Engineering's Tradition Turns Ideas into Reality

WHEN the Livermore branch of the University of California Radiation Laboratory first opened its gates in September 1952, many of its employees were engineers and machinists recruited from the original "Rad Lab" in Berkeley. Livermore's facilities were primitive—old wooden buildings, no air conditioning, not enough desk lamps or telephones. More important, from an engineer's perspective, the Livermore site—which had previously been the Livermore Naval Air Station—had no shops, no laboratories, no engineering infrastructure. Undaunted, the engineering staff rolled up its collective sleeves and went to work, making and assembling parts for the Laboratory's first nuclear device test in what had been the operating room of the Navy infirmary. Thus, from the beginning, Livermore's engineers and technical staff built a reputation for doing the seemingly impossible.

> **"Instead of an attic with a few test tubes, bits of wire and odds and ends, the attack on the atomic nucleus has required the development and construction of great instruments on an engineering scale."**
>
> —E. O. Lawrence
> Nobel Prize Acceptance Speech, 1940

Glenn Mara, associate director for Engineering, notes, "Engineering has a history of collaborating with programs throughout the Laboratory to turn scientific concepts into reality. This approach to 'grand challenge' science is in keeping with the tradition established by E. O. Lawrence of integrating and extending technologies, often simultaneously, and pushing them to their extremes to solve tough technical problems."

For 50 years, Livermore's engineers, designers, technicians, and skilled crafts people have, for example, helped develop and test reliable, safe, secure nuclear weapons; fielded complex high-speed diagnostic systems for nuclear tests; built and operated large magnetic fusion research facilities; designed and built the world's most powerful laser systems and tools for stockpile stewardship; invented compact instruments for detecting biological and chemical agents; and developed microsurgical tools. They made technological breakthroughs to help them do the job—in areas such as precision engineering, nondestructive evaluation, and computational engineering codes—with resulting advances that often had significant applications beyond the Laboratory's gates. (See the boxes on pp. 23, 24, and 26.)

Measuring the Sun's Heat and Density

In Livermore's Nuclear Test program, engineers faced the extreme challenge of creating systems that would measure the performance of an exploding nuclear device. In such an explosion, matter is accelerated to millions of kilometers per hour while experiencing densities and temperatures found only in stars. The Laboratory's early engineers met the challenge, designing instruments and radiation detectors that could capture data on the reaction history, time history, and overall yield of the explosion. The diagnostic systems that evolved over four decades of testing were incredibly complex, often consisting of dozens of specially designed oscilloscopes, hundreds of

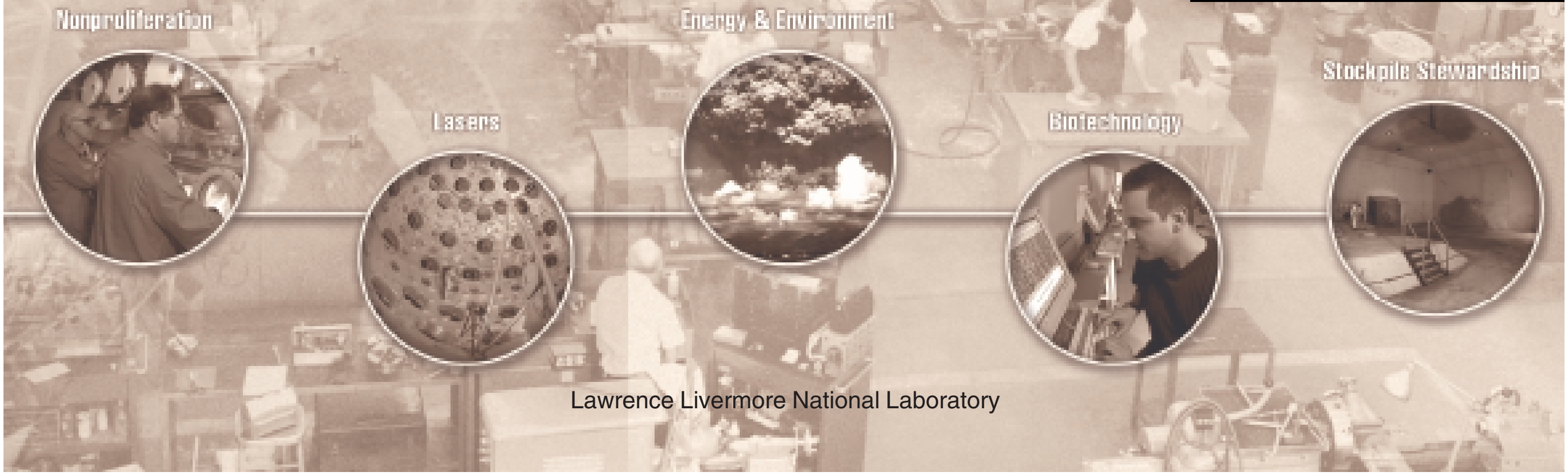
electronic chassis, miles of interconnecting cables, numerous control systems, and thousands of Livermore-developed detectors. Putting the whole together was no less an engineering feat than developing the parts. Timing accuracies, for instance, had to be less than a nanosecond between oscilloscopes connected to detectors over coaxial cables hundreds to thousands of meters long. In addition, because a test offered only one opportunity to gather the data, systems had to be redundant. Thus, detector and oscilloscope systems overlapped the coverage of adjacent systems so that no information would be lost.

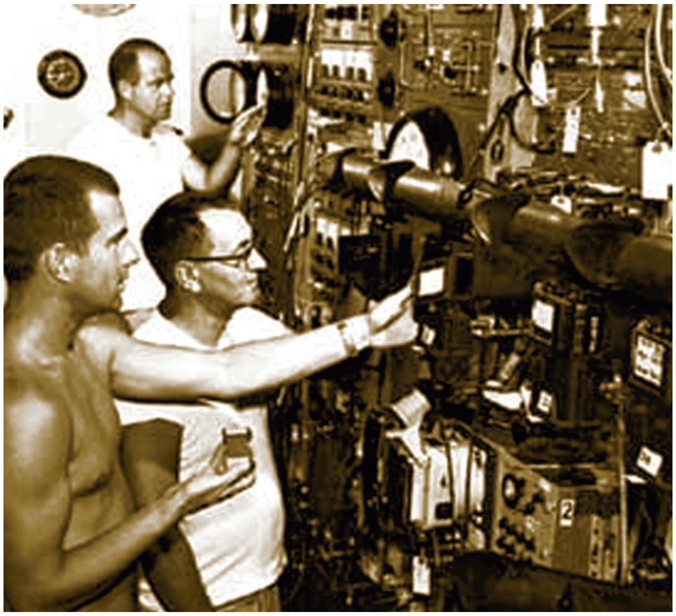
Electronics innovations—from vacuum tubes to solid-state devices to integrated circuits—also revolutionized the systems used in the Nuclear Test program. Livermore engineers designed new oscilloscope systems based on solid-state technology and began exploring digital systems to replace oscilloscopes altogether. One system designed during this time was an extremely fast pulse generator to measure the electrical length of coaxial cables. The generator, which fits into a small box, replaced an entire rack of equipment and reduced dry runs to test simultaneity from days to about an hour. Small digital computers also arrived on the scene. In the Test program, they took over many routine control, timing, and dry-run functions as well as recording or analyzing some of the data. Fiber-optic cables began appearing in underground electronic imaging or spectral analysis systems and were also used to bring digitized data to the surface.

With the cessation of testing in 1992, engineers turned their talents to developing high-speed diagnostic systems for other programs and projects throughout the Laboratory. One such diagnostic device, currently under development in Engineering, will be used in high-explosives tests to measure speeds over 6,000 kilometers per hour in a microsecond timeframe.

Getting the Inside Picture

One area of engineering expertise that grew beyond its initial Nuclear Test program applications is nondestructive evaluation (NDE)—a means of looking at and identifying flaws and defects in materials and finished parts without damaging them (*S&TR*, December 1997, pp. 4–11). Livermore engineers use ultrasonic, acoustic, and other noninvasive techniques to image defects, measure the properties of many kinds of materials, and accurately determine part thicknesses. NDE is used to inspect weapon components, characterize materials, and evaluate solid-state bonds. Engineers have also developed enhanced surveillance techniques, acoustic sensors, array technologies, medical applications, and flight-test sensors—often in concert with industrial partners. Two examples of recently developed NDE systems with applications outside the Laboratory are a system that assays containers of radioactive waste (see *S&TR*, December 2000, pp. 4–11) and the High-Performance Electromagnetic Roadway Mapping and Evaluation System (HERMES), a radar-based sensing system that diagnoses the problems of deteriorating bridge decks (see *S&TR*, October 1998, pp. 8–9). HERMES was successfully tested on a northern California bridge prior to the bridge's demolition.



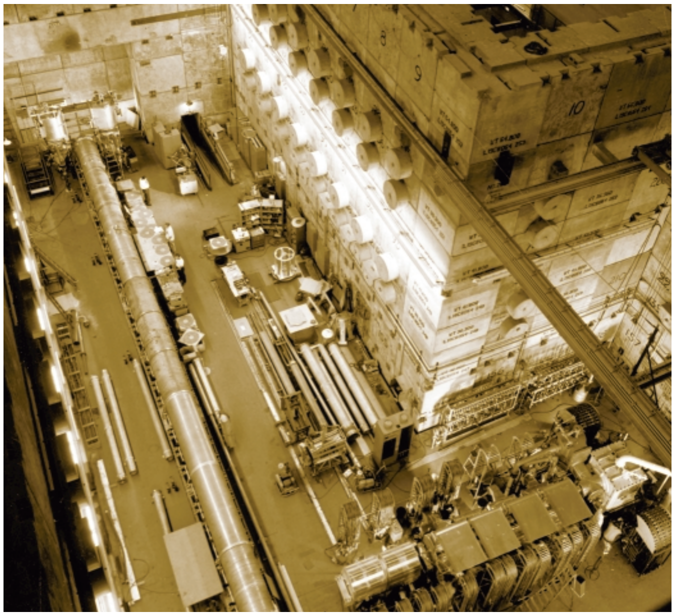


In about 1962, during the days of testing in the Pacific, Livermore engineers and scientists adjust cameras before Operation Dominic, the largest nuclear testing operation ever conducted. These cameras photographed with split-second timing the numerous traces of testing data that streaked across instrument screens in a fraction of an instant during tests. Laser measuring devices and computer techniques eventually replaced these early data-collection and -recording methods.

From Fusion Energy to X Rays

Along with nuclear weapons design and testing, magnetic fusion energy research was an early mission of the Laboratory. The 1970s and 1980s were the heyday of Livermore's research into magnetic mirror machines. Engineers designed and built a series of systems, starting with the Levitrons in the 1950s and moving on to Baseball I and II and the 2XII machine. These early machines led to the development of 2XII-B, which was the first mirror experiment to create a stably confined plasma at temperatures, densities, and durations that approached those needed for a power plant. Success with 2XII-B and the Tandem Mirror Experiment (TMX) in the early 1980s led the Laboratory to design the enormous Mirror Fusion Test Facility, which included the largest superconducting system ever built and equally large vacuum and pulse-power systems.

Livermore’s engineers first honed their expertise in linear accelerator design by designing and building the linear induction accelerator Astron for magnetic fusion research in the mid-1960s. After Astron, engineers went on to design a series of linear induction accelerators for the Weapons and Beam Research programs. This series included the Flash X-Ray (FXR), the Engineering Test Accelerator, and the Advanced Test Accelerator. Today’s FXR is a major upgrade of the original machine built in the late 1970s. This latest accelerator produces high-energy x rays that can penetrate more than 30 centimeters of steel, providing high-resolution images that show how materials



(left) The linear accelerator Astron, built in the 1960s for magnetic fusion research, was an engineering marvel of its time. No one had ever built such a high-current accelerator before. (right) The Flash X-Ray (FXR) Facility, the nation’s most sophisticated linear-induction electron beam accelerator, is a direct descendant of Astron. FXR is an important diagnostic tool in the U.S. weapons research community, enabling scientists to see into the heart of test objects at the very moment they are detonated.

move at ultrahigh speeds. FXR, dedicated in April 1982, remains the nation's most sophisticated linear-induction electron-beam accelerator and one of the most important diagnostic tools in the U.S. weapons research community. (See *S&TR* May 1997, pp. 15–17; March 1999, pp. 4–12.)

Lasers, Large and Powerful

Engineers who supported the Laser program brought with them many of the engineering technologies and systems developed to support the Weapons and Nuclear Test programs and took on a host of new challenges as well. When research into lasers coalesced into a program in the early 1970s, the goal was to produce well-diagnosed thermonuclear microexplosions and to use the laser systems developed at Livermore to study weapons physics and explore the feasibility of producing commercial power.The key engineering words here are "diagnosed" and "developed." Engineers adapted diagnostic systems created for the Nuclear Test program to fit laser researchers' needs. The types of data produced in the tiny explosions—the temperatures, pressures, spectral output—were similar to those of the Test program, as were the time scales.

"In some ways," says Ed Lafranchi, a retired electronics engineer who managed the electronics engineering side of the Engineering Directorate for nearly 15 years beginning in 1973, "the diagnostic requirements and the instrumentation for lasers were very similar to those in the Nuclear Test program, but on a smaller scale." Engineers took high-speed instruments, such as neutron detectors, calorimeters, and streak cameras, and tailored them for laser fusion experiments. As for developing the laser systems themselves, Engineering provided the design and construction expertise that made it possible for the Laboratory to build a series of large neodymium-doped glass lasers of increasing power—lasers that included thousands of high-precision optical components.

New sets of engineering challenges also evolved from the requirements of these enormous optical systems. "We were building some of the largest laser systems existing in the world at that time," explains Lafranchi. "These systems required superclean facilities and new ways to fabricate and polish glass." The National Ignition Facility (NIF), the latest of Livermore's high-energy lasers, will be used for science-based stockpile stewardship and to explore the feasibility of fusion energy for civilian power production and to conduct basic high-energy-density physics research. "NIF is certainly a system of extremes, from an engineering viewpoint," says Monya Lane, operations manager for Engineering. "To begin with, it's enormous in size and power as well as in the number of parts and subsystems involved."

The facility itself is as large as a football stadium and five stories tall. The 1.8-megajoule laser system will have 192 beam lines, 7,500 large optics, more than 30,000 small optics, and 60,000 control points. The 20-nanosecond pulses of laser light from each of the 192 beams must travel 450 meters—through a path of mirrors, lenses, amplifiers, switches, and spatial filters—and converge on a target the size of a BB pellet. Each pulse must be pointed at and hit the target with extreme precision—the equivalent of touching a single human hair from 90 meters away with the point of a needle.

Developing a way to align NIF's 192 laser beams automatically so that they precisely converge on a minuscule target is a formidable task for the engineers working on NIF. The alignment control system is one of NIF's largest systems.

Pioneering Precision

The precision engineering capability that now exists in the Engineering Directorate grew out of the needs of the Laboratory's Weapons program in the 1950s and 1960s. The first few mechanical engineers and machinists who came from Professor Lawrence's Berkeley Rad Lab to support Livermore's weapons design work had to produce high-precision parts from materials that were quite exotic for the times. These engineers and engineering staff became pioneers in the field of precision engineering, inventing new tools and machining techniques such as diamond-coated machine tool bits for improving the finish and accuracy of parts. Among their many accomplishments, Livermore's engineers designed and produced several large diamond-turning machines, each with greater contour accuracy than its predecessor, including the Large Optics Diamond Turning Machine (LODTM). (See *S&TR,* April 2001, pp. 12–14.)

Built in the early 1980s, LODTM was initially developed for strategic defense research to produce large-diameter, nonspherically shaped optics that had to be fabricated with a precision corresponding to a small fraction of the wavelength of light. It has continued to produce extremely precise optical devices for a variety of efforts, including three secondary mirrors for the Keck telescopes in Hawaii and the primary mirrors for a National Aeronautics and Space Administration's Space Shuttle experiment to measure wind speeds using a space-based lidar system. LODTM is still the most accurate large machine tool in the world.

Along with creating systems to machine to extreme precision, Livermore's engineers also developed instruments to measure dimensions, shapes, densities, and surface finishes with greater accuracy than was previously possible. For instance, a recent invention, the absolute interferometer, can measure optical surfaces to within one or two atoms, or less than 1 nanometer. (See *S&TR*, January/February 1998, pp. 12–20, for more information about precision engineering.)

(See *S&TR*, November 1998, pp. 4–11.) It consists of 600 video cameras distributed at 20 points along each beamline, 10,000 stepping motors, 3,000 actuators, 110 racks, 240 kilometers of cable, a high-speed network for transmitting digitized video images, and software to integrate all of these devices.

A Small, Small World

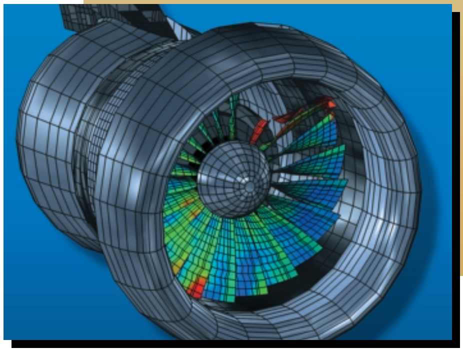
In the world of the very small—where the diameter of a human hair would be considered large—Engineering also made its mark early in the Laboratory's history. (See *S&TR*, July/August 1997, pp. 11–17.) Engineering's focus on microtechnology had its start in the late 1960s when Livermore engineers and scientists began making miniature devices for high-speed diagnostic equipment required for nuclear tests. For many years, before the emergence of Silicon Valley and the ready availability of microchips for a broad array of uses, Laboratory engineers fabricated chips to their own specifications for high-speed switches, high-speed integrated circuits, and radiation detectors. By the early 1980s, Livermore was fabricating thin-film membranes for use as x-ray windows in low-energy x-ray experiments and as x-ray filters. Thin films now serve as debris shields for the Extreme Ultraviolet Lithography program and as targets for high-energy electron experiments that generate x rays.

Microstructures have served as diagnostic devices for Livermore's Nova laser experiments and will do the same for experiments at NIF. In the mid-1980s, Livermore began combining microoptical devices with microelectronics for extremely high-speed, fiber-optic data transmission. Photonic devices have since found their way into many microtechnologies that incorporate optical fibers for transmission of laser light. Livermore's engineers stopped fabricating silicon-based electronic circuits when commercial microchips became available. But they continued to create and apply microfabricated components, including photonic devices, microstructures, and microinstruments, to a variety of Laboratory projects and programs, including stockpile stewardship, nonproliferation, and biomedical research. Recent developments include a silicon microgripper that can be used in microcatheters for medical applications (see *S&TR*, June 1997, pp. 14–21) and a miniature flow cytometer that features ease of alignment and increases the accuracy of flow cytometry, a powerful diagnostic tool used to characterize and categorize biological cells and their content (see *S&TR*, June 1998, pp. 4–9).

Of Computers and Computational Tools

Computers were just becoming a part of the landscape when the Laboratory opened its doors. Some of the Laboratory's first engineers operated, maintained, and modified the Laboratory's first computer, the Univac. Before long, they were also building hardware and designing interfaces, such as the first remote display system—the Television Monitor Display System. When the Laboratory decided to commission computers from commercial suppliers, engineers wrote the specifications. They also wrote "specs" for peripherals that were not commercially available at the time, including a high-speed printer that spat out seven pages a second, an extreme speed even by today's standards. Engineers were among the first to use small computers such as the PDP-11 to automate laboratory experiments throughout Livermore.

In the 1970s, Engineering began developing modeling tools critically needed by Livermore's nuclear weapons projects but unavailable commercially. This work continues to this day. (See *S&TR*, May 1998, pp.12–19.) One of the most well-known of Livermore's early engineering codes is DYNA. An industry observer once wrote: "DYNA is to finite-element codes what Hershey is to chocolate bars and Kleenex is to tissues." Begun in 1979, DYNA3D (the three-dimensional version of DYNA) is an explicit finite-element code that addresses the behavior of structures as they deform and fail. More than 500 companies, universities, and others have applied DYNA3D to problems from crash dynamics to human artery simulations.



In 1992, engineers began developing ParaDyn, the parallel-computing version of DYNA3D. ParaDyn has been used to simulate the structural behavior of weapons and to simulate car crashes, falling nuclear waste containers, ground-shock propagation, aircraft-engine interaction with foreign debris, and biomedical interactions.

In the 1960s, Livermore computational engineers began developing electromagnetic codes that simulate propagation and interaction of electromagnetic fields. Today's electromagnetic field experts study and model wave phenomena covering almost the entire electromagnetic spectrum. One code, EIGER, is a frequency-domain electromagnetic modeling package that has been used recently to model microelectromechanical-system devices, the human neck for speech recognition research, microwave circuits, full-scale Department of Defense systems such as missiles and ships, and phased arrays.

The scale of microtechnology just keeps shrinking. (left) In 1987, Steve Swierkowski inspects a Livermore-designed and -fabricated gallium– arsenide chip, about 3 square millimeters, under a scanning electron microscope. Instruments based on this technology were used at the Nevada Test Site to acquire nuclear test event data and in laser experiments to help shape precise electric pulses for detecting x rays. Today, microtechnology has become nanotechnology, and more features with more capabilities can be squeezed into a smaller area. (right) Livermore's engineers are supporting a Defense Advanced Research Projects Agency project to develop the BioFluidic Chip—essentially a clinical laboratory on a chip, small enough to be worn on an earlobe.

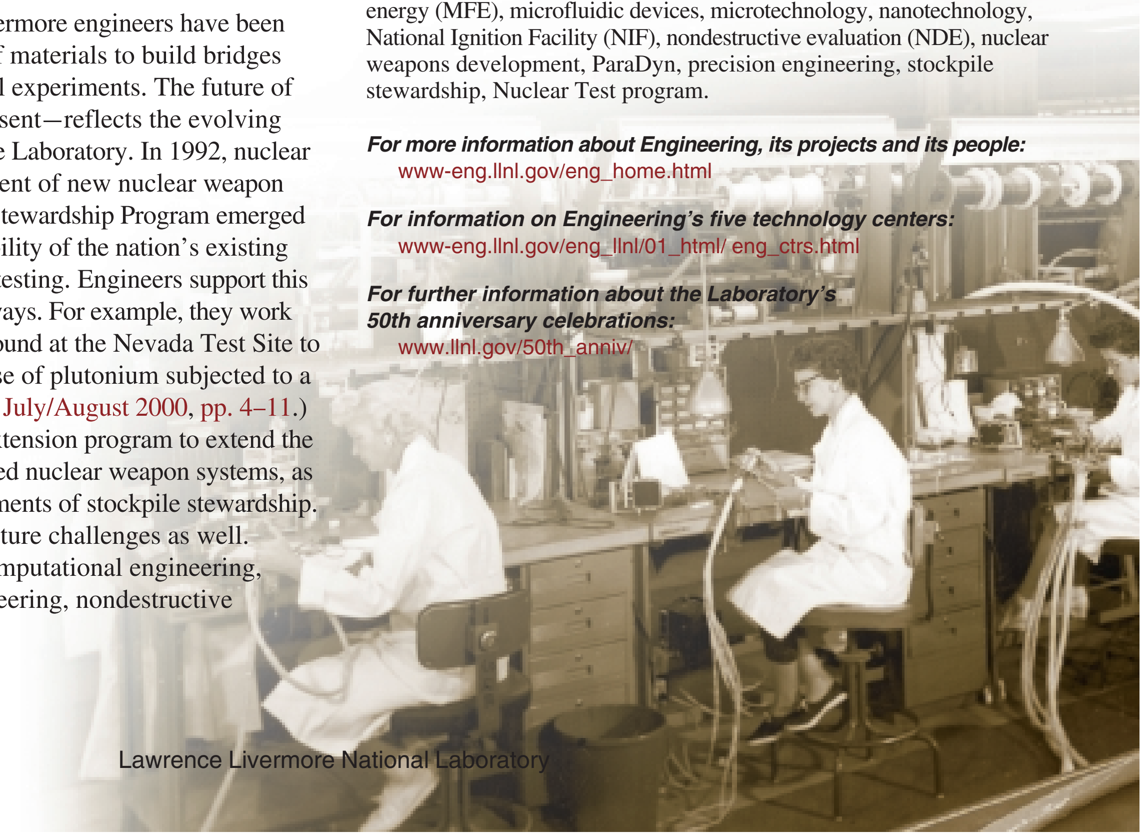
Engineers creating these tiny systems also have an eye to the future. One area showing great promise is that of microfluidic devices. (See *S&TR*, December 2001, pp. 4–11.) These miniature systems move fluids through a maze of microscopic channels and chambers that have been fabricated with the same lithographic techniques used for microelectronics. Microfluidic devices may soon provide a small analytical laboratory on a chip to identify, separate, and purify cells, toxins, and other materials. They might also be used in the future for detecting chemical and biological warfare agents, delivering precise amounts of prescription drugs, keeping tabs on blood parameters for hospital patients, and monitoring air and water quality.

Engineering and Lab Share the Future

Over the past five decades, Livermore engineers have been called upon to use a wide range of materials to build bridges between scientific ideas and useful experiments. The future of Engineering—like its past and present—reflects the evolving national challenges assumed by the Laboratory. In 1992, nuclear testing and engineering development of new nuclear weapon systems halted, and the Stockpile Stewardship Program emerged to help ensure the safety and reliability of the nation's existing nuclear stockpile without nuclear testing. Engineers support this critical national program in many ways. For example, they work on subcritical experiments underground at the Nevada Test Site to help evaluate the dynamic response of plutonium subjected to a high-explosive shock. (See *S&TR*, July/August 2000, pp. 4–11.) They also work on the Lifetime Extension program to extend the stockpile life of Livermore-designed nuclear weapon systems, as well as on NIF, one of the key elements of stockpile stewardship.

Engineering is preparing for future challenges as well. Its five technology centers—in computational engineering, microtechnology, precision engineering, nondestructive characterization, and complex distributed systems—are positioned to solve tomorrow's problems by exploring innovative and cost-effective engineering solutions to emerging technical challenges. "Whatever missions the Laboratory faces in the future," says Mara, "Engineering will be there to supply its special expertise. And if a project involves designing, building, fabricating, or operating a one-of-a-kind experimental facility or system or gathering data at the extreme edges of measurement— the final result will surely show the hand of a Livermore engineer."

—Ann Parker



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For more information about Engineering, its projects and its people:
www-eng.llnl.gov/eng_home.html

For information on Engineering's five technology centers:
www-eng.llnl.gov/eng_llnl/01_html/ eng_ctrs.html

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