Science & Technology Review

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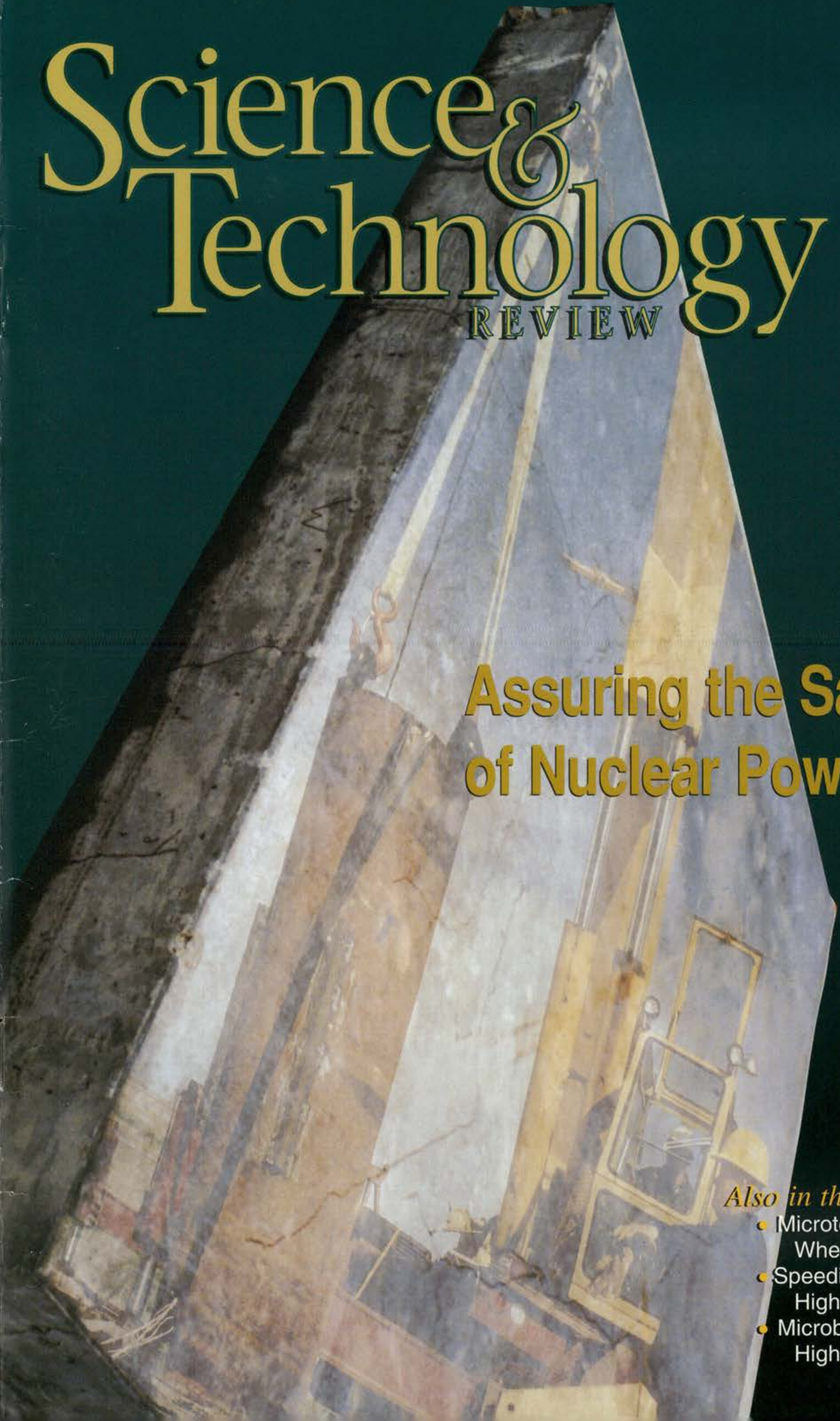


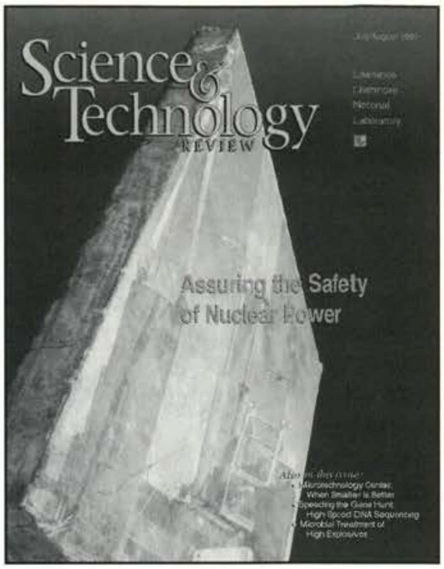
Assuring the Safety of Nuclear Power

Also in this issue:

- Microtechnology Center: When Smaller Is Better
- Speeding the Gene Hunt: High-Speed DNA Sequencing
- Microbial Treatment of High Explosives

About the Cover

Lawrence Livermore's Fission Energy and Systems Safety Program (FESSP) provides technical support to the Department of Energy and Nuclear Regulatory Commission in all facets of the nuclear energy fuel cycle. The result: Livermore responds to new issues with a broad technical and practical perspective. Pictured here are photos of a spent-fuel cask superimposed over the cement pad on which it was drop-tested. The Livermore analysis studied accident scenarios on one-third-scale shipping casks for spent nuclear fuel. The article begins on p. 4.



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About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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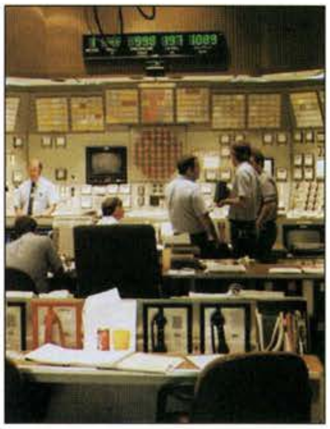

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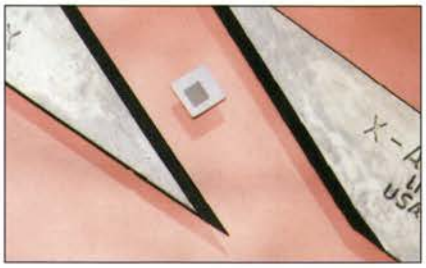

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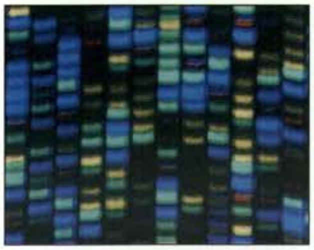

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Computing-power requirements to grow exponentially

Lawrence Livermore expects its need for computing power in the relatively near future to be one million times what is available today. According to Director Bruce Tarter, the U.S. computer industry, challenged by the Department of Energy's Accelerated Strategic Computing Initiative, could produce those gains within eight years. As hardware advances, massively parallel processors have become much easier to program and, therefore, more accessible. A 512-node IBM SP2 system, recently received, was running the Laboratory's most complex simulations two weeks after delivery, Tarter said.

Chemotherapy linked to sperm damage

Chemotherapy can cause chromosome abnormalities in sperm that make it unwise for men to father children while undergoing treatment, according to a study from Lawrence Livermore.

The findings, published in the May issue of Nature Genetics, resulted from an eight-year study in which Livermore biophysicist and geneticist Andrew Wyrobek and his team studied eight men at a Houston cancer center. The men had Hodgkin's disease, a cancer of white blood cells, which tends to strike people between the ages of 20 and 40.

The research team processed semen samples collected before, during, and after periods of chemotherapy treatment. The team used a technique developed at Lawrence Livermore called chromosome painting, in which fluorescent dyes are applied to specific gene bundles in individual cells. Vividly displayed on a computer monitor hooked up to a microscope, the colors indicate whether a chromosome was deleted, repeated, or damaged.

According to Wyrobek, the body restores itself after chemotherapy, and the sperm return to normal in about 100 days.

Wyrobek's methods could be used to study the effects of exposure to hazardous chemicals, smoking, or other factors that affect sperm. "We're going to apply this [technique] to studies of other risk factors—anything from personal habits like smoking or diet to drugs men might consume," he said.

Tools to catch smugglers of nuclear bomb materials

Lawrence Livermore has joined the competition to create better tools for catching smugglers of nuclear bomb materials. A portable radiation detector that can run on AA batteries is expected to be available later this month. The new sensor is a kind of semiconductor that finds hidden sources of radiation by detecting gamma rays and recording their distinctive signature.

Unlike standard hand-held detectors that only indicate that a radioactive material is present, this technology can distinguish one radioactive material from another.

Livermore completes new *Seismic Safety Manual*

The new edition of the Seismic Safety Manual—A Practical Guide for Facility Managers and Earthquake Engineers is now available from Lawrence Livermore National Laboratory.

Sponsored by the Department of Energy's Office of Environment, Safety and Health, Office of Nuclear and Facility Safety, the manual is intended for use by DOE managers responsible for the seismic safety of DOE facilities. It includes guidelines on hazard identification and evaluation; site planning; evaluation and rehabilitation of existing facilities; design of new facilities; lifelines, such as power, gas, and water-transmission systems; operational safety; emergency planning; and management of risks and liabilities.

The new manual is a revision and expansion of the original guide published in 1983 by Lawrence Berkeley National Laboratory. Since then, a number of damaging earthquakes have occurred, resulting in a wealth of new information on optimum seismic design, as well as new regulations.

To order the manual, send a check payable to University of California/SSM or a purchase order for $50 (to cover printing and distribution costs) to Dawn S. Francis, Lawrence Livermore National Laboratory, P.O. Box 808, L-224, Livermore, California 94551.

Contact: Dawn S. Francis (510) 423-9340 (francis4@llnl.gov).

Licenses issued for microreaction-chamber technology

Lawrence Livermore National Laboratory has issued limited exclusive licenses to two diagnostic instrumentation firms for use of its microreaction-chamber technology. The licenses, granted to Cepheid of Santa Clara, California, and Soane BioSciences of Hayward, California, allow the companies to use the technology specifically for amplification and detection of nucleic acids and for ligand-binding assays.

Licenses for microreaction-chamber technology in fields of use outside of amplification and detection of nucleic acids and ligand-binding assays are available from Lawrence Livermore National Laboratory.

Contact: James M. Sommercorn (510) 422-6416 (jsommercorn@llnl.gov).

The Vital Role of Nuclear Power

FOLLOWING its celebrated inception shortly after W.W.II, nuclear energy offered the public a vision of "electricity too cheap to meter." Indeed, nuclear power was heralded as the country's economic savior in response to dire predictions of soaring post-war electricity demand in the U.S.

Neither one of these scenarios has come to pass; in retrospect, meterless electricity never would have become a reality in a market economy such as ours. Listening to nuclear power's advocates and detractors alike, one would never know that nuclear power has been very successful. What do I mean by successful? In the 1950s, the U.S. switched on the world's first nuclear power reactors. Today, nuclear power accounts for 21% of the nation's—and 17% of the world's—electricity. In comparison with the rates at which other new energy production technologies have penetrated the marketplace, nuclear power has proven very successful. For example, historic U.S. growth rates for coal, oil, and gas utilization have all been about 7% per year, while the rate for nuclear power in the U.S. soared to 36% in the 1980s. To be sure, since then it has slowed considerably in this country; today the U.S. has no plans to build new nuclear power plants.

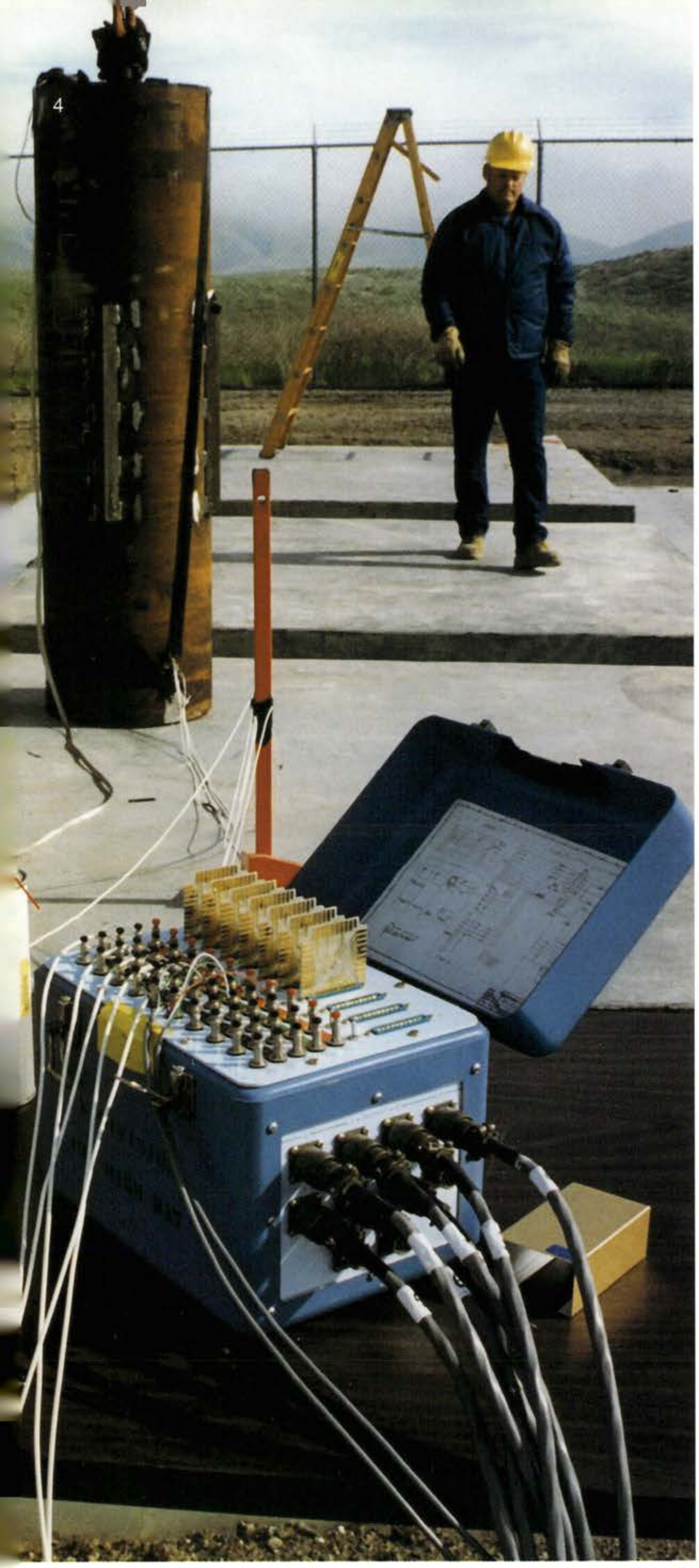
Most reasonable projections of world economic growth show that, even after generous allowances for possible improvements in energy efficiencies, a shortfall in energy production in the next half century will have to be made up by a mix of coal and nuclear power. Most of the world's economic growth is occurring in developing nations that contain some 80% of the planet's population. In fact, the projected growth rates of energy usage in the developing world are three times those of the developed world (and dominated by the Chinese), easily outstripping the projected increases in natural gas supplies from recent discoveries. As a result, nuclear power may well become the developing nations' prime option for providing new supplies of electricity, particularly if their governments recognize the importance to the environment of curtailing carbon dioxide emissions from burning wood, oil, gas, and coal.

It seems clear, then, that nuclear power will be with us globally for the foreseeable future. However, an important question remains: What role will the U.S. play in the nuclear world of the future? Will American know-how be used to influence the course of nuclear energy developments, or will we be relegated to bystanders to other nations' technical developments and marketing efforts? The answers are not simple and are not independent of related concerns about nuclear weapons proliferation, global climate change, dependence upon foreign sources of energy, and even jobs (through the export of U.S. technology). Yet the answers will most likely affect our quality of life and the stability of the economically developing world.

A vital U.S. nuclear energy systems and materials R&D program, involving both the federal government and the private sector, should be welcomed, not feared, by the general public. Such a program can help assure adequate mid to long term supplies of energy for this nation, but more importantly, for the developing world. Adequate and safe energy supplies can provide the increases in the standard of living to meet peoples' expectations that, if not met, historically have led to social and military upheaval. Adequate supplies of nuclear-power-generated electricity will help minimize air pollution and capture new foreign markets for U.S. industry. Perhaps most important, strong American technical leadership and influence in the global nuclear arena can pay tremendous dividends in global safety, security, and environmental quality.

Finally, only with strong R&D can we hope to increase the credibility and public acceptance of nuclear power. As described in the article beginning on p. 4, Lawrence Livermore National Laboratory has a long-standing commitment to providing its broad expertise and advanced technologies to virtually every aspect of nuclear systems and the nuclear fuel cycle. I expect that commitment to pay important dividends to this nation—and the world—for many years to come.

■ Robert N. Schock is Acting Associate Director for Energy Programs.



Assuring the Safety of Nuclear Power

Livermore's Fission Energy and Systems Safety Program is addressing the most important nuclear power issues for the federal government and, increasingly, foreign nations. The program's research is tied directly to each stage in the nuclear fuel cycle.

FEW areas of modern technology receive as much government—and public—scrutiny as nuclear power. With the goal of providing an independent authority to oversee the operation and licensing of civilian nuclear power plants, the federal government in 1972 formed the Nuclear Regulatory Commission (NRC). Since its inception, the NRC has relied upon national experts, including those at Lawrence Livermore, for independent, expert advice in virtually every aspect of nuclear power.

Indeed, the original group of Livermore nuclear power experts was named the NRC Program because it provided technical support for that government agency's regulations concerning nuclear systems. The Livermore program is now called the Fission Energy and Systems Safety Program (FESSP), but its goal remains the same, namely, to address the most important nuclear power issues for both the NRC and the Department of Energy (DOE), the nation's nuclear agencies.

Scope of the FESSP

The FESSP currently conducts more than 95 projects in 17 technical areas of nuclear energy. According to Mark Strauch, assistant deputy associate director for Energy Programs and deputy FESSP head, "All of our projects correspond to a part of the nuclear fuel cycle that begins when you dig uranium out of the ground and ends when you put the products back in the ground."

The Livermore program is unique because it was built around the nuclear fuel cycle (see box, p. 7). C. K. Chou, deputy

Figure 1. Control room of a nuclear power plant. Probabilistic risk assessment methodology from Lawrence Livermore is used by the Nuclear Regulatory Commission (NRC) and utility companies to evaluate risks in all stages of the nuclear fuel cycle.

associate director for Energy Programs and FESSP head, notes that Livermore's FESSP works on all aspects of the fuel cycle: mining; enrichment; power reactor operation; nuclear materials handling, storage, transportation, and waste management; repository development; nuclear facilities security; and regulatory reform. Such an umbrella organization, says Chou, fosters a broad perspective of nuclear power issues.

The program's activities have spun off to other national research programs at Lawrence Livermore, to Vice President Al Gore's office for using the power of electronic communication to make the federal government more efficient, and increasingly, to other countries for enhancing the safety of their national nuclear power programs (see box, p. 8).

The program taps the talents and expertise of many disciplines found at Livermore, including engineering; computer science; chemistry; geosciences, traditional environmental, health, and safety disciplines; safety analysis methodology; policy making; and safeguards and security. Besides their academic training, many FESSP people have practical experience in the nuclear industry.

One of the program's great strengths, its computer simulation codes for determining risks to nuclear safety systems, is derived from codes originally developed for Livermore's nuclear weapons development program. Indeed, all of the program's work benefits from a heritage of research on nuclear materials and processes dating from Lawrence Livermore's very beginning in 1952.

Addressing Public Concerns

Strauch notes that in providing about 20% of the nation's electrical needs, the 109 U.S. nuclear plants use processes and materials that are perceived by the public as extremely hazardous. In response to that concern, the nuclear industry has put into place safety systems comparable in complexity and integrity to those found on manned space flights. Assuring that these systems mitigate hazards requires an understanding of both external and internal threats. External threats include natural phenomena such as earthquakes, tornadoes, floods, and fires. Internal threats include everything inside the plant from a corroding pipe to a faulty instrument to human error.

The FESSP has long been involved in aspects of uranium mining and enrichment, the first two stages of the nuclear fuel cycle. The program has conducted studies of uranium tailings left over from mining uranium ore. It supports DOE's nuclear safety upgrade program at the United States Enrichment Corporation's (USEC) two enrichment plants that use gaseous diffusion technology.

FESSP experts are currently performing engineering and cost analyses for the selection of a long-term management strategy for the DOE's inventory of depleted uranium hexafluoride (UF_6). There now exist about 560,000 metric tons of depleted UF_6, left over from uranium enrichment activities. The results of the comprehensive analysis will assist DOE in evaluating the environmental impacts and costs of implementing management alternatives.

Once enriched fuel reaches reactors, it can be used only if structural, electrical, human, and safety systems are performing as designed. Over the past 20 years, the program has conducted a number of risk-assessment studies to support NRC regulations concerning reactor operation, ranging from the integrity of reactor coolant pipes to the software that controls critical systems.

The FESSP program has pioneered new approaches to determining risk (Figure 1) from many sources, but especially dangers posed by earthquakes. (For more information on risk assessment, see *Science & Technology Review*, August 1995, p. 16.) The Livermore staff conducted the first U.S. seismic probabilistic risk assessment for siting nuclear power plants from 1978 to 1985 using a new methodology called Probabilistic Risk Assessment (PRA) that is now used widely by the NRC and public utilities. The staff is currently helping the NRC to overhaul its seismic siting criteria for new nuclear power plants.

According to FESSP engineer Jean Savy, "PRA forces the user to rationally analyze a plant's components and their interactions in a systems framework. It reveals the weak links and calculates a scale of the relative likelihood of any component failing."

In an effort to diminish internal threats, Livermore Livermore is working with NRC to set new industry safety standards for digital control of instruments and safety systems being introduced in many power plants. "We want to ensure that digital systems are doing exactly what they're supposed to do," says computer afety and reliability manager Gary Johnson. In particular, Johnson's group works to ensure that the quality and diversity of software in redundant systems will minimize risk of common mode failures such as bugs in the software.

Fuel Storage and Transport

Risk analysis also comes into play to resolve issues that are related to storing and transporting spent nuclear fuels and other radioactive materials. FESSP experts have helped to determine the level of safety that must be provided when spent reactor fuel is transported to a nuclear waste facility. In the future, tens of thousands of spent nuclear fuel assemblies, now under temporary storage at power plants, will be transported to a federal repository for storage.

Shipment of spent fuel from U.S. commercial nuclear power plants, now occurring at a very low rate, is regulated by both the Department of Transportation and the NRC. The NRC evaluates and certifies the shipping casks, which are designed to protect the public from potential radiological hazard.

In one study for the NRC, the FESSP calculated the probable impact on shipping casks of 31 different truck accident scenarios and 24 different rail-accident scenarios. The safety analysis was based on extensive accident data and new computer analysis techniques developed at Livermore, and casks were field tested (Figure 2) (see *S&TR*, August 1995, pp. 18–19). In another study, FESSP staff reviewed several current cask designs for the NRC so that transporting spent fuel would be permitted to continue.

FESSP has developed an integrated software system called SCANS (Shipping Cask Analysis System), which the NRC uses to analyze the structural integrity of the storage casks under a series of normal operating loads and hypothetical accident loads. The software has been adapted for analyzing spent-fuel storage casks as well.

Currently, the program is reviewing DOE's proposals for changing the NRC's methods of evaluating the safety of a spent-fuel transport cask.

Safeguarding Data, Materials

One of the nuclear industry's most important tasks is ensuring that proper security is in place at nuclear power plants and other key facilities. FESSP is supporting the DOE in meeting security requirements throughout the agency's nuclear-related facilities.

The Argus security system, developed by Livermore's Safeguards and Security

Figure 2. One-third-scale casks that will be used to transport spent nuclear fuel are impact-tested at Site 300. Data are used to refine the codes that predict the casks' structural integrity.

program, is an interconnected, computer-based personnel access system that serves the Laboratory's Livermore and Site 300 facilities. The DOE has selected Argus as the standard automated electronic-security technology for its entire complex. Argus installations offer an access control function to allow entry by authorized personnel to specific buildings and areas, an intrusion detection system to monitor rooms containing classified documents or special nuclear material, and a central console dispatch system to oversee operation of both the access control and intrusion detection system.

FESSP people are providing Argus-type installations at DOE's Pantex Plant in Texas, the Idaho Chemical Processing Plant, the Air Force National Test Facility, and the Rocky Flats Environmental Technology Site. They are also assisting in the conceptual design of installations at Los Alamos National Laboratory and Idaho National Engineering and Environmental Laboratory.

Data can be as precious as nuclear materials, and FESSP people are working to control access to data, enhance secure communications, and achieve cost efficiencies in the process. For example, the program has developed an upgrade to the systems used by the Office of Personnel Management and DOE to process some 30,000 security clearances and reinvestigations annually (see *S&TR*, August 1996, pp. 18–19).

As part of FESSP's information security efforts, staff members have developed a strong capability in implementing so-called firewalls to protect information from unauthorized users. These information technology strengths were used to create the NRC's RuleNet World Wide Web page to elicit public comments and help make the

The Nuclear Fuel Cycle

The nuclear fuel cycle consists of the activities associated with producing electricity from enriched uranium, beginning with the mining of uranium and ending with the disposal of spent fuel and nuclear waste. The cycle is typically described as comprising a "front end" (preparing nuclear fuel for reactor operation) and a "back end" (managing the spent nuclear fuel).

Front End

At uranium mills, uranium oxide is extracted from ore containing between 0.1 and 1% uranium. The mill product, uranium oxide, is called "yellowcake" and contains more than 60% uranium. The uranium oxide is prepared for enrichment by chemical conversion to uranium hexafluoride (UF_6), a solid at room temperature but a gas at a slightly higher temperature.

In light-water-moderated reactors that are used by the U.S. nuclear power industry, enrichment is required because natural uranium's content of the fissile uranium-235 isotope (0.7%) is too low to sustain a nuclear chain reaction. The enrichment process boosts the concentration of uranium-235 to between 3.5% and 4.5%.

The gaseous diffusion enrichment process is currently used in the U.S. while gas centrifuge separation is employed in Europe. A third technology, AVLIS (atomic vapor laser isotope separation), is under advanced development by the United States Enrichment Corporation (USEC) at Lawrence Livermore. It uses 30% less uranium (and only 5% of the energy) than gaseous diffusion to produce a comparable amount of enriched product and does not require yellowcake to be converted to UF_6.

Currently, the enriched UF_6 is changed into pellets of ceramic uranium oxide that are sealed into corrosion-resistant tubes and placed in fuel assemblies. During reactor operation, the uranium 235 atoms fission, liberating heat, while the uranium 238 atoms absorb a free neutron and form uranium-239, which in turn decays to plutonium-239, a fissile isotope of plutonium.

The heat in the reactor core is carried away as steam, which passes to an electrical turbine generator for producing electricity. More than 40 million kilowatt-hours of electricity are produced from 1 ton of natural uranium, the equivalent of burning over 16,000 metric tons of black coal or 80,000 barrels of oil.

Back End

After its operating cycle (about 18 months), the reactor is shut down for refueling. The spent fuel rods are usually stored in water for both cooling and radiation shielding. Ultimately, the spent fuel will be transported for permanent disposal.

It is technically possible to extract the unused uranium and plutonium from spent nuclear fuel through chemical reprocessing and to recycle them as nuclear fuel. Currently both are done at plants in Europe with spent fuel from utilities in Europe and Japan. The U.S. has decided not to pursue the reprocessing option.

A current concern is the safe disposal and isolation of either spent fuel from reactors or, if reprocessing is done, wastes from reprocessing plants. Under the Nuclear Waste Policy Act of 1982, the U.S. Department of Energy has responsibility for the development of a national waste disposal system for spent nuclear fuel and high-level radioactive waste. Current plans call for the ultimate disposal of the wastes in solid form in deep, stable geological structures such as the proposed Yucca Mountain site in Nevada, but none is yet in operation.

regulatory process less burdensome. FESSP also helped to bring online the Vice President's Office of National Performance Review to communicate the federal government's latest efforts to make its operations more efficient.

The program also has established a Nuclear Systems Safety Center (NSSC) to serve as an online national resource for nuclear system information and analysis. The NSSC is linked via communications networks to the NRC, national laboratories, and other elements of the technical community.

A Home for Nuclear Waste

One of the greatest challenges facing DOE experts is determining the suitability of a potential underground site for the nation's first high-level nuclear-waste repository. By the year 2010, about 63,000 metric tons of nuclear waste from commercial nuclear power reactors and 7,000 metric tons of solidified nuclear waste from defense programs are slated for permanent disposal in an underground repository (see *S&TR,* April 1997, pp. 4–13).

Scientific studies are continuing in the evaluation of the suitability of the Yucca Mountain, Nevada, site as a potential long-term repository. Lawrence Livermore's contribution to

Livermore's Global Outreach to Enhance Nuclear Safety

Lawrence Livermore's Fission Energy and Systems Safety Program (FESSP) is involved in a host of international projects devoted to all aspects of the nuclear fuel cycle, but particularly to those concerned with enhanced reactor safety. FESSP experts are working with colleagues from Morocco, Britain, Australia, New Zealand, the Czech Republic, Japan, South Korea, Sweden, Spain, China, and nations of the Former Soviet Union.

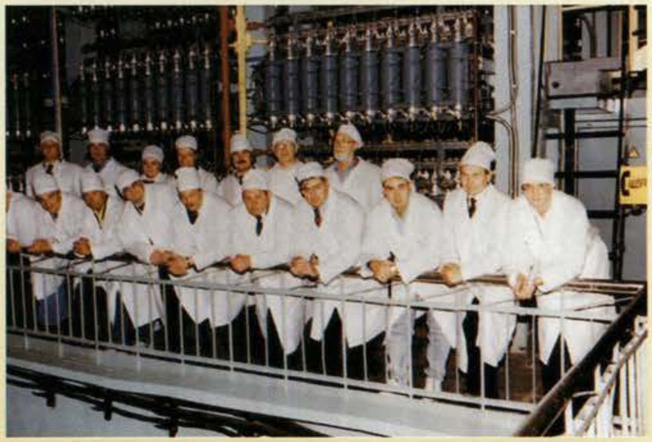
A major goal is to share expertise with the growing nuclear power industries in the Far East. Toward that end, Livermore is co-hosting a meeting in Las Vegas in September 1997 for industry representatives from South Korea, Taiwan, China, and Japan. The focus of the meeting, according to FESSP engineer Jor-Shan Choi, is repository issues and nuclear safety.

FESSP scientists are working with nations from the Former Soviet Union on two major projects. The first project is helping the NRC to provide the nuclear regulatory authority in Ukraine with information needed to establish regulatory control over radioactive wastes and spent nuclear reactor fuel. Ukraine, which formerly sent its wastes and spent fuel to Russia, must now build its own infrastructure.

The second effort is support to DOE in procuring highly enriched uranium obtained from dismantled Russian weapons. In 1994, Russia's Ministry of Atomic Energy agreed to dispose of 500 metric tons of Russian highly enriched uranium by converting it to low-enriched uranium and then selling it to the United States Enrichment Corporation (USEC). By the end of the 20-year contract, the weapons material from 20,000 Russian warheads will have been converted into enough fuel to generate an estimated 6 trillion kilowatt-hours of electricity, enough power to light the entire U.S. for about two years.

FESSP scientists and engineers are assisting DOE in developing and implementing so-called "transparency measures" to monitor the process that converts the highly enriched uranium to low-enriched fuel for nuclear power plants. The transparency measures, now in place at three Russian conversion facilities, ensure that the uranium comes from dismantled warheads. In exchange, the Russians will have periodic access to six U.S. power plants.

Finally, FESSP experts are aiding Livermore nonproliferation experts to enhance international safeguards for nuclear materials and to monitor reactor technology in developing countries.



Livermore provides technical expertise for implementing the transparency agreement under which the U.S. is purchasing low enriched uranium. Here, Scott McAllister (back row, left) and David Thomas (back row, second from right) are among a U.S. delegation and their Russian hosts, posing in front of centrifuges at Russia's largest uranium enrichment plant.

the project is the design of the engineered barrier system that will ensure containment of the nuclear waste. For several years, FESSP has been evaluating the waste form, the performance of candidate waste package materials, and the geologic environment.

FESSP scientists are also developing conceptual models, computer codes, laboratory experiments, and field tests to demonstrate the validity of their "localized dryout" concept for positioning the repository tunnels and placement of the waste containers. This approach uses the heat from the waste containers to drive moisture away from the tunnel walls, thus potentially delaying any container corrosion for tens of thousands of years.

According to FESSP project leader Bill Clarke, two important Livermore facilities have opened recently. The first is a heavily instrumented, room-size block of rock adjacent to the proposed Yucca Mountain site. Instruments in this rock gather data on moisture, temperature, water geochemistry, corrosion of metal samples, gas pressure and vapor, acoustics, deformation, and rock stresses (see *S&TR*, March 1996, p. 14–15).

The second facility is a new corrosion-testing laboratory at Livermore that allows the investigation of modes of corrosion in candidate materials for the waste package (Figure 3). This facility contains several dozen large vessels, each measuring about 1 meter square and 2 meters high, in which investigators simulate possible environmental conditions at an underground repository.

FESSP expertise is also being tapped as part of a DOE-led effort to study the best ways to dispose of weapons-grade plutonium recovered from dismantled weapons or in existing inventories that will remain unused. The program is working on new container designs that would allow the handling of plutonium oxide for mixed-oxide fuel fabrication for nuclear power reactors. FESSP experts are also aiding a wider Livermore effort to study the viability of two plutonium disposition options: immobilization in either glass or ceramic and burial in a deep borehole. The program also is performing safeguards and security studies for each of these options (see *S&TR*, April 1997, pp. 4–13).

Strong Future

With more than 100 U.S. nuclear power plants producing electricity, nuclear waste management policies still under discussion, and many foreign nations' nuclear industries seeking assistance on safety issues, it seems clear that the federal government will continue to require astute, independent technical expertise. In that regard, Chou says that the program's paramount goal is to be

Figure 3. The FESSP simulates underground corrosion of rock storage materials for the proposed Yucca Mountain storage site. Livermore's new corrosion testing facilities are pictured here.

responsive to the needs of the NRC and DOE.

Chou says that another way the FESSP can make a significant contribution is to address the growing national consensus that a more integrated view of nuclear power is needed to effectively solve complex issues such as waste management. He notes that Tom Isaacs, head of Livermore's Policy, Planning, and Special Studies, is making a start on meeting that challenge. With FESSP help, he is working on a systematic approach for dealing with all issues related to nuclear materials use and management.

Chou also expects that the FESSP's partnerships with colleagues from other nations will continue to grow. Although the U.S. has no new nuclear power plants planned, other nations are building new plants at a very rapid rate. Japan, for example, has a vigorous nuclear power development program.

"Other countries turn to the U.S. for advice on nuclear safety," says Chou. "We can provide that advice. For our part, working with them helps the U.S. keep current with state-of-the-art nuclear technology."

The federal government has long relied on FESSP for scientific expertise, says Chou. "We're confident we'll continue to earn their trust."

– Arnie Heller

Key Words: Argus, FESSP, nuclear fuel cycle, nuclear power, Nuclear Regulatory Commission (NRC), nuclear safety, Nuclear Systems Safety Center (NSSC), nuclear waste, plutonium disposition, United States Enrichment Corporation (USEC), uranium enrichment, Yucca Mountain.

For additional information contact Mark Strauch (510) 422-1469 (strauch1@llnl)

About the Engineer

MARK STRAUCH came to Lawrence Livermore from the University of Michigan, where he received his B.S. and M.S. in electrical engineering in 1976 and 1978. An electrical engineer, he joined the Electronics Engineering Department to work on the Magnetic Fusion Energy Program. Since then, he has also supported the weapons program and O Division and was an Engineering group leader and division leader. He became deputy program leader of the Fission Energy and Systems Safety Program and assistant deputy associate director in the Energy Programs Directorate three years ago. Strauch is an active member of the Institute of Electrical and Electronics Engineers and currently is financial chair of the San Francisco Bay Area Council.

The Microtechnology Center

When Smaller Is Better

From thin-film windows to microactuators to photonic devices—the Center contributes to stockpile stewardship, bioscience, and nonproliferation projects at Livermore.

A dime-sized amplifier makes fiber-optic communications faster and clearer. A portable DNA analyzer helps detect and identify organisms in the field, including human remains and biological warfare agents. A tiny gripper inserted in a blood vessel treats aneurysms in the brain to ward off potential strokes. What do these technologies have in common? Each one is smaller than any comparable product, opening up a host of new applications. And each originated in Lawrence Livermore National Laboratory's Microtechnology Center.

In the late 1960s, Livermore scientists and engineers began making miniature devices for high-speed diagnostic equipment required for nuclear tests. For many years, before the development 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, as x-ray filters, as debris shields for the Extreme Ultraviolet Lithography Program, and as targets for high-energy electron experiments in which x rays are generated.

These passive microstructures have been applied to dozens of projects. They have served as diagnostic devices for Livermore's Nova laser experiments and will do the same for experiments at the National Ignition Facility (NIF). Another microstructure, a novel thin-film window developed by Glenn Meyer and Dino Ciarlo, plays a critical role in a new, more efficient electron-beam system for processing inks, adhesives, and coatings. Laboratory scientists, led by Booth Myers and Hao-Lin Chen, teamed with American International Technologies Inc. of Torrance, California, on this project and won an R&D 100 Award in 1995. Conventional electron-beam processing systems are inefficient, delivering about 5% of the beam's energy to the polymer being cured. With this new window, efficiencies greater than 75% were achieved. The team also recently won a 1997 Federal Laboratory Consortium Award for Excellence in Technology Transfer.

In the mid-1980s, Livermore began combining micro-optical 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 stopped fabricating silicon-based electronic circuits when commercial microchips became available in almost every configuration imaginable. But invention by no means stopped. Today, the Microtechnology Center, now headed by physical chemist and engineer Ray Mariella, invents and applies microfabricated components, including photonic devices, microstructures, and microinstruments, to directly support Laboratory projects in science-based stockpile stewardship, nonproliferation, and biomedical research. At any given moment, the Center has about 25 projects in the works. The Center's major recent and ongoing projects are highlighted here.

The Center's state-of-the-art fabrication facilities are centered in a building whose location was selected because the area had the smallest vibrations within the Laboratory site, permitting the high-resolution microlithography that the Center performs. Microdevices can be fabricated there in any of three material systems:

- Silicon and silicon compounds for microstructures and microelectromechanical systems applications.
- Gallium-arsenide for photonics applications.
- Lithium niobate for electro-optic applications, such as phase and amplitude modulators.

The Center has the equipment and infrastructure needed for lithography, etching, diffusion, wafer bonding, and thin-film deposition and vacuum techniques. Its dry laboratories are used for surface inspections, packaging, and electrical and optical device testing. Groundbreaking recently took place for an addition that will increase clean-room space by 65%. The backbone of the Center is an interdisciplinary group of about 50 electronics, mechanical, chemical, and biomedical engineers, physicists, and technical support personnel (Figure 1). According to Mariella, "Ideas, technologies, and capabilities are shared at frequent brainstorming sessions, so staff can find solutions to programmatic problems quickly."

Putting Light to Work

Photonics work at Livermore got its start from the need to obtain remote, highly accurate measurements at nuclear weapons tests. Photonic systems—which manipulate and exploit light for control, communication, sensing, and information display—were the ideal solution because signals can travel on them for long distances at the speed of light with very little power loss. After several years of development, Livermore successfully fielded its first photonic system for measurement of ionizing radiation from a nuclear weapon at the Nevada

Figure 1. Most members of the Microtechnology Center staff.

Test Site in 1989. This system made available very high-resolution data that conventional measuring techniques could not deliver. In 1991, Livermore was awarded the DOE Weapons Excellence Award for this work.

A photonic network is typically made up of optical fibers, waveguides, amplifiers, receivers, wavelength selection elements, and modulators, sometimes all on a single chip. One of the Laboratory's contributions to the photonics field has been its novel application of silicon micromachining capabilities, which have been critical to packaging photonic components in a cost-effective manner. In 1994, Mike Pocha, Dan Nelson, and Ted Strand won an R&D 100 Award for the development of a silicon "microbench" that reduces the time needed to align and connect the optical fiber in photonic components. Because of the submicrometer alignment tolerances, the standard manual process was extremely time consuming and therefore expensive. The team's technique (Figure 2) provides just enough heat to melt the microdrops of solder needed to make the connection, allowing a rapid manual alignment and connection of the fiber to a laser diode or a lithium niobate modulator in less than five minutes and reducing the cost for this work by 90%.

Photonic devices are finding their way into two different parts of the Laboratory's science-based stockpile stewardship program. One is ultrascale computing, which soon will be used for simulations of nuclear tests; the other is diagnostics for NIF.

Computing on a large scale requires the cooperative action of thousands of microprocessors sharing tremendous volumes of data. This data sharing demands a communication "fabric" of very high bandwidth and low latency (short time delay) to enable the microprocessors to function without waiting for data. Optical fibers are an ideal medium provided that the optical signals are sufficiently amplified so that there are enough photons to go around for the many receiver nodes. Existing amplifiers had problems: erbium-doped fiber amplifiers are bulky and expensive, and conventional semiconductor optical amplifiers produce too much crosstalk at transmission rates above 1 gigabit per second.

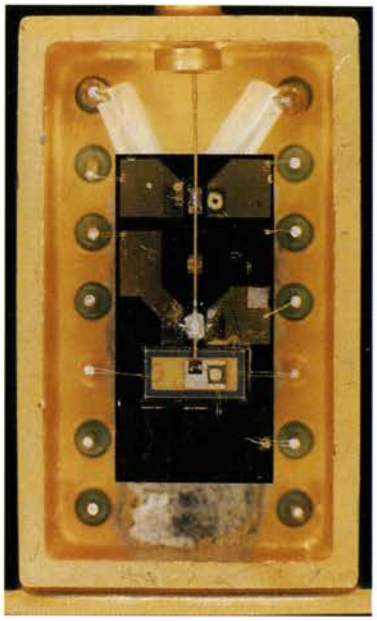


Figure 2. With the silicon microbench, two polysilicon heating elements and gold solder attachment bases provide the means for attaching the optical fiber. While the fiber is held in position, current is passed through the heater to reflow the solder, which wicks around the metalized fiber without disturbing the alignment. This new method avoids thermal shifts and simplifies the alignment process.

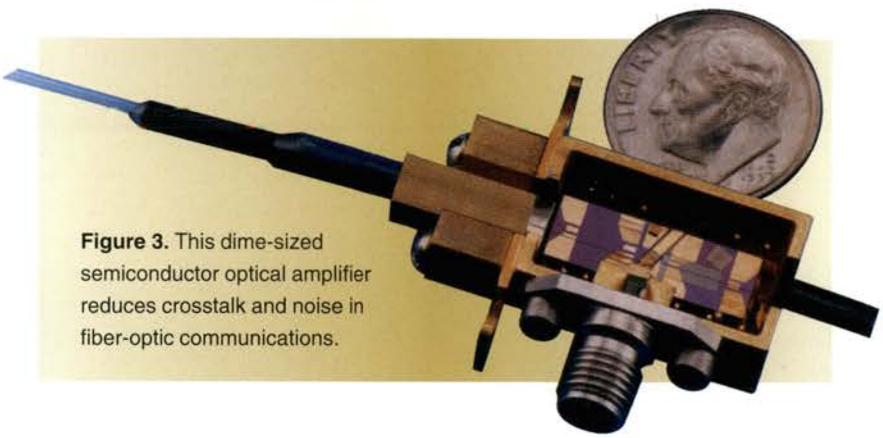


Figure 3. This dime-sized semiconductor optical amplifier reduces crosstalk and noise in fiber-optic communications.

To solve this problem, Sol DiJaili, Frank Patterson, Jeff Walker, Robert Deri, William Goward, and Holly Peterson developed a miniature, low-cost semiconductor optical amplifier (Figure 3). They applied state-of-the-art microfabrication techniques including molecular beam epitaxy to grow device wafers and chemically assisted ion-beam etching to make the device structures. The team won a 1996 R&D 100 Award for their new device, which can be used not only for computer interconnections but also in wide-area networks and for transmitting visual images.

They then replaced the standard gain medium inside the waveguide of the amplifier with a tiny vertical-cavity surface-emitting laser and took advantage of some basic laser properties to reduce crosstalk by a factor of 10,000. The photons' stimulated emission in the gain medium when lasing occurs acts as a clamp on the signal gain, eliminating the fluctuation. Signal channels at multiple optical wavelengths can pass through the waveguide with virtually no crosstalk among these channels. The lasing action also speeds recovery time of signals through the waveguide, from a billionth of a second to about 20 trillionths of a second. Thus, the amplifier can successfully track the amplification of a serial bit stream at very high bit rates.

The Microtechnology Center is also applying photonics technology at NIF. Because NIF's 192 laser beams will be aimed at such small targets (about the size of mustard seeds), NIF will need much faster radiation diagnostics than those used at the Nevada Test Site. Mike Pocha and Howard Lee are developing photonic radiation sensors that will modulate an optical beam in response to an ionizing radiation input and then record it using single-shot optical samplers having a response time of 100 femtoseconds (quadrillionths of a second). Pocha and Lee are investigating the use of waveguides made of nonlinear optical material to perform the extremely high-speed signal gating required to sample at these high data rates. (A nonlinear optical material is one whose index of refraction can be changed by the introduction of another light beam.) These nonlinear gates will be capable of switching sequential slices of the radiation-modulated optical signal into an array of relatively slow-speed optical detectors. A material that may have the right nonlinear properties is fullerene (C_{70}), whose discoverers recently won the Nobel Prize in Chemistry. (Fullerene is a van der Waals crystal with molecules shaped like Buckminster Fuller's geodesic domes, hence its name.) The world's first fullerene waveguide array, which is still undergoing development, is shown in Figure 4. Work continues on this project so that a fully functional system will be on line in time for the testing of NIF, which is scheduled for 2002.

Analyses in Miniature

Analyzing DNA, testing for HIV, and identifying pathogens and poisons used in biological and chemical warfare all require sampling a range of products. Supporting the Laboratory's bioscience research program and its nonproliferation efforts, the Microtechnology Center has developed several cutting-edge microdevices that facilitate biological and chemical sampling and analysis in the field, allowing real-time detection. Because some samples cannot survive transport from the field to a remote laboratory, field analysis is often the only solution.

Biological and chemical sampling with micro-instruments offers other advantages as well. Smaller instruments have lower power requirements. Highly integrated and automated sample handling systems usually result in improved productivity and less sample contamination. Also, because analytical diagnostic procedures sometimes produce hazardous wastes, smaller systems mean less waste. However, extremely small-volume chambers require greater sensitivity in order to identify the extremely small trace samples.

A team led by Ray Mariella has patented a new system that eases alignment and increases the accuracy of flow cytometry. Flow cytometry is a powerful diagnostic tool used to characterize and categorize biological cells and/or their contents, such as DNA. It is used by laboratories throughout the world for blood typing and for testing for a wide variety of diseases and viruses, including HIV. The cells flow in single file in solution while the experimenter directs one or more beams of laser light at them and observes the scattered light, which is caused by variations in the cells or DNA. Instead of using a microscope lens or an externally positioned optical fiber as a detector, Mariella's system uses the flow stream itself as a waveguide for the laser light,

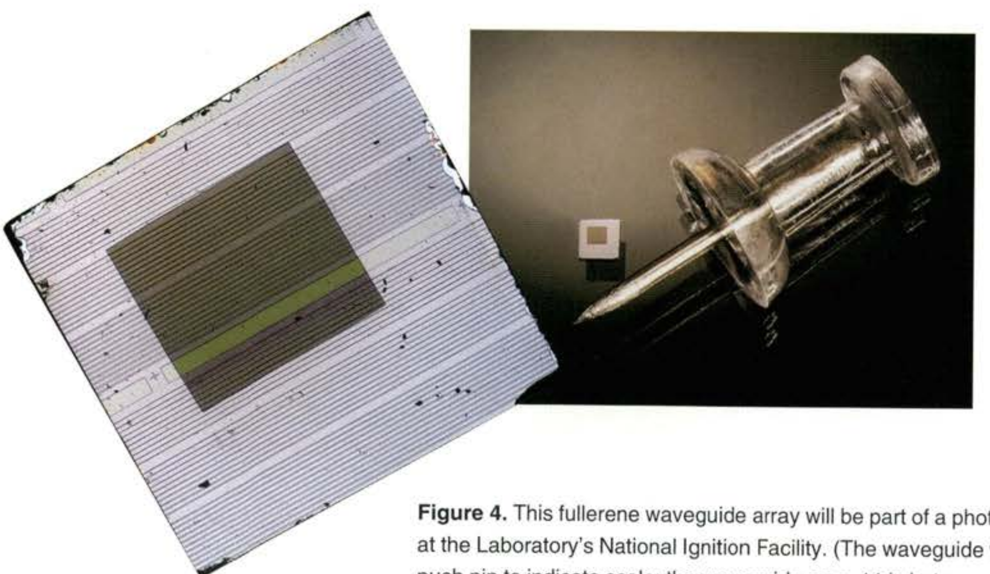


Figure 4. This fullerene waveguide array will be part of a photonic radiation sensor system at the Laboratory's National Ignition Facility. (The waveguide was photographed next to a push pin to indicate scale; the waveguide on p. 11 is between two X-acto knife blades.)

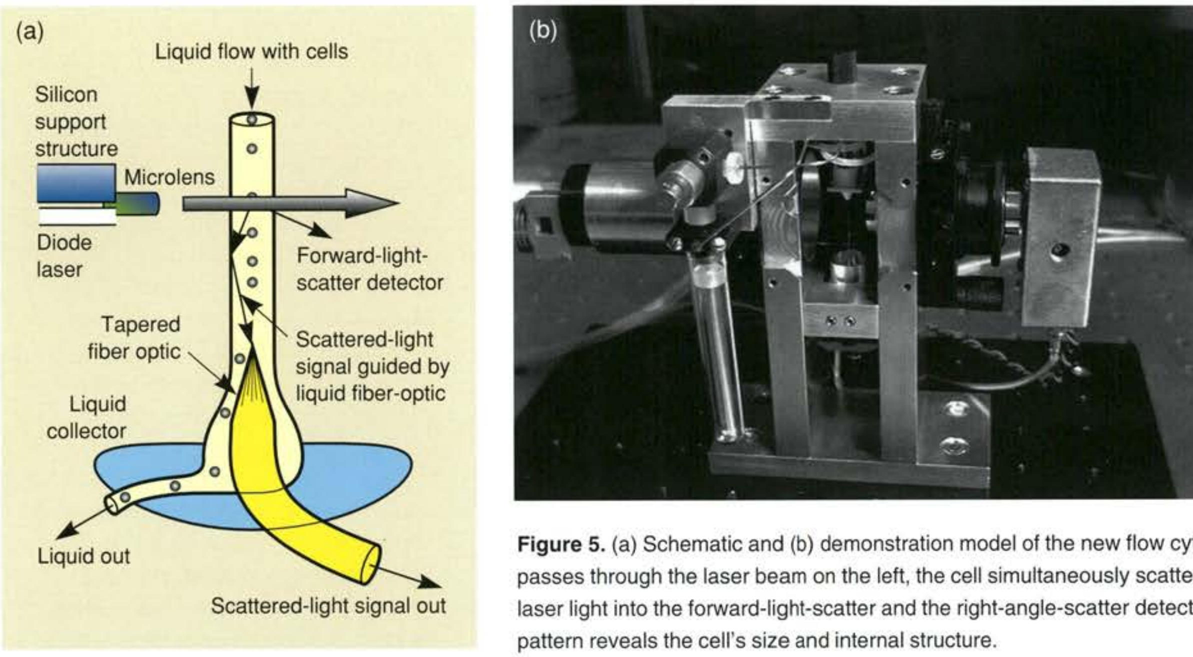


Figure 5. (a) Schematic and (b) demonstration model of the new flow cytometer. As a cell passes through the laser beam on the left, the cell simultaneously scatters (reflects) the laser light into the forward-light-scatter and the right-angle-scatter detectors. The scatter pattern reveals the cell's size and internal structure.

capturing the light and transmitting it to an optical detector. Alignment simply requires lining up the light source onto the flow stream and placing the detector into the same stream (Figure 5). With this system, measurements are up to three times as accurate as those taken with conventional systems.

At international joint field trials last fall at Dugway, Utah, the new flow cytometer performed extremely well detecting simulated biological warfare agents. Participants from the U.S., the U.K., Canada, and France used a variety of instruments to detect four simulants. The Livermore flow cytometer detected 87% of all the unknowns with a false positive rate of just 0.4%.

Dino Ciarlo, Jim Folta, and William Benett developed a miniature sample injector that can be used in Mariella's flow cytometer. Flow channels are formed by etching three silicon wafers and bonding them into a single chip. Fluidic connections are made to this injector chip via a plastic block. A thin gasket, laser-cut from an elastomeric material, forms a seal between the silicon chip and the block. The front edge of the silicon chip remains exposed to allow fluid to freely exit through an edge port into the optical detection system.

A Laboratory team headed by M. Allen Northrup has developed an portable DNA analyzer that is small enough to fit in a briefcase. It is also fast (Figure 6). This unit, the world's only battery-powered DNA analyzer, moves analysis out of the laboratory for the first time. Folta and Benett developed a disposable polypropylene liner for the analyzer's tiny heated chamber where the polymerase chain reaction occurs. The liner facilitates rapid reuse of the chamber and eliminates tedious cleaning and possible contamination. The entire chamber is a tiny chip of silicon. As the reaction progresses, the team uses a fluorescent signal to analyze the DNA to determine whether it matches that of a particular subject.

LLNL has delivered one of these units to the Department of Defense

Figure 6. The Microtechnology Center's DNA analyzer and computer system fit in a briefcase. The polymerase chain reaction chamber and related analysis equipment are on the right side of the case.

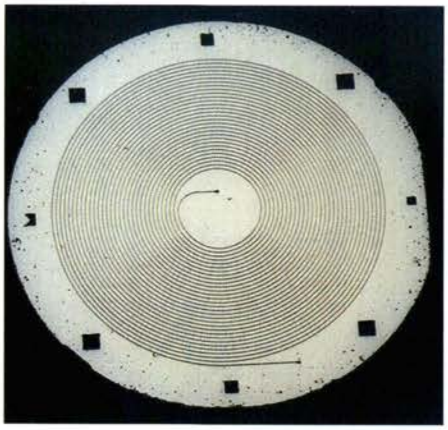


Figure 7. The column for the miniature gas chromatograph has been reduced to two silicon wafers bonded together. Here, one wafer is shown with its coiled groove 100 micrometers wide and several meters long.

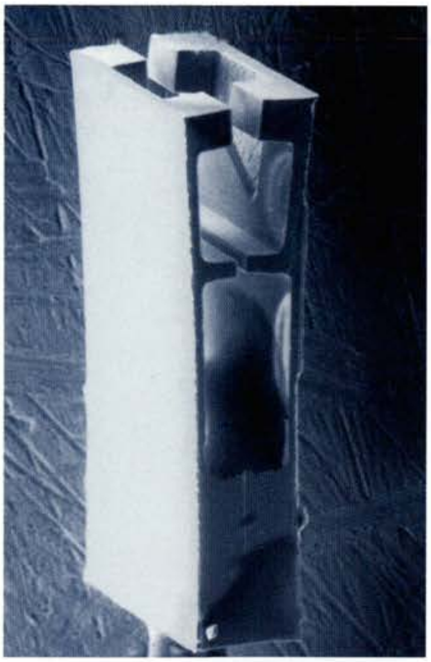


Figure 8. The microgripper, the size of two grains of salt, is the first in a series of new surgical microtools being developed by the Laboratory's Center for Healthcare Technologies.

Armed Forces Institute of Pathology, which is using it to quickly identify human remains in the field, test food and water for contamination in remote locations, and identify pathogenic bacteria on the battlefield.

The Microtechnology Center is also supporting the Laboratory's DNA sequencing work for the Human Genome Project. As described in the research highlight beginning on p. 18 of this issue, the Center has developed etched and bonded microchannel glass plates to speed up the sequencing process. A patent is pending on the new bonding process.

Conrad Yu of the Center is participating in work on a miniature, portable, low-power gas chromatograph to support the Laboratory's program in nonproliferation to counter the spread of chemical weapons. Gas chromatography is a proven method for identifying liquid or gas species, with detection sensitivities as high as parts per billion. Conventional gas chromatographs, however, are several cubic feet in size and typically take about 20 minutes to analyze a gas sample. A mini unit works faster, often requiring just one minute to complete an analysis, and would be very useful to carry into an area where chemical weapons or other poisonous gases are suspected to have been used. Someday this unit could also be used at home for sniffing out radon gas.

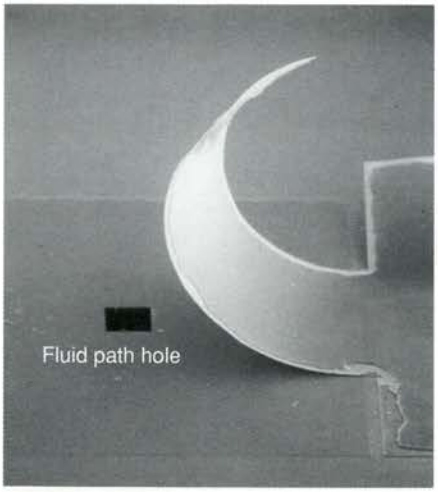


Figure 9. The 200-micrometer-long microvalve is shown in the open position, revealing an etched hole.

Yu has developed a micromachined, silicon sample injector about the size of a little fingernail. He has also reduced the size of the chromatograph's column where the various elements in the sample are separated before being directed to the detector where they are identified. The column has been reduced from 1.6 liters (100 cubic inches) for a laboratory-sized unit to a coil etched on a silicon wafer. A circular column 100 micrometers wide and several meters long is etched on two silicon wafers that are bonded together. The entire instrument occupies about 0.16 liter (10 cubic inches) (Figure 7).

Microtools for Better Health

A new surgical tool for treating aneurysms, the silicon microgripper is about the size of two salt grains—1 by 0.2 by 0.4 millimeters. With guidance from researchers at the University of California, San Francisco, Abraham Lee, M. Allen Northrup, and Peter Krulevitch developed this micro-electromechanical device. As shown in Figure 8, the microgripper is like a tiny hand that surgeons can use to place clot-inducing agents to fill an aneurysm. A surgeon may also use it to perform minimally invasive *in vivo* biopsy or catheter-based endovascular therapy. Nonmedical uses include assembling small parts for manufacturing and remote handling of small particles in extreme environments, such as high or low pressures and hazardous fluids.

A key to the microgripper's effectiveness is a thin-film microactuator that is fabricated from a shape-memory alloy (SMA). At low temperatures, SMAs are easily deformed, but when heated, they recover their original shape. This reversible transformation forms the basis for shape-memory actuators, in which a biasing force, produced by a spring, for example, deforms the SMA element at low temperature, and the SMA element overcomes the bias when heated. For the microgripper, the team developed a sputter-deposited shape-memory actuator of nickel–titanium–copper, with a transformation temperature just above body temperature. The microgripper is inserted into a blood vessel in the closed (deformed) position. Through a thin wire connected to the microgripper, an electrical current of 0.1 milliamp activates the actuator, deflecting each arm up to 55 micrometers and returning the gripper to its undeformed (open) position. As it cools, the gripper will open again. (A patent was recently issued for another microgripper made of plastic with a balloon actuating system. It is briefly described on p. 23.).

Lee, Julie Hamilton, and Jimmy Trevino have also built a low-leakage, high-efficiency microvalve (Figure 9). Effective microvalves are an important link in creating miniature total analysis systems that can be used for drug delivery and bioanalytical instrumentation. Nonmedical applications for the microvalve include fluid injection analysis, chemical processing and analysis, and atmospheric and temperature control equipment. In this design, an electrode is sandwiched between two polyimide films with different coefficients of thermal expansion. (Polyimide is a flexible plastic material.) Delivery of less than 1 milliwatt of power causes the "cantilever" to clamp down, sealing an etched hole beneath it.

And the Work Goes On

Two relatively new areas of expertise for the Microtechnology Center are treaty verification and counterproliferation, which require low-cost, efficient, autonomous processing of large numbers of chemical and biological samples. Integrated microdevices are critical to the success of these new fields.

Microtechnologies and microdevices have never been an end in themselves at Livermore. Rather, they are problem solvers. As Lawrence Livermore researchers search for solutions to mission-specific challenges, they often find that commercial products do not meet their needs. They turn to the experts at the Microtechnology Center, whose creations are often what enable a Laboratory experiment or diagnostic tool to function successfully. Integrated microdevices are thus finding their way into increasing numbers of Laboratory projects.

— Katie Walter

Key Words: bioanalysis, DNA analysis, DNA sequencing, flow cytometry, gas chromatography, microactuators, microdevices, microstructures, photonics, polymerase chain reaction, semiconductors, shape-memory alloys, thin films.

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About the Scientist

RAY MARIELLA, JR., is head of the Microtechnology Center. For the last five years he has been a team leader for bioinstrumentation and the thrust area leader for microtechnology. Mariella joined Lawrence Livermore in 1987 as a project engineer in the Electronics Engineering Department's Engineering Research Division to establish a capability in molecular beam epitaxy. He received his B.S. in mathematics, chemistry, and chemical engineering from Rice University in 1969 and his M.A. and Ph.D. in physical chemistry from Harvard University in 1970 and 1973. Before coming to Livermore, he worked at the Allied Signal research facility in Morristown, Virginia. He has published more than 30 articles and holds 5 patents.

Speeding the Gene Hunt: High-Speed DNA Sequencing

FAST. Faster. Fastest. In the commercial arena, getting big jobs done fast requires automation, For the Human Genome Project at Lawrence Livermore National Laboratory, the key to uncovering thousands of yet-to-be-identified human genes is to automate and speed up the specialized biotechnical equipment that prepares and sequences DNA samples.

The point of all this urgency is the gold mine of information contained within the structure of the genes themselves. Genes and the proteins they produce hold the key to unlocking the mysteries of genetic diseases. Once the genetic code for a disease is understood, researchers can begin developing gene and drug therapies for that particular disease. The ultimate goal of the worldwide Human Genome Project is to find all the genes in the DNA sequence, develop tools for using this information in the study of human biology and medicine, and improve human health.

Sequencing involves determining the exact order of the four individual chemical building blocks, or bases, that form DNA. The total DNA in a single human cell has approximately 3 billion pairs of the chemical building blocks adenine, thymine, guanine, and cystosine. (For more information on the Laboratory's other work in DNA sequencing, see *S&TR*, November 1996, pp. 24–26.)

For a multidisciplinary team of engineers, chemists, computer scientists, and biologists at Livermore, Joe Balch is project leader for developing a next-generation instrument for sequencing DNA. When this high-throughput DNA sequencer is built and its operating conditions are optimized, it will ultimately read nearly 600,000 bases per eight-hour shift, about 12 times faster than current instruments, which manage at most 48,000 bases per shift.

"There is a worldwide push in the field to 'pick up the speed' with which DNA is sequenced," said Balch. "The current strategy is to do it with existing technology and just turn the crank a lot of times with more people. It's very people-intensive. The next-generation sequencing machine we are developing will allow us to leave the old technology behind and take the next step in automation." Livermore expertise in microfabrication, bioinformatics, and biochemistry makes this move possible.

Faster sequencing will also provide other Livermore programs with faster access to information in nonproliferation projects to detect biological signatures of collected samples and in bioremediation projects to optimize micro-organism action.

Figure 1. Computer-generated image of fluorescent bands after the fragments are detected by the laser.

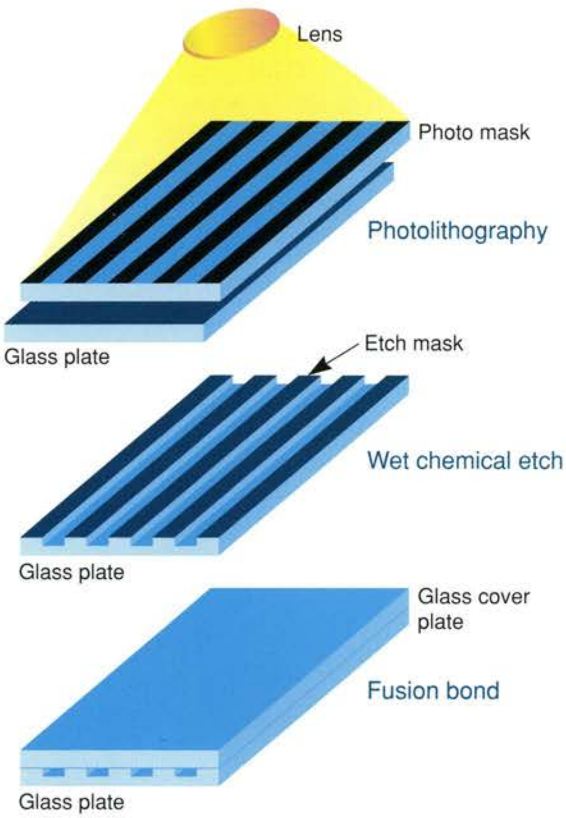
Sequencing: How It Works

When biological researchers want to sequence a section of DNA, they clone fragments of that section and then run four nearly identical reactions on those fragments. In these reactions, the four bases are chemically labeled with four different fluorescent dyes.

The sequencing machines currently used at the Laboratory are based on a gel-electrophoresis system, which works like this. The DNA samples are loaded by hand into a 200- to 400-micrometer-thick polyacrylamide gel, rather like thin Jello, which is sandwiched between two large glass plates, 48 centimeters long by 25 centimeters wide. The plates can hold 36 samples at a time. An electric current is then applied to the gel, and, because the DNA itself has a negative charge, the fragments migrate in 36 columns or "lanes" from the top to the bottom of the plate. The DNA fragments move at different rates depending on their size: smaller ones move faster than larger ones. As the fragments migrate past a certain point in the gel, a laser beam scans back and forth across the plate, exciting the dyes on the DNA bases. As the fragments pass the laser, the bases are separated from smallest to largest. The fluorescent signals generated by the laser are detected by photomultiplier tubes (or other detectors), and a computer captures, stores, and processes them (Figure 1).

When cleaning, loading, and running times are all taken into account, it takes between five to seven hours to complete a run. Each sample contains about 500 bases, which means each run of 36 samples yields no more than 18,000 bases. According to

(a)



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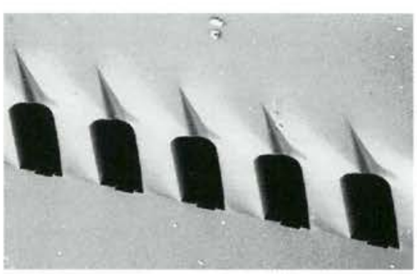

Balch, conventional technology is expanding the number of lanes to 64, which will increase the yield to about 32,000. But to increase those numbers significantly, say, by an order of magnitude, requires applying some new technologies.

There are a number of ways to increase this yield, explained Balch, who is also the former head of the Laboratory's Microtechnology Center. (For an overview of the Center, see pp. 11–17 of this issue). "You can increase the number of lanes on a single run. You can increase the speed at which you do a run—in other words, apply more electric field to the fragments. You can also look for ways to cut down on the loading and cleanup times, which often take a couple of hours. But to do all of these things, you need to move outside the current technologies and look for different ways to get the job done." That is what they are doing for their new sequencing machine (Figure 2).

Increase the Lanes

In the current system, although the samples travel in "lanes," no physical barriers divide one lane from the next. "And even though you have an electric field pulling the fragments to the bottom, they still wander a bit," said Balch. "Right now, we correct the wandering with software, with what is called 'lane tracking.' But if we start packing more lanes in, there's a problem with the columns blurring into each other."

So Balch and his team are taking a different tack: fabricating small, exact lanes, or microchannels, in large glass plates through which the gel medium flows. This effort got its start in 1993 with seed money from the Lawrence Livermore's Laboratory Directed Research and Development Program. In 1994, the Laboratory entered a year-and-a-half agreement with Perkin Elmer's Applied Biosystems Division to further develop this technology and some of the others

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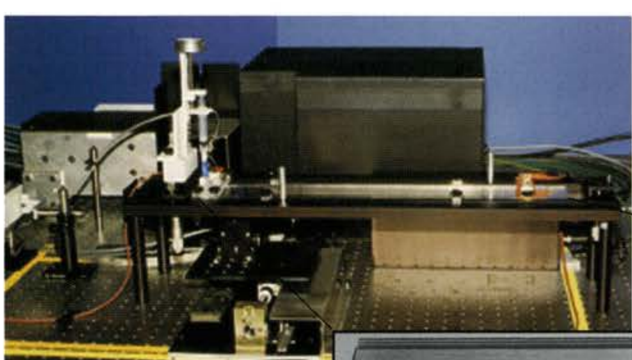

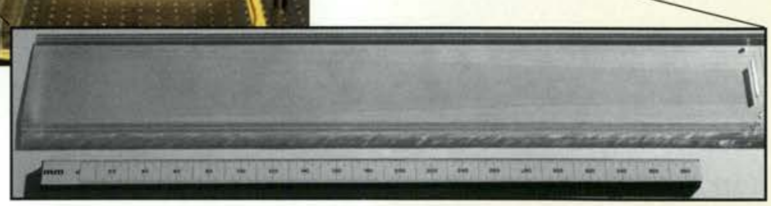

Figure 2. During fabrication of the new 96-lane sequencing machine, the pattern of channels is first defined by (a) photolithographic processing on a photoresist plate. (b) Then, that plate is used to chemically etch the pattern on the glass. (c) Finally, the top piece of glass is bonded to the etched glass plate.

needed for the new system. This effort is now being supported by grants from the National Institutes of Health and the DOE Human Genome Project.

Last year, Steve Swierkowski and Courtney Davidson of the Microtechnology Center successfully demonstrated the fabrication of a 96-lane array on a piece of glass 7.5 centimeters wide and 55 centimeters long—in other words, twice the lanes that current technology can offer in less than a third of the space. Ultimately, the team will be producing plates with 384 channels.

"These high-density microchannel glass plates are the really novel piece of our instrument," noted Balch. "The fabrication process involves three steps, each of which we need to continue to build and improve upon." (See Figure 2a.)

The first is the photolithography step, where the pattern of the channels is defined on a photomask plate. The second involves using that plate to chemically etch that very small pattern on the glass to very exact specifications. The final step is bonding the top piece of glass to the etched glass plate. Figure 2c shows the current prototype instrument developed by Davidson, Larry Brewer, Joe Kimbrough and Ron Pastrone.

Increase the Speed

Another way to speed up the process is to increase the electric field. The velocity of the DNA increases proportionally. In the current system, however, just increasing the field leads to other problems.

A higher electric field increases the power dissipation, which increases the temperature in the sieving media, explained Balch. And when the gel heats up—and the DNA samples in it—thermal diffusion causes the fluorescent bands to spread out. The bands run into each other and can no longer be identified as individual and distinct bands. This problem can be significantly reduced by using a very thin gel (about 50 micrometers thick) or other sieving media in place of the polyacrylamide gel now being used. The thinner gel means that the temperature gradient across the width of the gel is smaller, and the thermal diffusion of the DNA fragment bands is less.

With this thin sieving media, the instrument can run with an electrical field three to four times higher than that used on the conventional instrument. Thus, the speed of the run increases by the same factor.

Decrease the Clean-Up Time

Another improvement involves using small syringe pumps to inject thin sieving media into the microchannels of the new instrument when a run begins and then automatically pumping it out when a run is complete. This procedure will significantly speed up the overall time it takes to complete a run.

"With the polyacrylamide gel now in use, you have to go through a lengthy preparation at the start of a run to make a fresh gel. Then at the end, you have to take the plates apart, remove the old gel, and clean the plates for the next run. With this new media, we just pump it in and out through channels and capillaries without removing the microchannel plate from the instrument," said Balch. "We figure that when the system is up and running, one run will take two to three hours from start to finish, compared with four to five hours using the polyacrylamide gel."

Putting It All Together

Because the new system has different performance specifications than the old, simply loading the new glass plates with the new medium into the old machine is not the only change.

For instance, because the DNA fragments are moving at a higher velocity when they come to the laser, the laser has to scan across the plates faster. In addition, given the 96 lanes now and the 384 to come in the future, Balch and his team are exploring several concepts for automatic sample loading.

Other systems being developed include the laser-induced fluorescent detection system, the fluidic and pumping system for the polymer medium, a temperature control system, and analysis software. "These improvements plus the microchannel plates themselves add up to seven major parts of the high-throughput DNA sequencer that we must eventually meld together," said Balch. "The final production system is still down the road. When it's ready, we plan to make it available to others within the Department of Energy and the human genome community."

— Ann Parker

Key Words: DNA sequencing, Human Genome Project, microchannel, polyacrylamide gel.

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The Human Genome Center's Internet home page is at http://www.llnl.gov/bbrp/genome/genome.html. The Department of Energy's "Primer on Molecular Genetics" is located at http://www.gdb.org/Dan/DOE/intro.html.

Microbial Treatment of High Explosives

Figure 1. The pilot test system for biological treatment of high-explosive waste at DOE's Pantex Plant.

WHILE we may not want bugs crawling around our homes, some of them make remarkable little workers. Special micro-organisms that possess certain enzymes effectively degrade the pollutants in sewage at treatment plants. They also clean up soil contaminated by petroleum products. At closed gasoline stations, the large mounds of earth contaminated by leaking underground storage tanks are being composted by a variety of microbes that occur naturally in soils.

Microbial treatment of contaminated materials has become increasingly common. In 1989, Lawrence Livermore National Laboratory chemist John Knezovich and environmental scientist Jeffrey Daniels began a study with Professor Michael Stenstrom of the University of California, Los Angeles, an expert in wastewater treatment, to determine the feasibility of using similar, naturally occurring micro-organisms to treat materials contaminated with high explosives. The goal: to break down the hazardous compounds into nonhazardous units. The success of this inexpensive method could have wide ramifications. The Department of Energy's Pantex Plant in Amarillo, Texas, disassembles nuclear weapons as it reduces the size of the stockpile and generates high-explosive waste in the process. The Department of Defense must dispose of an even larger quantity of high explosives. Various international treaties require the demilitarization of large numbers of conventional weapons, all of which contain high explosives.

Both DOE and DoD use water and/or steam in the process of removing high explosives, resulting in large quantities of contaminated water. This water typically is run through activated carbon filters, which remove the high explosives and leave clean water, but the process contaminates the carbon filters. In fact, activated carbon laden with high explosives is considered a hazardous waste by the U.S. Environmental Protection Agency. To dispose of the carbon, the Pantex Plant has been burning it, but this disposal process is becoming unacceptable for environmental, health, and safety reasons. Some DoD facilities have been storing it, but this is only a short-term solution. The current best method for decontaminating the carbon is to heat it in a relatively expensive process called thermal regeneration, which requires shipment of the contaminated carbon to an offsite treatment facility.

Livermore's 1989 study, funded by the Laboratory Directed Research and Development Program, first demonstrated the feasibility of biologically treating the small quantities of high-explosive waste that are in wastewater produced at the Laboratory's high-explosives testing range at Site 300. The results of experiments were encouraging and led to the Livermore team developing, installing, and testing a pilot plant at Pantex in 1993 for the direct treatment of wastewater and the regeneration of contaminated carbon (Figure 1). Measurements at that plant have proved that naturally occurring micro-organisms can directly degrade RDX and HMX, the most commonly used high explosives within the DOE.

By late 1997, with funding from DOE and DoD, the project team will install another pilot plant at the Hawthorne Army Depot's Western Area Demilitarization Facility in Hawthorne, Nevada. That facility presently uses a steam-out process for removing high explosives from conventional ordnance, resulting in an annual production of up to 25 million gallons (95,000 kiloliters) of water contaminated with high explosives. Subsequent treatment of the wastewater by activated carbon filters generates approximately 120,000 pounds (130 metric tons) of contaminated carbon.

Bugs Need Help

Microbes that clean up sewage and gasoline-contaminated soil often directly feed on those materials. During the feasibility study, the project team learned that bugs do not "eat" the high explosives. Instead, a systematic process of supplying various nutrients showed that when the micro-organisms are fed ethanol and other simple compounds containing carbon in the presence of high explosives, they produce enzymes that degrade RDX and HMX.

Although the pilot plant at Pantex demonstrated that microbial treatment of water contaminated with high explosives was feasible, this process would not be efficient for the large quantities of wastewater that are generated at demilitarization facilities. Accordingly, the team developed a method that couples a chemical process that removes and degrades the high explosives on the carbon with subsequent biological treatment of the wastewater to render the by-products nonhazardous.

As illustrated in Figure 2, the procedure now in development involves first flushing the carbon-filled column with heated (80°C) alkaline water (pH ≥ 12). This process, known as base hydrolysis, regenerates the carbon by removing the trapped high explosives and transforms the explosive materials into nonexplosive but easily degraded hazardous carbon compounds. As the wastewater flows from the carbon column to the "bioreactor" column, ethanol and other nutrients are added to the mixture. The microbial action in the bioreactor rapidly completes the breakdown process to nonhazardous products.

All high explosives contain nitrogen, in the form of nitro-groups, nitrates, or nitramines. The team analyzed the compounds in the effluent from the bioreactor column and found that essentially complete denitrification of those compounds occurs. Ideally, denitrification would reduce the compounds to nitrogen gas only. In this case, over 98% of the gas released by the micro-organisms is nitrogen, and the remainder consists primarily of oxygen, carbon dioxide, and hydrogen, none of which is a hazardous material. In addition, the majority of carbon-containing molecules have been converted to carbon dioxide, with the remainder converted to low-molecular-weight fragments that are below detection limits. Studies conducted with high-explosive compounds tagged with carbon-14 have verified that microbial action has converted all of the materials to their smallest possible units, which is the goal of any microbial treatment.

The pilot plant at the Pantex facility included pilot-scale biological treatment and will add pilot-scale chemical regeneration of carbon by the end of the year. Results from laboratory experiments for chemical regeneration of carbon and operation of the Pantex pilot plant indicate that the coupled chemical and biological method of regenerating activated carbon laden with high explosives is feasible, effective, safe, and efficient. Preliminary calculations also show that this process should be significantly less expensive than thermal regeneration and can be performed on site. Thermal treatment of 120,000 pounds of carbon per year (the amount produced annually at the Hawthorne facility) is estimated to cost about $0.79 per pound, while the coupled chemical/biological method should cost from $0.21 to $0.30 per pound.

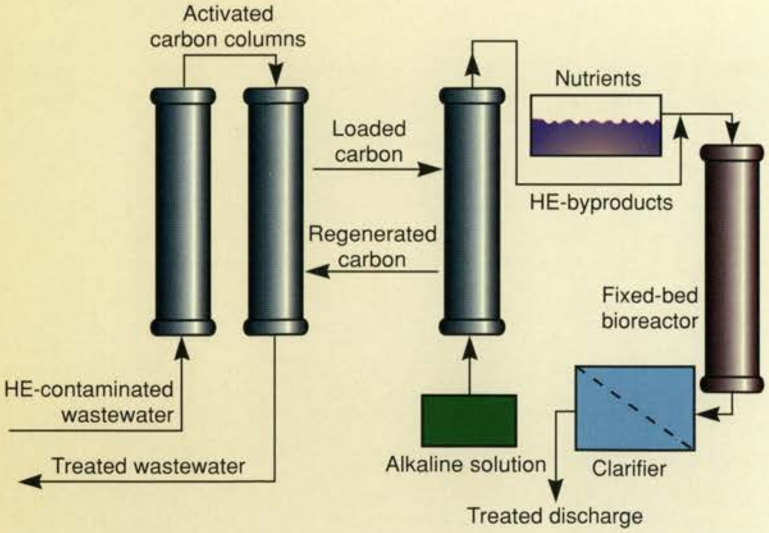

Figure 2. Schematic of the coupled system of carbon regeneration and biological and carbon treatment of high-explosive wastes.

The Next Step

The pilot plant at Pantex is relatively small because it was used to define the feasibility of the process and to determine the operating parameters for a larger treatment system. The bioreactor containing the micro-organisms is a column 1.7 meters (5.5 feet) high with an interior diameter of 0.18 meters (7 inches). The explosives-laden solution flows through the bioreactor just once at a rate of 60 milliliters per minute, staying in the bioreactor for about 8 hours.

A similarly sized pilot plant is planned for installation and operation at Hawthorne later this year. It will have a significantly greater capacity, however, because it will incorporate the carbon treatment via base hydrolysis, which is more efficient than biological treatment alone.

Knezovich, Daniels, Stenstrom, and their colleagues are expanding the process so that it could be applied to other high explosives. For example, ongoing research is addressing the treatment of TNT, in which the U.S. Army is particularly interested. Because TNT is more difficult for micro-organisms to degrade than RDX and HMX, the team is working to improve the base hydrolysis process to convert TNT to products that are more amenable to biological degradation. The results of this work will be used to optimize the treatment process at Hawthorne over the next two years. The team will also be looking at the feasibility of expanding these approaches for treatment of other high-explosive wastes.

– Katie Walter

Key Words: decontamination, demilitarization, hazardous waste, high explosives, microbial treatment.

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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
Steven T. Mayer James L. Kaschmitter Richard W. Pekala	**Carbon Aerogel Electrodes for Direct Energy Conversion** U.S. Patent 5,601,938 February 11, 1997	A device, such as a fuel cell, that uses carbon–aerogel electrodes loaded with a noble catalyst, such as platinum or rhodium, and soaked with phosphoric acid. A separator is located between the electrodes, which are placed in a cylinder having plate current collectors positioned adjacent to the electrodes and connected to a power supply; a pair of gas manifolds, containing hydrogen and oxygen, is positioned adjacent the current collectors. Because of the high surface area and excellent electrical conductivity of carbon aerogels, problems are overcome regarding high-polarization resistance of carbon composite electrodes conventionally used in fuel cells.
Chi Y. Fu	**Laser Programmable Integrated Circuit for Forming Synapses in Neural Networks** U.S. Patent 5,602,965 February 11, 1997	A customizable network wherein all the resistors in the synaptic array are identical, thus simplifying processing. Doped, amorphous silicon is used as the resistor material to create extremely high resistances occupying very small spaces. Connected in series with each resistor in the array is at least one severable conductor whose uppermost layer has a lower reflectivity of laser energy than typical metal conductors at a particular laser wavelength. The neural-network-integrated chip may include a plurality of input isolation buffers for driving the input lines in the synaptic array and a plurality of neuron circuits receiving inputs from several of the synaptic-array output lines.
Thomas E. McEwan	**Electronic Multi-Purpose Material Level Sensor** U.S. Patent 5,609,059 March 11, 1977	A sensor based on time-domain reflectometry of very short pulses. Pulses are propagated along a transmission line or dipstick that is partially immersed in a liquid, powder, or other substance. A launcher plate can be used to help launch the pulses and to produce a fiducial pulse. The time difference of the reflections at the start of the transmission line and the air–material interface determine levels to about 1% accuracy. The low-cost sensor is essentially independent of circuit-element and temperature variations.
William J. Benett Peter A. Krulevitch Abraham P. Lee Milton A. Northrup James A. Folta	**Miniature Plastic Gripper and Fabrication Method** U.S. Patent 5,609,608 March 11, 1997	A gripper, constructed of either heat-shrinkable or heat-expandable plastic tubing, formed around a mandrel, then cut to form gripper prongs or jaws, and the mandrel removed. The gripper is connected at one end with a catheter having an actuating balloon at its tip, whereby the gripper is opened or closed by inflation or deflation of the balloon. The inexpensive gripper can be used for gripping, sorting, and placing of micrometer-size particles for analysis; endovascular release of embolic material for the treatment of neuro-aneurysms; and placement of small plugs into ovarian tubes for contraception.
Daniel W. Shimer Arnold C. Lange	**E-Beam High Voltage Switching Power Supply** U.S. Patent 5,610,452 March 11, 1997	A circuit coupled to a voltage source and a current source for limiting voltage spikes across two input circuit lines of a voltage-spike-producing circuit. The circuit consists of a capacitor having a first end connected to one input circuit line and first leads of the voltage and current sources; a resistor having a first end connected to the other end of the capacitor and a second end connected to second leads of the voltage and current sources; and a diode having an anode connected to the second end of the capacitor and a cathode connected to the other input circuit line and a third lead of the current source. Excess current flows from one input circuit line through the capacitor and diode to the other input circuit line, and voltage across the two circuit lines is clamped to the voltage source.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Thomas E. McEwan	**High Accuracy Electronic Material Level Sensor** U.S. Patent 5,610,611 March 11, 1997	An electronic dipstick that incorporates a high-accuracy time base that is referenced to a quartz crystal; an ultrawideband directional sampler to allow operation without an interconnect cable between an electronics module and a guide wire; and constant fraction discriminators that allow accurate measurements regardless of material dielectric constants and reduce or eliminate errors induced by triple-transit or "ghost" reflections on the interconnect cable. The dipstick permits "custody transfer" measurements in large tanks that can be relied upon over temperature extremes and with aging.
Leon V. Berzins Bradford A. Bratton Paul W. Fuhrman	**Probe for Measurement of Velocity and Density of Vapor in Vapor Plume** U.S. Patent 5,610,704 March 11, 1997	A probe to measure velocity, density, temperature, and flow direction of vapor in a vapor plume. The vapor flows through a housing with a central passageway. A light generator provides a beam of light in the probe. Reflectors divert the path of the light beam to cross the vapor flow through the central passageway a plurality of times, at least once at an acute angle to the vapor flow. A photodetector measures the energy of the light beam after it has crossed the vapor flow in the central passageway.
Lloyd A. Hackel Patrick Reichert	**Faraday Imaging at High Temperatures** U.S. Patent 5,612,538 March 18, 1997	A laser viewing system that can be attached to a laser processing system to allow viewing and subsequent adjusting of the input laser beam focus and power on surfaces being welded, heat-treated, and machined by a high-power laser. The filter rejects background light from self-luminous thermal objects, but transmits laser light at the passband wavelength of the filter, providing an ultranarrow optical bandpass filter. The filter preserves images so a camera, looking through a Faraday filter at a hot target illuminated by a laser, will not see the thermal radiation, but will see the laser radiation.
Chi-Yung Fu Loren I. Petrich	**Image Compression Technique** U.S. Patent 5,615,287 March 25, 1997	A method of compressing an image by identifying edge pixels of the image, creating a filled edge array of pixels, and subtracting the filled edge array from the image array to create a difference array. The edge file and the difference array are then separately compressed and transmitted or stored. The original image is later reconstructed by creating a preliminary array in response to the received edge file and adding the preliminary array to the received difference array. Filling is accomplished by solving Laplace's equation using a multigrid technique.

Awards

Lawrence Livermore scientists **Mike Key** and **George Zimmerman** are among the recipients of the **1997 Edward Teller Medal**, awarded "in recognition of pioneering research and leadership in the use of lasers and ion particle beams to produce unique high-energy-density matter for scientific research and for controlled thermonuclear fission." Teller, Director Emeritus of the Laboratory, and a Hoover Institution Senior Research Fellow, presented the awards at the International Conference on Laser Interactions and Related Plasma Phenomena.

Key, now a senior scientist at Livermore, is the former head of the Central Laser Facility of the Rutherford-Appleton Laboratory in England and led the building of the world's brightest KrF laser there. He is also known for key technical contributions to x-ray laser research including x-ray streak-camera development, plasma energy transport, and high-field ionization.

Zimmerman, a group leader at Livermore, is responsible for development of advanced numerical models including the LASNEX code system. He is known internationally for his development of LASNEX and received the U.S. Department of Energy's E. O. Lawrence Award for this work. He has made key contributions to the development of models for equations of state, charged-particle and photon transport, opacity, magnetic field generation, and hydrodynamics. LASNEX is the principal inertial confinement fusion design code at Livermore, Los Alamos, and Sandia national laboratories.

Assuring the Safety of Nuclear Power

Since its inception more than 20 years ago, the Fission Energy and Systems Safety Program (FESSP) has been providing to the Nuclear Regulatory Commission and the Department of Energy expert, independent advice on virtually every aspect of nuclear power. The Livermore program is unique because it was built around the nuclear fuel cycle, thereby fostering a broad perspective of nuclear power issues. The program presently conducts projects in such areas as mining; enrichment; power reactor operation; nuclear materials handling, storage, transportation, and waste management; repository development; nuclear facilities security; and regulatory reform. The program is also involved in many international projects devoted to all aspects of the nuclear fuel cycle, but especially those concerned with enhanced reactor safety.

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The Microtechnology Center: When Smaller Is Better

Miniature electronic devices of all kinds have played an active role in Livermore projects since the late 1960s. First developed for nuclear test diagnostic equipment, these miniature devices have since been used in a wide array of projects for weapons development, biomedical research, nonproliferation, and, more recently, science-based stockpile stewardship. The Microtechnology Center today specializes in development of photonic devices, micro-electromechanical devices, passive microstructures such as thin-film windows, and other miniature structures made of silicon and silicon compounds, semiconductors such as gallium arsenide and lithium niobate.

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