to better understand fallback accidents. One part of that program is being performed by chemical engineer Jon Maienschein and his colleagues. They have developed a computer model that describes in detail the propellant response to fallback accidents and predicts the extent and effects of their energy releases. Simulations using this model will enable launch safety personnel to assess and provide safeguards against the hazards of these accidents.

The model developed by Livermore scientists is called PERMS (propellant energy response to mechanical stimuli). One part of the model describes how a shock front, generated by the impact of a falling booster rocket, causes ignition and burning of explosive material. Data about shock initiation used in the model were obtained through field tests (conducted by Phillips Laboratory at Edwards Air Force Base) that used large explosive boosters to generate shocks from 30,000 to 40,000 times atmospheric pressures over a long duration (Figure 5). Experimenters shocked a sequence of propellant samples up to 5 feet in diameter. Propellant mass in this test was over 48,000 pounds. From these data, they developed a model for the initiation mechanisms and estimated the diameter of propellant necessary to support steady propagation of a reactive shock wave.

The other component of the model is a description of how the booster segment fragments at impact. Fragmentation creates additional burning surfaces as the propellant deforms. The rate at which explosive burning occurs is related to the size and hence surface area of the fragments. Input data for fragmentation and burning rate models were derived from laboratory experiments. The resulting models were validated using large-scale (thousands of pounds of propellant) tests with either steel impact plates or hollow imploding cylinders to simulate the propellants at pressures less than 15,000 times atmospheric pressure.

These two descriptive components form the PERMS model, which is implemented in the CALE hydrodynamic code. Once the conditions of the booster fallback are specified, the model calculates the propellant reactions, considers fragmentation effects, and tracks the progress of reactions over time. The force of the propellant reaction is translated into the equivalent TNT energy release.

Adding Capabilities to the Code

PERMS provided both significant new information about propellant hazards and remarkably good estimates of the explosive behavior that results from both the nose-on and side-on impacts of booster motors falling from the sky. Now, its developers want to look at historic data of incidents in which motor segments fell in orientations where three-dimensional effects are important. To study those effects, they would use the three-dimensional Lagrangian–Eulerian code called ALE3D, which has its origins in Livermore's DYNA3D code.

ALE3D has recently been improved to better model the response of energetic materials to heat and explosive processes. It is now undergoing testing by Laboratory developers Albert Nichols and Richard Couch. The upgraded ALE3D has additional thermal and chemical capabilities as well as calculational options that allow it to accurately depict events over time scales ranging from microseconds to days. It is designed to simulate a typical fire scenario, for example, by following the transport of heat from the exterior of an explosive device to the explosive itself, followed by the thermal decomposition of the explosive. The decomposition gradually changes the material properties of the explosive and induces motion. Depending on how the explosive is

Figure 5. Data for describing the initiation and burning of explosive material are obtained through large-scale tests performed at Edwards Air Force Base, where propellants were shocked at 30,000 to 40,000 times atmospheric pressure, which caused them to explode. (Photograph courtesy of Dr. Claude Merrill, Phillips Laboratory, Edwards Air Force Base.)

confined, the simulation will then depict a slow, relatively benign response or a fast, catastrophic explosion, as happens in real life.

The code has successfully simulated a U.S. Navy "cookoff" safety test in which a slowly heated high explosive is deformed over a long time span (see *S&TR*, June 1997, p. 11). It has also been used in simulations to investigate the use of electron beams for clearing land mines (Figure 6).

The developers are planning to do more testing, using different material models for the chemical reactions and mixtures associated with the explosive processes. They also look forward to using ALE3D to solve other kinds of problems associated with the forging, casting, and extruding processes of manufacturing.

Continuing the Collaboration

As Lawrence Livermore scientists and engineers fulfill their DOE missions, they often find their work tying well to DOD needs and applications. Thus, providing products and services to DOD is both a natural extension of their scientific and technical work as well as a fruitful leveraging of research funding. Aside from accruing advantages to both agencies and the Laboratory, this leveraging ensures that science and technology at Lawrence Livermore are fully in step with national security and defense requirements, whatever they may be.

—Gloria Wilt

Key Words: ALE3D, CALE, Cheetah, explosives, Department of Defense (DOD), fiber-composite sabot, fuse, GLO (global local optimizer), Memorandum of Understanding (MOU), Penetration Augmented Munition (PAM), PERMS (propellant energy response to mechanical stimuli), safety assessment, warhead.

For further information contact Cory Coll (925) 422-2103 (coll1@llnl.gov).

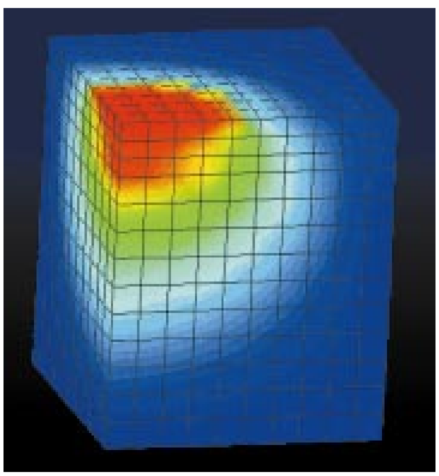


Figure 6. Recently, a representative of the U.S. Navy used Livermore's ALE3D code to investigate the use of electron beams to clear land mines. The thermal-only model shown here is a snapshot in time of a circular region of a land mine being radiatively heated by an electron beam.

About the Scientist

CORY COLL received his A.B. in physics from Johns Hopkins University and his Ph.D. in physics from the University of Pennsylvania. After working at Sandia National Laboratories, California (1974 to 1981), he joined Lawrence Livermore's weapons program as a design physicist and participated in three underground tests at the Nevada Test Site. His career at Livermore was interrupted between 1984 and 1986 when he became, first, staff to the Deputy Undersecretary of Defense for Strategic and Nuclear Forces and, later, a program manager at the Defense Advanced Research Projects Agency (DARPA).

Coll returned to Livermore in 1988 as deputy program manager for Advanced Applications in the Laser Programs Directorate and moved to the Laboratory Director's Office in 1992. Currently, he is staff to the director of the Department of Defense Programs Office at the Laboratory.

The Revelations of Acoustic Waves

Livermore researchers are developing advanced techniques to extract information from acoustic signals.

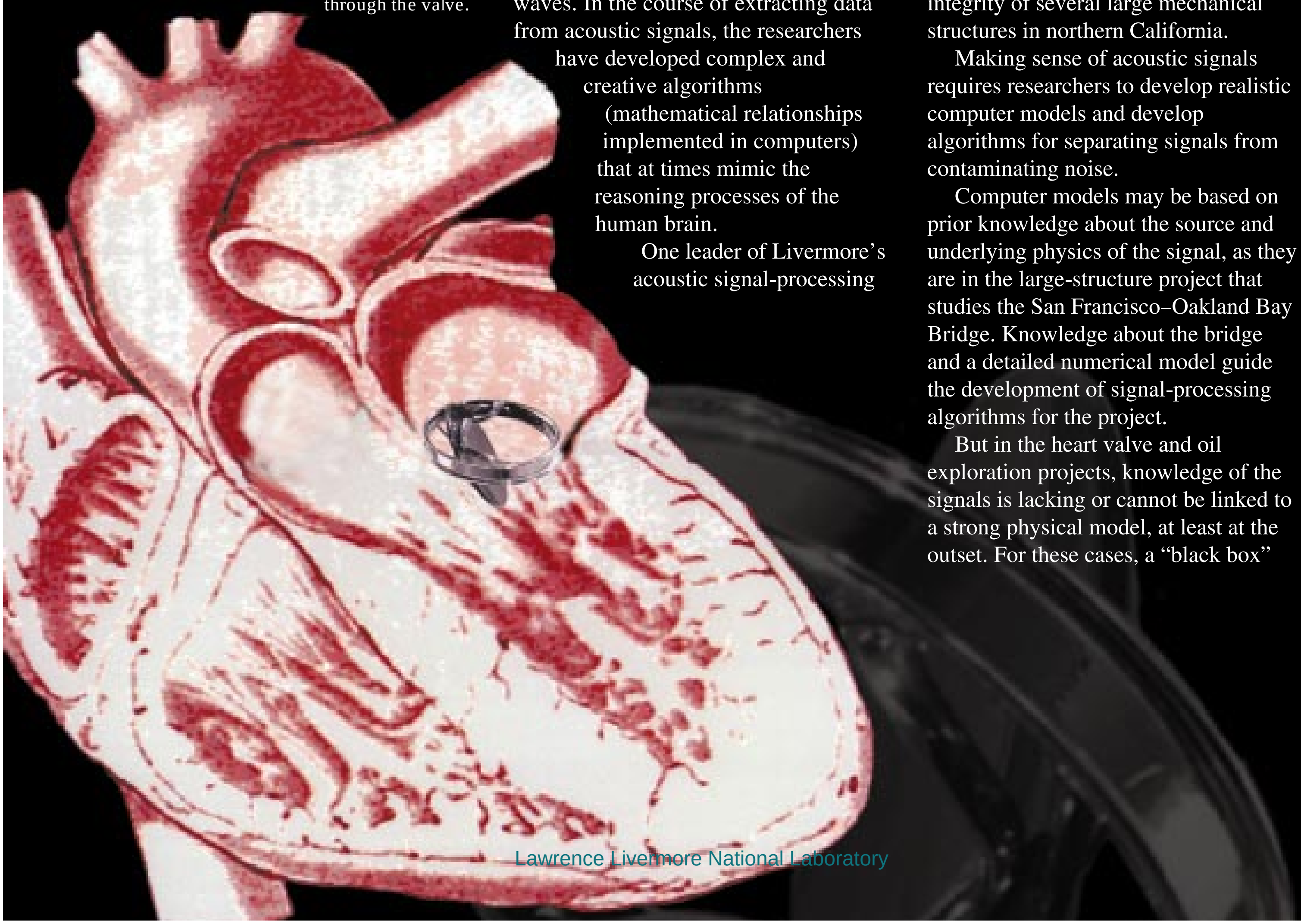


Figure 1. A heart with an artificial heart valve. The valve consists of a disk held in place by two struts that let it flip open and shut during pumping of blood through the valve.

FROM analyzing speech to recording earthquakes, tracking submarines, or imaging a fetus, measuring and analyzing acoustic signals are increasingly important in modern society. Acoustic waves are simply disturbances involving mechanical vibrations in solids, liquids, or gases. Lawrence Livermore researchers are developing advanced techniques for extracting and interpreting the information in these waves. In the course of extracting data from acoustic signals, the researchers have developed complex and creative algorithms (mathematical relationships implemented in computers) that at times mimic the reasoning processes of the human brain.

One leader of Livermore's acoustic signal-processing research is electronics engineer Greg Clark, who is involved in three disparate acoustics projects: heart valve classification, where acoustic signal processing is determining whether an artificial heart valve is intact or needs replacing; oil exploration, where Livermore experts are automating a key procedure used for locating undersea oil deposits; and large-structure analysis, where Livermore is preparing to use acoustic wave vibrations to assess the integrity of several large mechanical structures in northern California.

Making sense of acoustic signals requires researchers to develop realistic computer models and develop algorithms for separating signals from contaminating noise.

Computer models may be based on prior knowledge about the source and underlying physics of the signal, as they are in the large-structure project that studies the San Francisco–Oakland Bay Bridge. Knowledge about the bridge and a detailed numerical model guide the development of signal-processing algorithms for the project.

But in the heart valve and oil exploration projects, knowledge of the signals is lacking or cannot be linked to a strong physical model, at least at the outset. For these cases, a "black box" model, derived only from the data (that is, input and output signals), without details of the underlying physics, is used to guide the development of algorithms.

For the three projects, Clark uses advanced signal-processing techniques, including statistical neural networks, which are systems of computer programs that approximate the operation of the human brain. Current uses for neural networks include predicting weather patterns, interpreting nucleotide sequences, and recognizing features in images. In a supervised learning mode, a neural network is "trained" with large numbers of examples and rules about data relationships. This training endows the network with the ability to make reasonable yes–no decisions on whether, for example, a geologic data plot indicates a geologic layer that could mark the presence of an oil deposit, or whether energy in a frequency spectrum of a recording signifies a damaged artificial heart valve.

In every acoustic signal project, vital data must be separated from noise that contaminates and inevitably degrades signal quality. The noise is caused both by the surrounding environment and the very system recording the signals. For example, the remote system designed by Livermore engineers for monitoring large structures can introduce noise into the signal in the course of relaying it over cellular phone lines to the Laboratory for analysis. In another example, the delicate sounds of a heart valve flipping up and down can be buried by acoustic scattering inside the body. Similarly, multiple ricocheting reflections from underwater explosions can contaminate the precise data needed to isolate geologic strata.

Often, Livermore engineers can reduce noise by using filters for certain frequency spectra. For example, if they know that the structural failure of a bridge will cause a vibrational response at 5 hertz (cycles per second), they can design a filter to monitor the energy content in that part of the frequency spectrum.

Hearing the Heart

For medical diagnostic applications, acoustic signals provide advantages in being noninvasive and harmless. These advantages are being exploited by a team of Livermore engineers who are developing an acoustic processing technique for sifting through a seeming cacophony of heart and body sounds to isolate the few telltale signals of a faulty artificial heart valve. Their technique would spare patients, many of them elderly, from open-heart surgery to determine if an artificial valve needs replacement.

The four valves of the human heart continually open and close, allowing blood to be pumped through the heart's four chambers. When a valve becomes diseased, pumping ability decreases. Prosthetic heart valves correct this deficiency and extend the life spans of many people with serious heart conditions. But Livermore engineer and project co-principal investigator Jim Candy points out that prosthetic valves, while extremely reliable, are eventually susceptible to long-term fatigue and structural failure, as might be expected from any mechanical device operating over a long time.

The Livermore experts are working to find ways to identify faulty heart valves made by one medical device manufacturer whose heart valves were implanted from 1979 to 1986 in 86,000 patients. To date, more than 600 of these valves have failed, and more than 300 people have died. A court-appointed panel is funding research to find the best screening technique or combination of techniques to determine, with a high degree of accuracy, if one of the manufacturer's implanted valves is failing. Livermore's acoustical processing method is a leading technique. Tests show it is more effective than x-ray procedures, which cannot capture a clear image of moving heart valves.

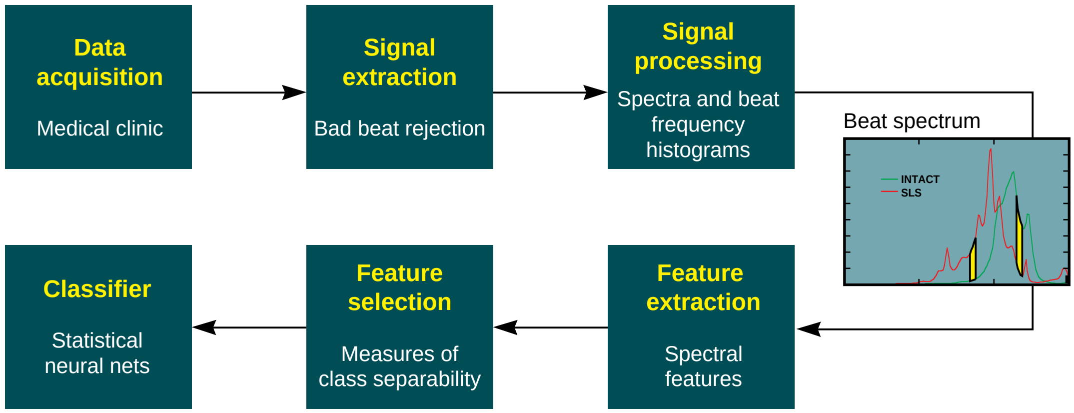
An artificial heart valve is essentially a small ring with two small struts welded to it, opposite each other. One is an inlet strut, and the other, an outlet strut. Each is two-legged. The two struts hold a disk that flips up and down to open and close the valve (Figure 1).

Over time, the struts can develop cracks at or near their weld joints and break loose from the ring. Livermore signal experts are trying to detect heart valve failure indicated by one leg of a strut breaking loose from the ring. (If both legs break loose, the valve loses control of blood flow to the heart, leading to death in two of three cases.)

To determine the condition of an artificial valve, the Livermore researchers use acoustic signals of recipients' heart valve sounds that have been recorded at clinics using high-sensitivity microphones. They first collect a database of heart valve sounds of about 100 beats per patient, discarding heartbeats with too low a signal-to-noise ratio or with characteristics statistically different from the other beats. The team uses algorithms to classify the recordings as indicative of a valve that is either intact or not. The algorithms scrutinize the frequency spectra of each opening sound of a valve and select key features of the spectra, usually parts of certain peaks. A statistical pattern classifier—in this case, an artificial neural network trained on the recorded acoustic fingerprint of known faulty valves—decides whether the valve is indeed damaged (Figure 2).

The team's efforts are focused on the sounds made when the valve opens—sounds caused by the disk hitting the outlet strut—because those sounds yield direct information on the condition of

Figure 2. The process for classifying heart valves includes acquiring clinical data, rejecting heartbeats that have low signal-to-noise ratios or are statistical outliers, estimating signal spectra, extracting the spectral features to be used to discriminate between intact and nonintact valves, selecting only the most important features, and finally, classifying the valves as intact or not.



the strut. A closing valve, in contrast, causes the entire ring to vibrate, and that masks the strut's vibrations. Clark compares the sound of a faulty valve to the thud of a cracked bell.

Unfortunately, the opening sounds have much lower intrinsic signal levels than the valve's closing sounds. Candy notes that measuring heart sounds noninvasively in this noisy environment puts significant demands on the signal-processing techniques to extract the desired signals, especially when the data of interest last only 10 to 20 milliseconds. "Finding the opening sound caused by a strut separating from the heart valve is more difficult than searching for a single violin string that is out of tune in an entire orchestra," Candy says.

Clark points out that every valve recording is distorted by the body cavity and the recording process itself. That is why Livermore researchers are conducting studies at a U.S. Navy laboratory in San Diego in which acoustic sensors are submerged in water while collecting the sounds of valves that have been surgically removed from patients. This submersion isolates the pure sounds of both intact and damaged valves. "The test will allow us to measure the heart valve sounds without the acoustic scattering effects caused by the body," Clark says. "The pure data should allow us to mitigate the distortion in patient recordings."

Listening for Oil

Some of the same approaches taken to analyze the subtle sounds of human heart valves are used to locate the interfaces of undersea geologic layers, particularly slate and sandstone layers where oil tends to accumulate around salt domes, or "plugs" (Figure 3). Mapping these geologic layer interfaces (called event horizons or, simply, events) helps geologists decide where to site oil drilling rigs.

One such mapping project is sponsored by the Department of Energy National Gas and Oil Technology Partnership. It is a cooperative effort involving Shell Oil of Houston, Texas, as Lawrence Livermore's industrial partner and a Ph.D. student from the University of California at Davis who is being supported by the Laboratory to work on the project.

The purpose of the Livermore–Shell–UC Davis project is to automate a technique used to analyze acoustic oil

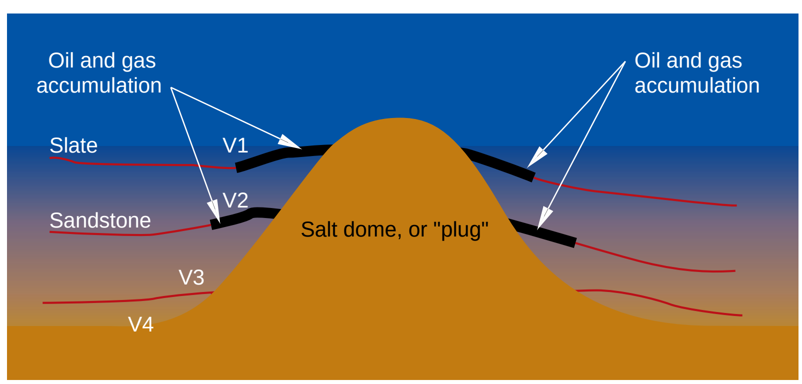


Figure 3. Acoustic techniques can be used to locate the interfaces between undersea geologic layers (usually slate and sandstone) and salt domes, where oil tends to accumulate.

exploration data. The current technique is a significant bottleneck because it is performed manually, at great cost in time and money. The project's goal is to reduce manual effort to only about 0.1 percent of the data processed. Current results show that this goal is achievable, says Clark.

Oil companies obtain acoustic signals by having a ship set off underwater explosions that generate acoustic waves that reflect from geologic layers as deep as 15 to 20 miles under the sea. A 5-mile-long linear array of some 100 hydrophones, which is towed by the ship, measures the signals (Figure 4).

The signals are organized into two-dimensional images, called common reflection point (CRP) panels, which represent vertical sections of the earth (Figure 5a). The panels show multiple reflections of the acoustic waves as they bounce off various strata of earth (Figure 5b). "You get a horrendous number of reflections," says Clark. "It gets very messy to sort out."

Sorting out the reflections depends on correcting for the velocity of the sound waves as they travel through different layers of the earth. If the velocity computer model is correct, the imaged events appear as approximately straight horizontal (flat) lines in the CRP panel, because the true depth of the event horizon is approximately constant across the panel.

If, as typically occurs, the initial velocity computer model is incorrect, the event depths vary across the panel and do not appear flat. As part of an iterative velocity estimation process, an expert must visually inspect the panels to pick out event locations manually. The expert's picks are then used as input to refine the velocity model. This process is repeated several times, until the model produces events imaged as flat lines. The corrected panels are combined to obtain a two-dimensional image of the subsurface strata to help geologists determine where to site an offshore drilling platform.

When Clark inspected the CRP panels at Shell facilities in Houston, he suggested a new approach for analyzing reflection data. Instead of analyzing one signal or a few signal traces at a time, as is conventionally done, he proposed treating the set of 45 traces that forms a CRP panel as a single image. "I pointed out that if you treat the panel as an image, there's a whole set of literature and a lot of powerful tools available to you," he said (Figure 5c).

The Livermore team developed a technique that breaks the panels into small pixels (picture elements) to determine if the data represented within each pixel are part of an event or simply background noise. The technique uses advanced algorithms from the areas of automatic target recognition, computer vision, and signal–image processing. For example, using algorithms similar to those employed for computerized military target recognition, the technique

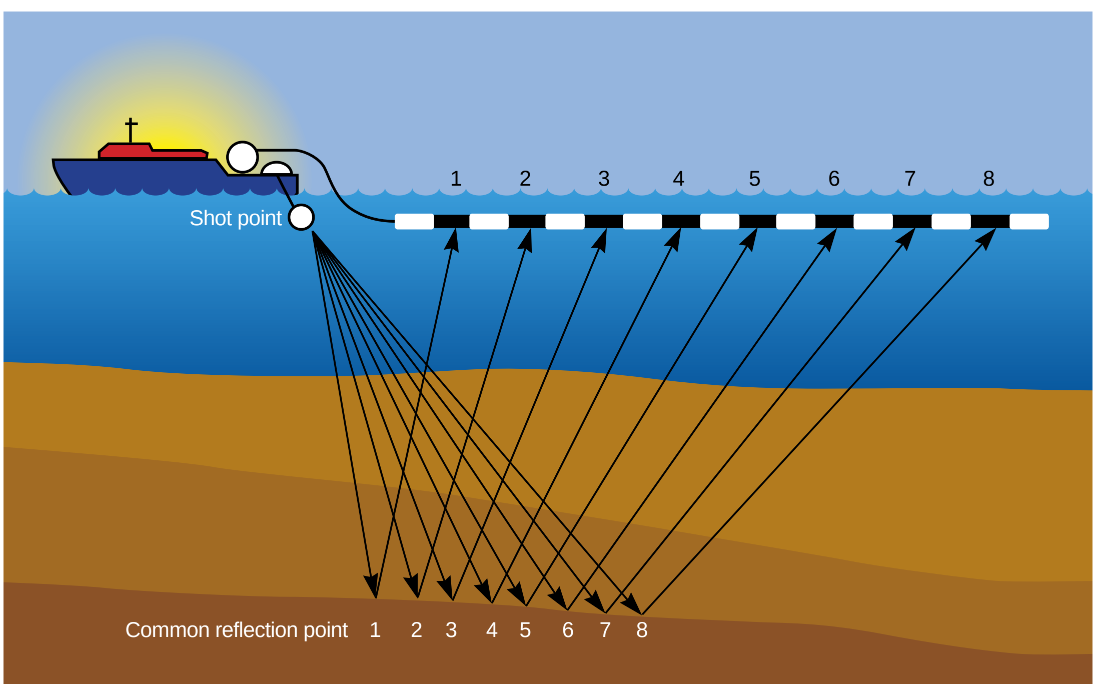


Figure 4. Underwater explosions are set off to generate acoustic waves that reflect off geologic layers and are received by a linear array of equally spaced hydrophones.

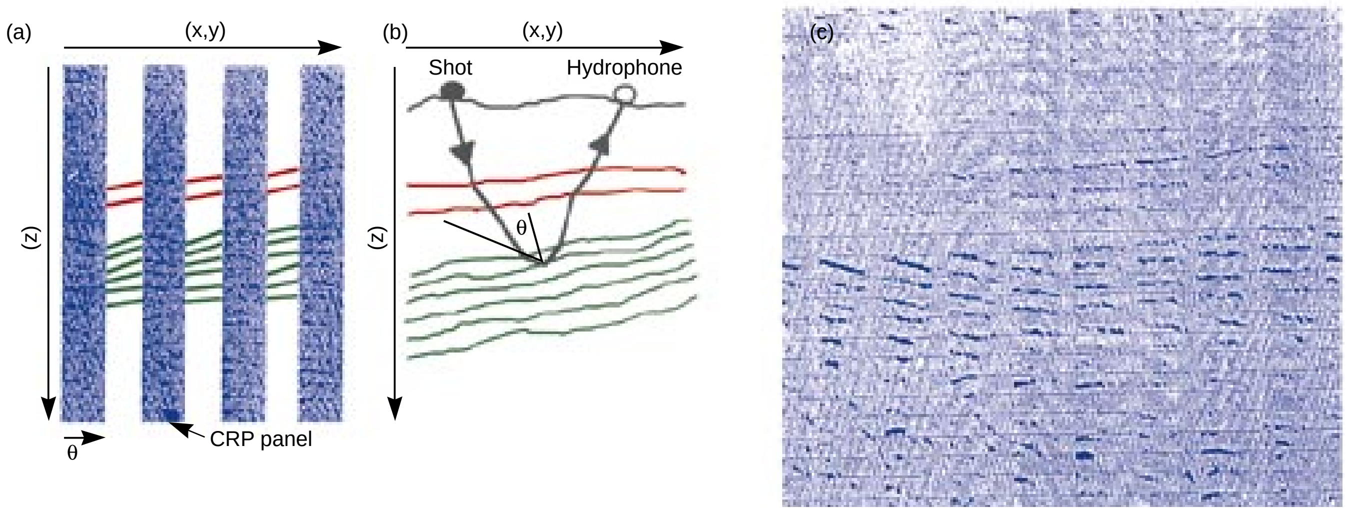


Figure 5. (a) A series of common reflection point (CRP) panels that represent vertical sections of the earth. (b) A depiction of explosive shots causing the wave reflections that are recorded by hydrophones and imaged into CRPs. (c) The CRP panels plotted side by side to form a mosaic.

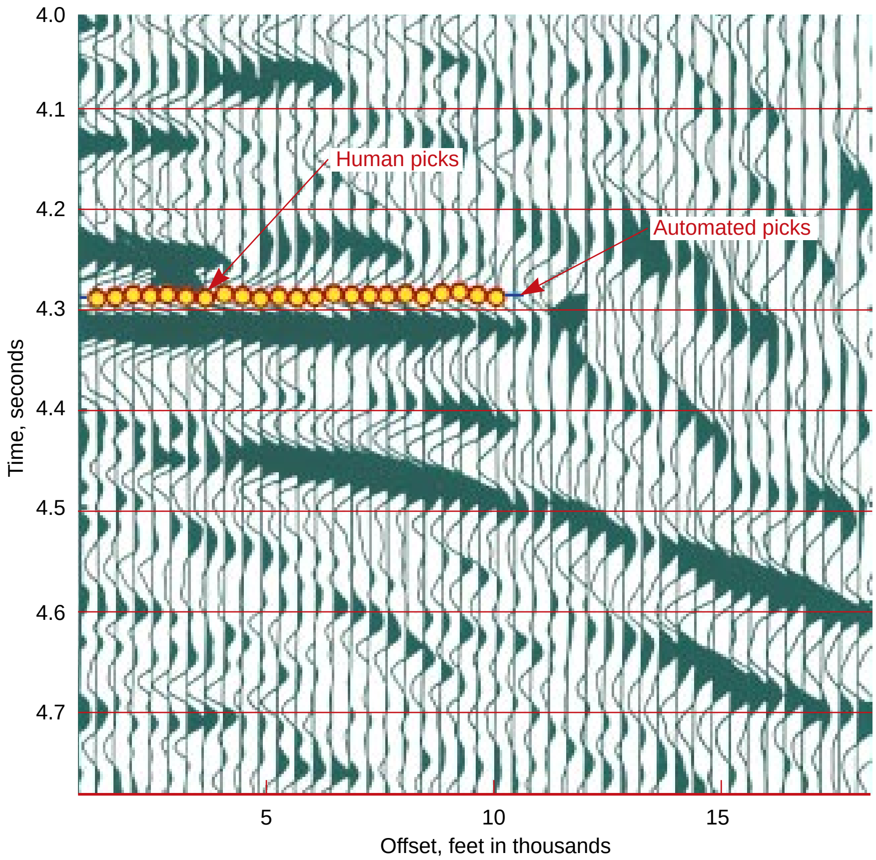


Figure 6. Results of Livermore's automated process for picking out geologic layer interfaces (called events) compare favorably with those attained by experts. The circles depict manual picks, while the blue line, barely visible behind the circles, depicts the automated picks. The manual picks and automated picks overlap so closely they are hard to differentiate.

scrutinizes the neighborhood of each pixel at various orientations and scales and looks for common features with neighboring pixels. Whenever possible, prior knowledge of known events is incorporated into the procedure. The results of the Livermore process compare favorably with those attained by experts (Figure 6).

Clark has made many trips to Shell to collaborate with their scientists on the project. "It's been a wonderful marriage of disciplines," he says. "I introduced them to a lot of advanced signal-processing techniques, and they educated me about their world of exploration geophysics." Clark's Ph.D. research involved analysis of seismograms for Livermore's Comprehensive Test Ban Program, so he already had an elementary geophysical background.

Shell Oil estimates that the Livermore work will significantly affect the oil industry. Shell's current implementation of the Livermore algorithms already reduces data-picking time from about one work day to about 90 minutes. Once the software is completely converted from research code to production code, Shell estimates the cost of performing a single velocity analysis could be reduced from $75,000 and 12 weeks to $6,000 and one week. An oil company performing 100 velocity analyses per year could save nearly $7 million annually. Potential annual savings for the U.S. oil industry could amount to roughly $140 million.

Clark points out that it costs about $1 billion to erect an oil platform in the Gulf of Mexico. Such costs make it crucial to respond quickly to business opportunities. The Livermore signal-processing techniques, providing time savings of a factor of 12, could significantly enhance the industry's responsiveness.

Vibrational Fingerprints

Acoustic signal processing may also make it possible to analyze vibrations and thus assess large mechanical structures for damage after earthquakes or other destructive events. One Livermore project is combining signal processing with advanced numerical models and new remote monitoring systems to better understand large structures and provide a unique way to quickly monitor them for damage.

"Our task is similar to that of the heart valve project: use sophisticated signal processing to enhance our understanding of the way large structures vibrate to find out if there is damage," says project leader and mechanical engineer David McCallen.

There is a critical need for a speedy method to assess the integrity of a structure after an extreme event, adds McCallen, who has worked with Caltrans (California's Department of Transportation) on earthquake-related projects. Current procedures require lengthy, largely visual inspections.

McCallen readily acknowledges the technical challenges of using vibration measurements to determine the health of a structure. "We're asking a lot of our signal-processing people," he says. "We're telling them, we'll give you enough data and insight into the structure so it won't be a black box situation, and we want you to tell us if there is damage, what it is, and where it is."

The Livermore project involves three northern California case studies: the Bixby Creek Bridge in Big Sur, the San Francisco–Oakland Bay Bridge, and the National Ignition Facility (NIF), the world's largest laser under construction at Lawrence Livermore. Each structure previously has been studied at Livermore; as a result, a detailed numerical model exists for each (Figure 7).

The numerical models provide information useful for designing sensors (accelerometers) that Livermore researchers will install on large structures for remote monitoring. The models indicate what frequencies are of interest and also

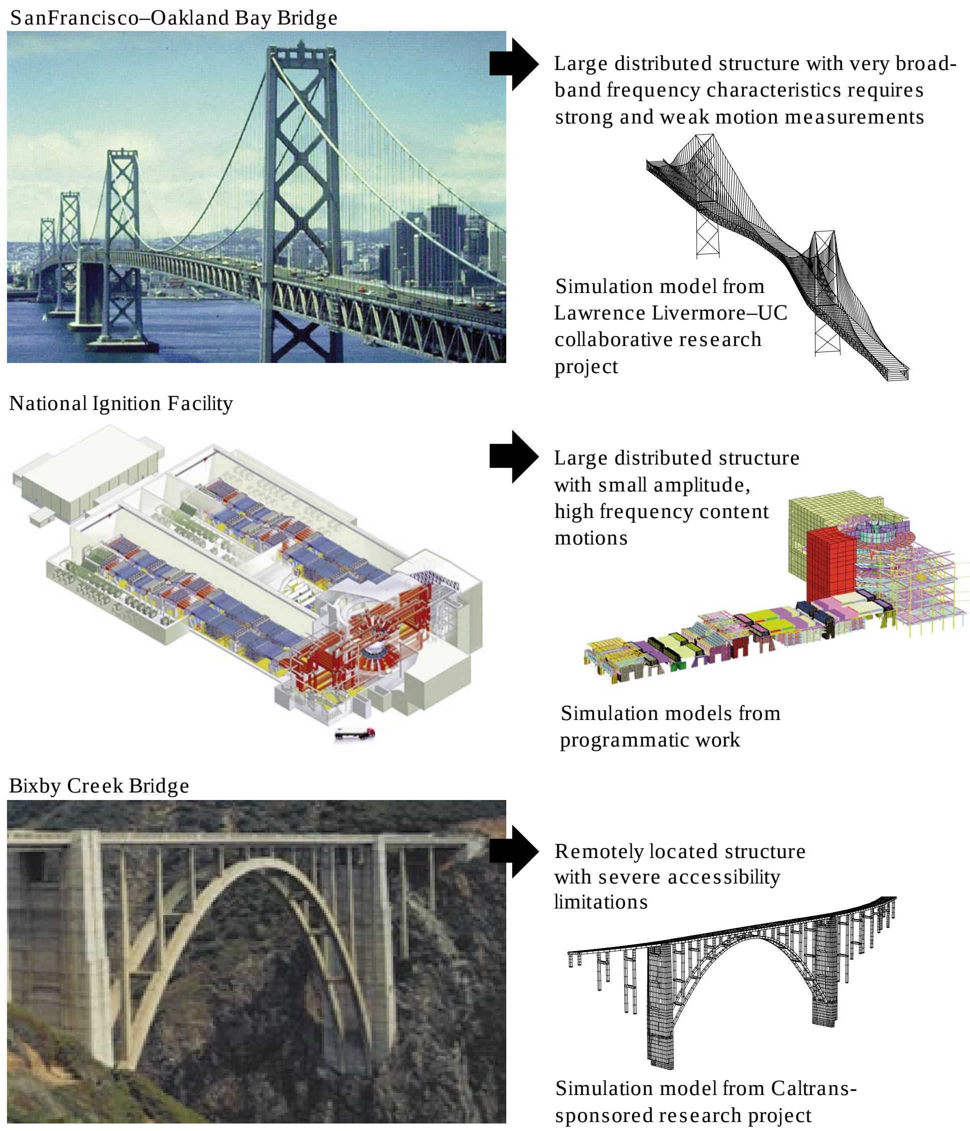


Figure 7. Livermore's detailed numerical models of three large structures are the basis for developing algorithms that analyze acoustic wave vibrations to determine whether these structures have sustained damage in an earthquake or other extreme event.

help determine the best locations for the sensors.

The monitoring system developed by Livermore engineers will continuously record, time stamp, and store sensor data. Researchers can contact the system at any time by cellular phone to download the data for analysis.

In developing signal-processing algorithms, Clark and colleagues integrate data from the sensors, models of sensor noise and the structure's unique environment, and a state–space numerical model. State–space models (common in electronics engineering) transform standard finite-element computer models (common in mechanical engineering) to render them more suitable for signal processing.

The resulting algorithms compare numerical model simulations with measurements of the real structure. A discrepancy between the two is a sign that the structure has suffered damage. Future algorithms will attempt to determine the source of discrepancies between the numerical model and the structure. Statistical classifiers, including artificial neural networks, could then come into play to classify what kind of damage the structure has sustained.

Data were collected recently to test the ability of signal-processing algorithms to detect differences between the numerical model and the actual structure. An experimental structure at the Nevada Test Site, a scale model of a five-story building some 14 feet tall, was the testbed for verifying these algorithms (Figure 8).

Engineers used the experimental structure both to evaluate the sensor systems and to acquire data for

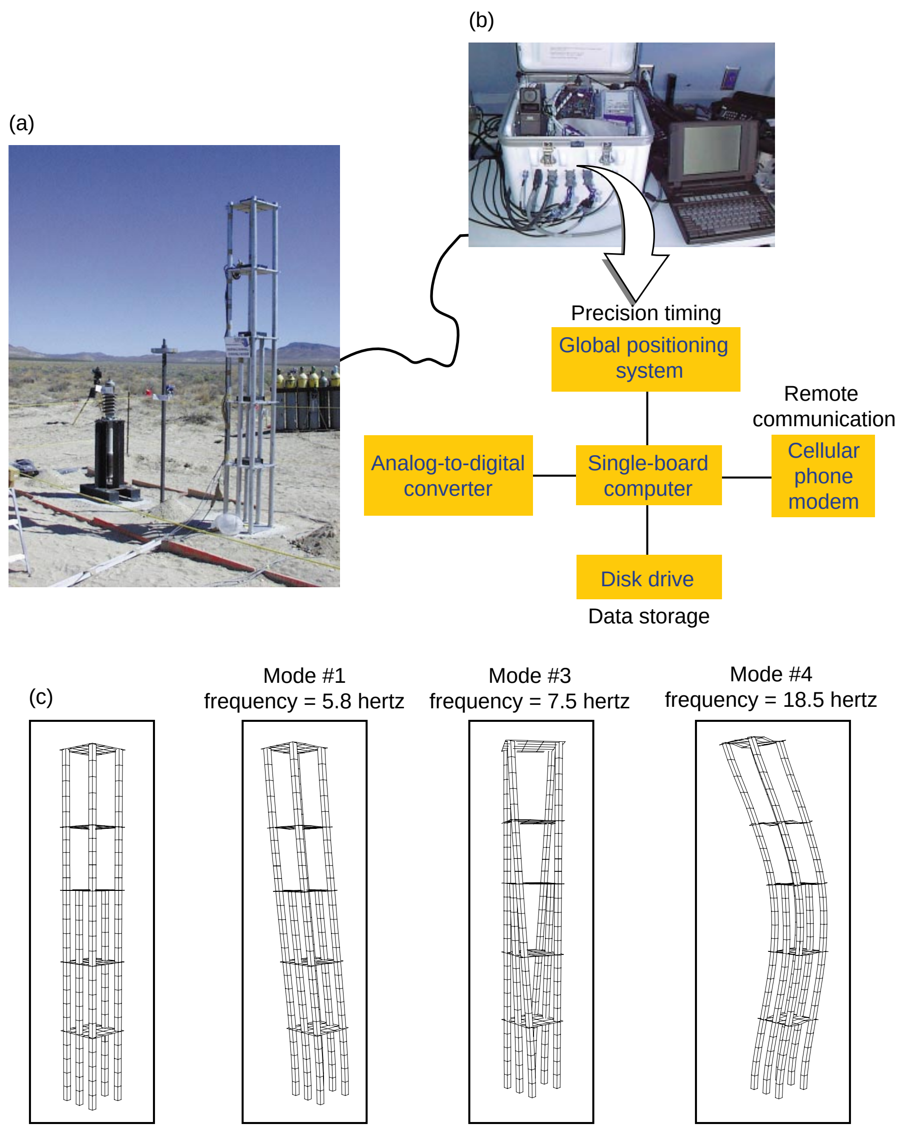


Figure 8. (a) A scale-model building at the Nevada Test Site was used to evaluate how well signal-processing algorithms could detect damage from earthquakes or other events. (b) Vibration data could be analyzed at the experimental site or downloaded in near real-time to remote locations via a cellular phone included in the data acquisition system. (c) Measurements of the scale-model building were compared with finite-element models to determine whether the structure had suffered damage as a result of the simulated earthquake. The figure indicates the first three natural modes computed with the computational model.

evaluating the signal-processing algorithms. For the latter purpose, they simulated an earthquake using a small amount of explosives contained in a rubber bladder. They also vibrated the structure continuously to excite every frequency at which it might vibrate.

This summer, a dozen sensors will be placed on the Bixby Creek Bridge to record vibrational ground motion from small earthquakes. Placement and design of the sensors were guided by the existing numerical model of the bridge, made by Livermore engineers for Caltrans to evaluate the retrofitted bridge in a large earthquake.

Also this summer, a remotely monitored sensor and data acquisition system will be installed at various locations on the San Francisco–Oakland Bay Bridge. The system will monitor both ambient vibrations from traffic and wind and the structure's response to ground motion from small earthquakes. The guiding numerical model of the bridge is a product of a Livermore–University of California at Berkeley project (see *S&TR*, December 1998, p. 18). Data from the system will allow researchers to identify the bridge's "healthy fingerprint" and assess how well the signal-processing tools detect and identify discrepancies between model simulations and measured structures.

Prototype instruments are also being placed on NIF for long-term structural monitoring. The monitoring will help ensure that the giant laser facility's sensitive optical systems can perform under ambient vibration conditions, which include traffic, air conditioners, and other "cultural noise" effects, as well as microearthquakes. The NIF numerical model was made prior to beginning construction of the $1.2-billion laser facility.

The Livermore team hopes the work will provide a structural monitoring capability for Caltrans that can also be applied to critical DOE sites such as hazardous material facilities. In this way, says McCallen, authorities could have a much better handle on assessing damage to important structures and determining response and upgrade priorities.

Listening to the World

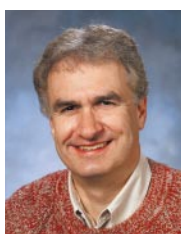
Acoustic waves permeate the natural and cultural world. The sound of a heart valve, the acoustic reflection from a pool of oil, and the vibration of a building are only three examples. But techniques developed for these research projects may well be applicable to other research fields. "Everything we're currently developing will help us to solve problems in other areas," says Clark.

—Arnie Heller

Key Words: accelerometers, acoustic signals, algorithms, artificial neural networks, Bixby Creek Bridge, Caltrans, Department of Energy National Gas and Oil Technology Partnership, heart valves, National Ignition Facility, Nevada Test Site, numerical models, oil exploration, San Francisco–Oakland Bay Bridge, signal processing, structure analysis.

For further information contact Greg Clark (925) 423-9759 (clark9@llnl.gov).

About the Scientist

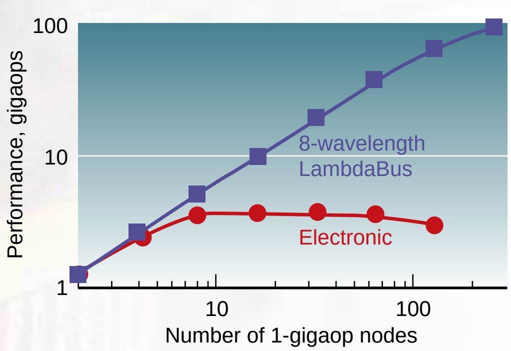


GREGORY A. CLARK received his B.S. and M.S. in electrical engineering from Purdue University in 1972 and 1974, respectively, and his Ph.D. in electrical and computer engineering from the University of California at Santa Barbara in 1981. His research activities are in the theory and application of automatic target recognition, computer vision, sensor fusion, pattern recognition–neural computing, estimation–detection, signal and image processing, and automatic control. He joined Lawrence Livermore in 1974 and is currently a principal investigator for several projects in the Defense Sciences Engineering Division. He has contributed to over a hundred technical publications and serves as a reviewer for several professional journals.

Pulses of Light Make Faster Computers

SO inexorable is the demand for ever-greater computing power that attempts are being made to exceed Moore's Law—that computer performance doubles roughly every 18 months. This effort is particularly evident in ultrascale computing, also known as parallel multiprocessing. Parallel supercomputers integrate as many as a thousand processors into a single system to achieve calculating speeds up to several trillion operations per second (teraops). However, further advances have been thwarted by bottlenecks in shunting data from processor to processor via traditional electronic interconnects.

A team of Lawrence Livermore researchers believes it has found a way to overcome communications limitations by replacing the flow of electrons interconnecting the processors of a supercomputer (or conceivably, the computers of a network) with pulses of light of different wavelengths. By combining Livermore advances in optoelectronics with off-the-shelf hardware, they are pointing the way to communication speed improvements up to 32-fold. And because optical interconnects can be packaged very tightly, additional microprocessors can be added to a supercomputer (or more workstations can be added to a network) for much greater overall performance with no decrease in communication speeds.



Lambda-connect transmitter–receiver modules handling only eight wavelengths easily outperform electronic interconnects, particularly as the number of nodes (processors or machines networked together) increases.

The technology development project is called lambda-connect (the Greek letter lambda represents wavelength in scientific notation). Funded by the Laboratory Directed Research and Development Program, the project has made rapid progress and resulted in the filing of four patents based on different aspects of the project. Lambda-connect appears so promising that several supercomputer and computer component companies have begun discussions with the Livermore researchers on ways to incorporate the new technology into their products. It has also been well received by government agencies that need new technologies capable of processing unprecedented volumes of data in as short a time as possible.

According to electronics engineer and principal investigator Robert Deri, ultrascale computers are essential for the Department of Energy's Accelerated Strategic Computing Initiative, which is developing capabilities to simulate nuclear weapon performance in lieu of nuclear testing. Ultrascale computers are also envisioned for climate and biomedical simulations as well as for specialized intelligence and Department of Defense missions.

The full potential of ultrascale computers has not been realized because standard approaches for sharing data among their many processors have limited their speed. Because traditional wire cable connections can carry only one "message" at a time, data become backed up while waiting to be processed or routed to another processor. These bottlenecks substantially degrade computational performance, complicate programming, and cause inefficient use of memory. Simply adding additional processors can compound the congestion without significantly improving performance.

Performance Gap Is Widening

Unfortunately, the performance gap between communications and other system components is widening. More demands have been placed on communications capabilities by more powerful computer boards (with more powerful processors and more processors per board), faster memory, increasing use of memory caches and shared memory, and new sensor systems that generate enormous amounts of data for processing.

Deri says that users need new tools to break the bottlenecks and meet the increasing communications demands to fully use computing power, memory, and sensor data. Several solutions have been offered, but they fail to relieve two key problems: inadequate throughput (the rate at which data flows) and high latency (initial time delay in transferring data).

The novel Livermore approach attacks both problems by building on the growing commercial practice of replacing electrical connections with optical signals of a particular wavelength. Optical signals transmitted along glass fibers are an attractive communication medium because they do not suffer from electromagnetic interference and other drawbacks associated with electrical signals.

The Livermore technology calls on wavelength division multiplexing, or WDM, to vastly increase the utility of optical connections. Instead of a single wavelength, many different wavelengths are carried by parallel, multimode glass fibers (MMFs) that are already in use in local area networks. In that respect, says Deri, "We don't need to invent a whole new infrastructure." An MMF connection is about six to ten times larger than the ubiquitous glass fiber that carries telecommunications signals. The larger cabling reduces cost and improves reliability because it requires significantly looser alignment tolerances.

With lambda-connect, every parallel optical fiber within a cable carries data of different wavelengths, with each wavelength assigned a destination. Thanks to filters developed by Livermore engineers, data are "source-routed," with their wavelength determining the ultimate destination.

Running like an Express Train

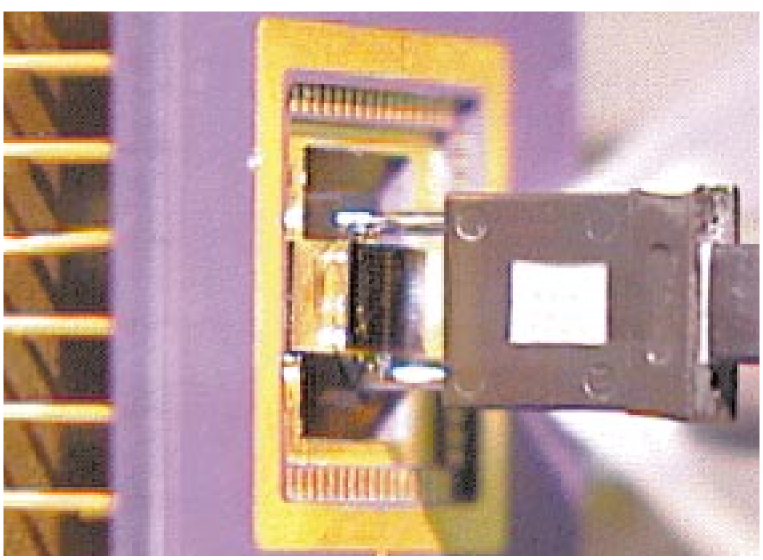
In this way, says Deri, each processor can communicate simultaneously with a large number of others without significant increases in cabling or processor complexity. Lambda-connect makes possible optical-fiber "express channels," which like express trains, go to their designated destinations directly, requiring no electronic routing. What's more, the number of processors can be increased significantly for powerful performance boosts with no communications delay.

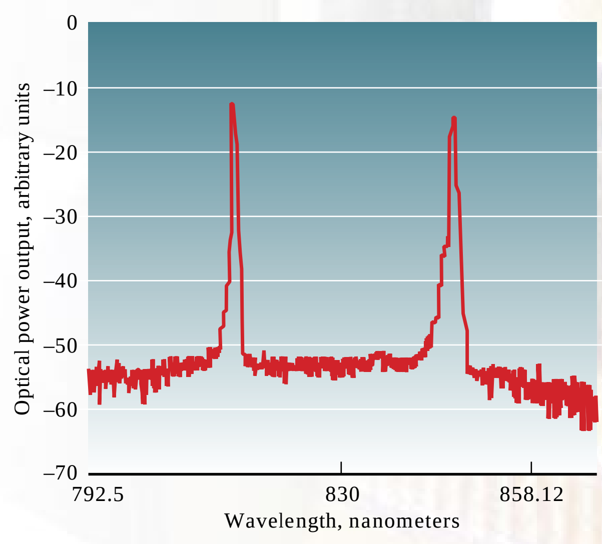
With standard electronics, Deri says, every communication is like a local train making numerous intermediate stops. Electronic express channels are difficult because they strain the processing capabilities of electronic interconnects and in some cases require such long cables that electrons cannot travel their lengths effectively.

The Livermore technology achieves unprecedented gains in bandwidth combined with significant decreases in latency. "The fact that all data travel simultaneously solves the bandwidth problem, and the fact that data all travel to different destinations solves the latency problem," says Deri. He also notes that the data error rate has been measured at less than 10^{-11}, or 1 bit in 100 billion, meaning that the technology transmits data essentially error-free.

The team is presently developing key components for transmitter–receiver modules that can handle optical data of up to 32 wavelengths. To date, their modules can route four different wavelengths on optical-fiber cabling and are integrated with standard processor boards.

Achieving the project goal requires significant innovation in filter and microoptics technologies as well as advances in vertical-cavity, surface-emitting laser (VCSEL) diode technology. Laser diodes and associated electronics inside the transmitter–receiver modules turn electrical codes into optical pulses at distinct wavelengths for data transmission to

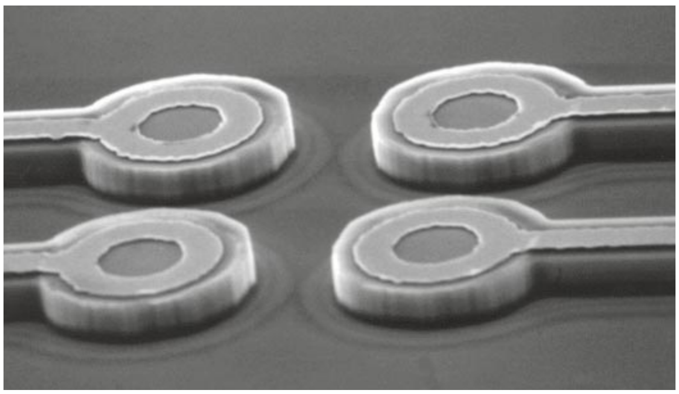




Transmitters with four wavelengths of optical data have been developed; the project's goal is a transmitter capable of handling 32 wavelengths. The figure shows a dual-wavelength transmitter and its optical output. Wavelengths are separated by about 30 nanometers (billionth of a meter).

wavelength-encoded destinations. The optical output of the VCSEL lasers is emitted perpendicular to the semiconductor wafer surface (which is the dominant plane shown in the figure below). This surface-normal emission requires package mounting innovations over the more conventional edge-emitting laser diodes.

Deri says that the team is well suited to develop the required components because microoptics, microassembly, and photonics are all Livermore strengths. Team members have four R&D 100 awards in the area of photonics and over 75 years of accumulated photonics experience. The team includes co-principal investigator Mark Lowry and investigators Mike Larson, Steven Bond, Mike Pocha, Raj Patel, Rick Ratowsky, Mark Emanuel, Henry Garrett, Holly Peterson, Bill Goward, Claire Gu (from the University of California at Santa Cruz), and Rhonda Drayton (from the University of Minnesota).



A cluster of vertical-cavity, surface-emitting lasers (VCSELs) that turn electrical codes into optical pulses for data transmission. The cluster is a closely spaced, two-by-two configuration that allows coupling into a single multimode fiber. Twelve of these clusters are coupled into fiber-ribbon arrays that are 12 fibers wide.

Deri says that "leaders in the supercomputing field have told us this approach is the most innovative and highly leveraged use of optical interconnects they have seen." The first commercial products incorporating lambda-connect technology may appear as early as 2003. Deri notes, however, that adoption of the Livermore approach depends on continued demonstration of its effectiveness to industry leaders. The team has also developed relationships with organizations that are traditionally aggressive, early adopters of advanced computing technology.

Deri expects lambda-connect advances to be used by other Livermore programs. The surface-mounted laser diodes, for example, will be used in advanced diagnostics and sensors for physics experiments. Furthermore, the project is generating interest in optical interconnects at the semiconductor chip level. However, the greatest impact on Livermore research programs will be the arrival of commercial machines using lambda-connect technologies to boost computer performance to record heights.

—Arnie Heller

Key Words: embedded systems, lambda-connect, Moore's Law, multimode glass fiber (MMF), optoelectronics, photonics, vertical-cavity, surface-emitting laser (VCSEL) diode, ultrascale computing, wavelength division multiplexing (WDM).

For further information contact
Mark Lowry (925) 423-2924 (lowry3@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
Andrew M. Hawryluk	**Forming Aspheric Optics by Controlled Deposition** U.S. Patent 5,745,286 April 28, 1998	Controlled deposition of a material onto a spherical surface of an optical element to form an aspheric surface of desired shape. A reflecting surface can then be formed on the aspheric surface by evaporative or sputtering techniques. Aspheric optical elements are suitable for deep ultraviolet and x-ray wavelengths. The reflecting surface may, for example, be a thin (about 100-nanometer) layer of aluminum, or in some cases the deposited modifying layer may function as the reflecting surface.
Gary D. Power	**Ground Plane Insulating Coating for Proximity Focused Devices** U.S. Patent 5,780,961 July 14, 1998	The ground plane of a microchannel plate is coated with a thin layer of aluminum oxide that does not cover its pores, so its performance is not affected. The thin dielectric coating greatly improves the spatial resolution of proximity-focused image intensifiers. The phosphor screen can be run at 9,000 volts, compared with 3 kilovolts without the coating.
Stephen E. Sampayan George J. Caporaso Hugh C. Kirbie	**Enhanced Dielectric-Wall Linear Accelerator** U.S. Patent 5,811,944 September 22, 1998	A dielectric-wall linear accelerator comprising a stack of paired fast and slow Blumlein modules. The stack is shaped as a hollowed round cylinder through whose core charged particles are accelerated. To withstand acceleration gradients that can reach 20 megavolts per meter, a novel insulator structure is used to construct a dielectric sleeve that fits tightly into the core. The insulator comprises flat annular rings of fused silica, with thicknesses on the order of 1 millimeter, arranged with their planes perpendicular to the core axis. At least one metal is deposited and diffused into each of two sides of the fused-silica, flat-annular rings. The rings are fused together into one hollow cylinder by applying enough heat and pressure to weld, braze, or solder the metal-to-metal interfaces. Exothermic multilayer foils can also be sandwiched in the stack under pressure and then ignited to flash bond the fused-silica, flat-annular rings together.
George J. Caporaso Stephen E. Sampayan Hugh C. Kirbie	**Dielectric-Wall Linear Accelerator with a High Voltage Fast Rise Time Switch That Includes a Pair of Electrodes between which Are Laminated Alternating Layers of Isolated Conductors and Insulators** U.S. Patent 5,821,705 October 13, 1998	A high-voltage, fast rise-time switch that includes a pair of electrodes in between which are laminated alternating layers of isolated conductors and insulators. A high voltage is placed between the electrodes sufficient to stress the voltage breakdown of the insulator on command. A light trigger, such as a laser, is focused along at least one line along the edge surface of the laminated alternating layers of isolated conductors and insulators extending between the electrodes. The laser is energized to initiate a surface breakdown by a fluence of photons, thus causing the electrical switch to close very promptly.
Paul G. Carey Patrick M. Smith John Havens Phil Jones	**Plastic Substrates for Active Matrix Liquid Crystal Display Incapable of Withstanding Processing Temperature of over 200°C and Method of Fabrication** U.S. Patent 5,856,858 January 5, 1999	Bright-polarizer-free, active-matrix liquid-crystal displays are formed on plastic substrates. The primary components of the display are a pixel circuit fabricated on one plastic substrate, an intervening liquid-crystal material, and a counter electrode on a second plastic substrate. The pixel circuit contains one or more thin-film transistors (TFTs) and either a transparent or reflective pixel electrode manufactured at sufficiently low temperatures to avoid damage to the plastic substrate. Fabrication of the TFTs can be carried out at temperatures less than 100°C.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Robert S. Glass	**Urea Biosensor for Hemodialysis Monitoring** U.S. Patent 5,858,186 January 12, 1999	An electrochemical sensor capable of detecting and quantifying urea in fluids resulting from hemodialysis procedures. The sensor is based upon measurement of the pH change produced in an aqueous environment by the products of the enzyme-catalyzed hydrolysis of urea. The sensor may be fabricated using methods amenable to mass fabrication, resulting in low-cost sensors and thus providing the potential for disposable use. The sensor could be used in treatment centers for determining the hemodialysis endpoint and in home tests to determine whether dialysis is necessary.
Alex V. Hamza Mehdi Balooch Mehran Moalem	**Process for Forming Silicon Carbide Films and Microcomponents** U.S. Patent 5,861,346 January 19, 1999	Silicon carbide films and microcomponents grown on silicon substrates at surface temperatures between 900 and 1,700 kelvins via carbon-60 precursors in a hydrogen-free environment. Selective crystalline silicon growth can be achieved on patterned silicon–silicon oxide samples. Patterned silicon carbide films are produced by making use of the high-reaction probability of carbon-60 with silicon at surface temperatures greater than 900 kelvins and the negligible-reaction probability for carbon-60 on silicon dioxide at surface temperatures less than 1,250 kelvins.
Richard F. Post	**Fail Safe Controllable Output Improved Version of the Electromechanical Battery** U.S. Patent 5,861,690 January 19, 1999	Mechanical means are provided to control the voltages induced in the windings of a generator/motor. In one embodiment, a lever is used to withdraw or insert the entire stator windings from the cavity where the rotating field exists. In another, voltage control and/or switching off the output is achievable with a variable-coupling generator/motor. A stator is made up of two concentric layers of windings, with a larger number of turns on the inner layer. The windings connect in series. One or both windings can be rotated with respect to the other. The design for the stator assembly of electromechanical batteries provides knife-switch contacts that are in electrical contact with the stator windings.

Awards

Ronald Natali recently traveled to DOE Headquarters in Washington, D.C., to represent the Laboratory's **Hazardous Materials Packaging and Transportation Safety (HMPTS) Assurance Office** at the **Hammer Award** ceremonies. These awards are given annually by Vice President Al Gore's National Partnership for Reinventing Government to federal and contractor employees who have contributed significantly to making government more efficient and cost-effective. The HMPTS Assurance Office won as part of a group of DOE contractors, the Suppliers Quality Information Group (SQIG), that shares supplier assessment information to save money by eliminating the need for each contractor to evaluate the same suppliers.

HMPTS is responsible for making sure all packaging and containers purchased by the Laboratory for transporting hazardous materials and waste meet applicable regulatory requirements. The office, like all SQIG contractors, contributes to and shares in SQIG's database of supplier evaluation information gathered from assessment visits. In fiscal year 1998, 36 percent of the HMPTS supplier assessments were done through the SQIG database, resulting in a significant cost saving for the Livermore program and ultimately DOE. SQIG participants are also working to standardize the assessment process, work beneficial to both DOE and vendors.

Laboratory scientist **Grant Logan** has received the **Fusion Power Associates Leadership Award** for his nearly 25 years of contributions in both magnetic and inertial fusion energy. The award is presented each year to individuals who have shown "outstanding leadership qualities in accelerating the development of fusion."

Logan, who has been a Livermore employee since 1975, is deputy director of DOE's Heavy-Ion Fusion Virtual National Laboratory and coordinator of inertial fusion energy technology for DOE's Fusion Energy Virtual Laboratory for Technology—both based at Lawrence Livermore. The citation on Logan's award states, "Your outstanding leadership qualities, your innovative contributions to both magnetic and inertial fusion energy programs, as well as to fusion power and fusion applications in general, have provided researchers a rich array of options to explore."

Leveraging Science and Technology in the National Interest

A sampling of current projects at Lawrence Livermore demonstrates the many ways in which the Laboratory's science and technology support Department of Defense missions. These projects range from engineering and fabricating munitions and explosives to developing the advanced computer codes that optimize warhead design or assess their hazards. The Penetration Augmented Munition is a portable, multistage weapon that not only provides offensive capability for diminishing adversaries' mobility and capability but also gives U.S. soldiers an additional margin of security in a hostile encounter. Livermore's fiber-composite sabot makes weapons more lethal and is particularly effective in tank warfare. The GLO (global local optimizer) code optimizes the design of shaped-charge warheads, while the CHEETAH thermochemical code improves explosives formulation. CALE, a multiuse mechanical code, is used to help the Air Force assess missile launch site safety and in particular to predict hazards from propellant that falls to the ground when rockets misfire. ALE3D, now being upgraded, will increase the capability of codes to assess safety hazards.

Contact: Cory Coll (925) 422-2103 (coll1@llnl.gov).

Extracting Valuable Information from Acoustic Waves

Lawrence Livermore researchers are developing advanced techniques for interpreting acoustic signals, focusing on complex algorithms that at times mimic the reasoning processes of the human brain. Three current acoustic signal-processing projects, involving heart valve classification, oil exploration, and large-structure analysis, demonstrate the wide range of acoustic signal usefulness.

To determine whether an artificial heart valve is intact or needs replacing, a suite of Livermore algorithms sift through heart and body sounds to isolate the telltale signals of a faulty artificial heart valve. If successful, the new technique would spare patients from surgery to determine if their artificial valve needs replacement.

Livermore experts and colleagues from Shell Oil are automating a key procedure used for locating undersea oil deposits. The procedure uses acoustic signals from underwater explosions that are detected by hydrophones. The project's goal is to reduce manual analysis of the signals to only about 0.1 percent of the data processed, thereby saving millions of dollars in oil exploration costs.

Finally, a Livermore team is using acoustic wave vibrations to assess the integrity of several large structures in northern California. The goal is to develop a fast and reliable method to check for damage after earthquakes or other destructive events. A scale-model building at the Nevada Test Site is serving as a testbed for the project.

Contact: Greg Clark (925) 423-9759 (clark9@llnl.gov).

Coming Next Month

Responding to Atmospheric Emergencies

A report on how Livermore's Atmospheric Releas Advisory Capability is using advanced computer simulations t protect the Earth and its people from hazardous and toxic release to the atmosphere.

Also in June

- *Unraveling the mystery of explosive detonation.*
- *Livermore's productive collaborations with the Laboratory for Laser Energetics.*

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