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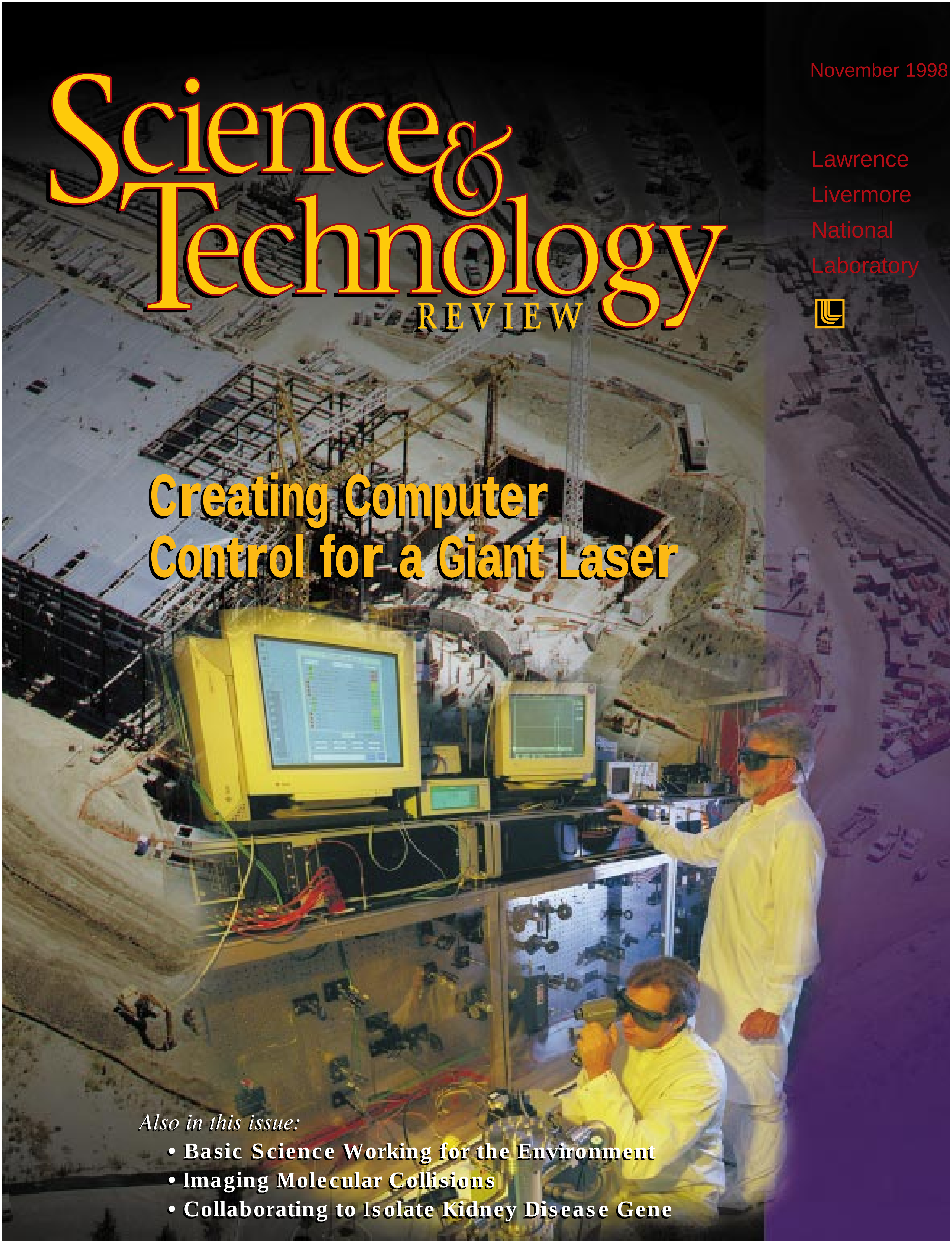
Science & Technology REVIEW

Lawrence Livermore National Laboratory



Creating Computer Control for a Giant Laser

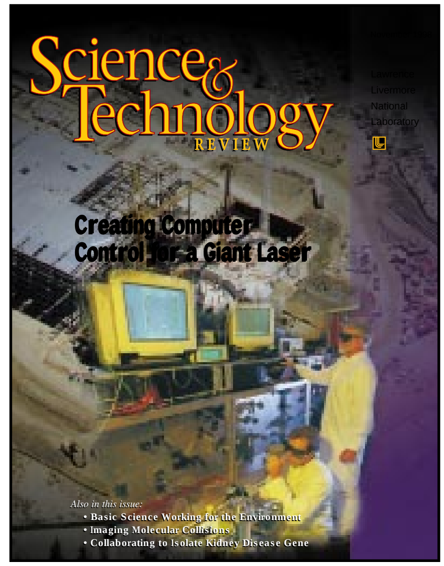
Also in this issue:

- **Basic Science Working for the Environment**
- **Imaging Molecular Collisions**
- **Collaborating to Isolate Kidney Disease Gene**

About the Cover

Electronics and software engineers at Lawrence Livermore are making excellent progress in designing and developing the highly complex, yet flexible computer system for controlling the National Ignition Facility. This system will monitor and synchronize some 60,000 points—motors, sensors, amplifiers, high-voltage power supplies, diagnostics, cameras—that are necessary to every shot of the giant NIF laser. The story of this control system begins on p. 4.

On the cover, Michael Gorvad (standing) and Bryan Moran use a part of the NIF control system to integrate the controls of the testbed of a NIF preamplifier. The background shows NIF construction progress in the summer of 1998.



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

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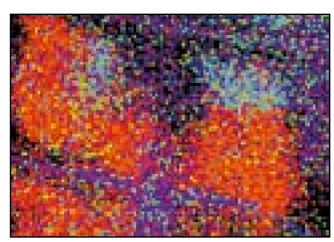

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FBI/Forensic Science Center to fight terrorism

During Energy Secretary Bill Richardson's recent visit to Lawrence Livermore, he joined FBI Deputy Director Randall Murch, Representative Ellen Tauscher, and Laboratory Director Bruce Tarter in announcing a partnership between the FBI and the Laboratory's Forensic Science Center to fight terrorism from weapons of mass destruction, protect U.S. infrastructure, and support law enforcement.

By partnering with the Laboratory, the FBI is broadening its technical foundation for responding to threats from weapons of mass destruction. In addition, the partnership will allow emerging Laboratory technologies developed for the Department of Energy's Stockpile Stewardship Program at the Forensic Science Center to be quickly shared with the FBI.

Referring to recent terrorist bombings in Africa, Richardson said that "America has seen the way that terrorism strikes at the very core of the American way of life. Today, I am proud to say that the Department of Energy will play a role in striking back, by giving the FBI additional high-tech tools in the fight against high-tech terrorism."

Formed in 1991, the Laboratory's Forensic Science Center provides expertise in analytical chemistry, nuclear science, biochemistry, and genetics useful for supporting law enforcement and for verifying compliance with international treaties and agreements. Using sophisticated analytical equipment, much of it developed at Livermore, center experts in organic, inorganic, and biological chemistry determine the composition and often the source of the most minute samples of material.

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Promising leads in dark matter search

An international team from four continents, including researchers from Lawrence Livermore, has reported a possible solution to the mystery of "dark matter," the unseen material believed to make up 90 percent of the Milky Way's mass. Interpreting observations made at Australia's Mount Stromlo Observatory near Canberra, Livermore astrophysicist Charles Alcock has reported increased evidence that some or all of our galaxy's dark matter consists of huge lumps—whimsically called MACHOs, for massively compact halo objects—believed to be unlit stars about half the mass of the sun.

The total mass of all the matter that can be observed or inferred in the universe is far from enough to provide the gravity needed to keep the universe from expanding infinitely. Several theories are under investigation to explain the unseen mass, among them MACHOs.

Alcock and his team recently completed more than 1,600 nights gathering data in Australia and detected more than 16 peculiar and hitherto invisible objects within a vast halo surrounding the Milky Way. They believe these objects to be MACHOs.

Their method of detection is gravitational microlensing. When an otherwise unobserved MACHO passes in front of a star being observed by the telescope, the MACHO's gravitational field acts like a lens, bending the star's light rays and making the star appear brighter. The star's sudden brightening signals the presence of a MACHO.

Alcock has conceded that "substantial uncertainty and controversy" surround the MACHO findings. Yet, he and his team have recorded and analyzed terabytes of data using computers at Livermore and more recently at the Mount Stromlo telescope. "We now have two and a half times as much data, and so the results are much more secure than when first reported [several years ago]," commented Alcock.

For more information on MACHO research, see *S&TR*, April 1996, pp. 6–11, and *http://wwwmacho.mcmaster.ca/*.

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Lab gives high-tech help in tire fire

Scientists from Lawrence Livermore's Atmospheric Release Advisory Capability (ARAC) program recently had yet another opportunity to use technology developed to study radiation releases and nuclear fallout for a different environmental safety purpose. At the request of the California Environmental Protection Agency, they used computer simulations to monitor the intensity and direction of the smoke billowing from millions of burning tires at a 30-acre tire graveyard near Tracy, California, a community about 20 miles from the Laboratory.

James Ellis, ARAC program deputy director, and his team worked through the night shortly after the fire began to simulate the smoke cloud and project particle concentrations in the air, plotting according to wind direction where the elements would disperse. "We were able to make projections . . . and give that information to environmental agencies so they could use the data to calculate health risks and long-term effects of the fire," said Ellis.

The ARAC team's computer models predicted that more than half of the smoke would move north and rise high in the atmosphere, away from human contact. Other smoke would stay lower and drift to the east. These predictions proved generally accurate and helped health officials determine that the immediate public health risk would, fortunately, be low.

Atmospheric modeling capabilities similar to those used in the Tracy tire fire have also been used to monitor the impact of radiation dispersal accidents, to study air conditions after natural disasters, and to track the course of environmentally hazardous releases to the atmosphere.

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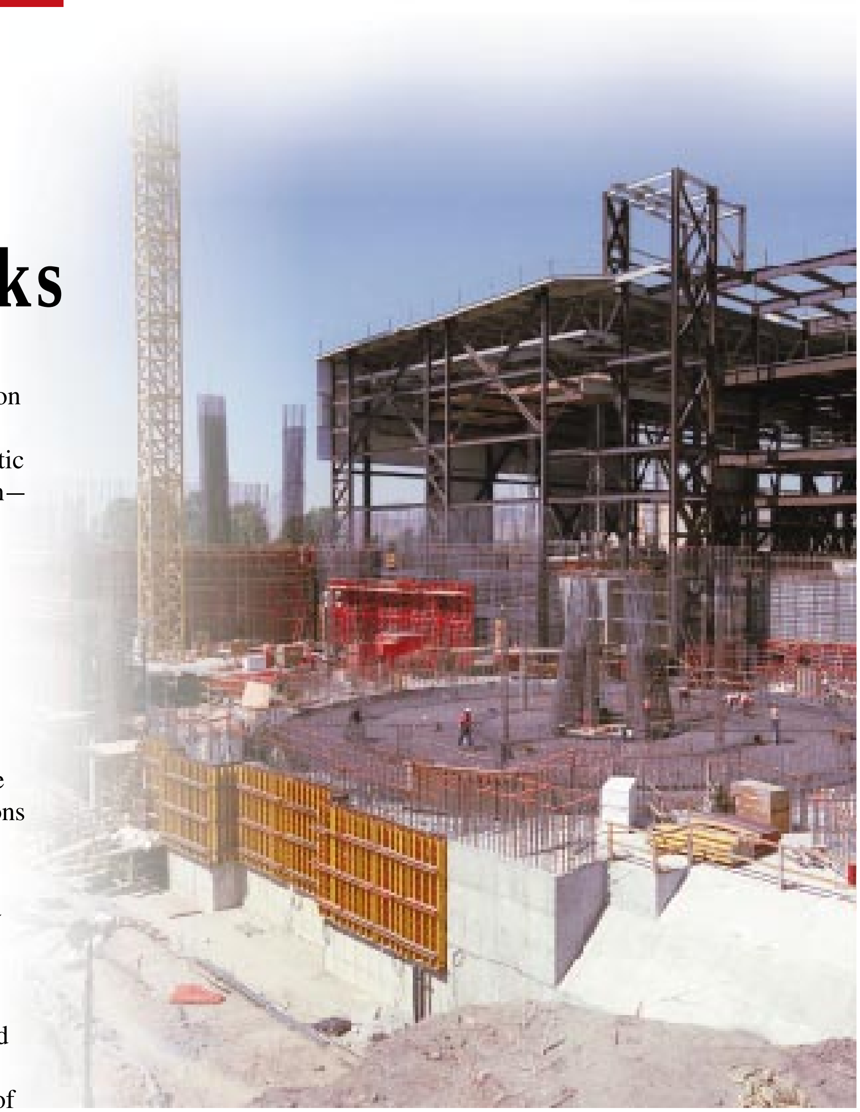
A Big Payoff for Taking Risks



THE National Ignition Facility, currently under construction at Lawrence Livermore, will be a showcase for the most modern laser technologies, optical components, and diagnostic instruments available. Another showcase of advanced design—perhaps not as visible, yet essential to the success of the facility—will be NIF's distributed computer control system. Now under development, this system (detailed in the article beginning on p. 4) will precisely control and monitor tens of thousands of components to ensure that the world's most powerful laser works precisely as planned. Indeed, NIF's computer control system provides the nervous system for a facility that the Department of Energy considers vital to America's Stockpile Stewardship Program. NIF is one of the cornerstones of this program and makes important contributions to fusion energy development and the basic sciences.

The NIF control system's hardware will feature proven processors, workstations, file servers, and data networks in a design permeating nearly every meter of the 192-arm laser facility. It is in the area of software development, however, that our engineers have decided to take some major risks by adopting the latest developments in software engineering and design based on new, international standards. These new concepts, such as object-oriented programming and the use of the internationally recognized Common Object Request Brokerage Architecture (CORBA), offer tremendous advantages because they will allow us to easily modify, extend, and upgrade the control system years from now.

Until NIF, no one had ever used these concepts for a large experimental facility. But as the article relates, adopting these new standards makes sense, given the sheer scale of hardware and expected modifications to NIF over its anticipated 30-year lifespan. Indeed, in light of the astonishing rate of change of computer hardware, the growing capability of diagnostic equipment, and the new directions our experiments are likely to take, it's a safe bet that, as we did for Nova, we will be making many changes to NIF and its control system over its entire lifetime.

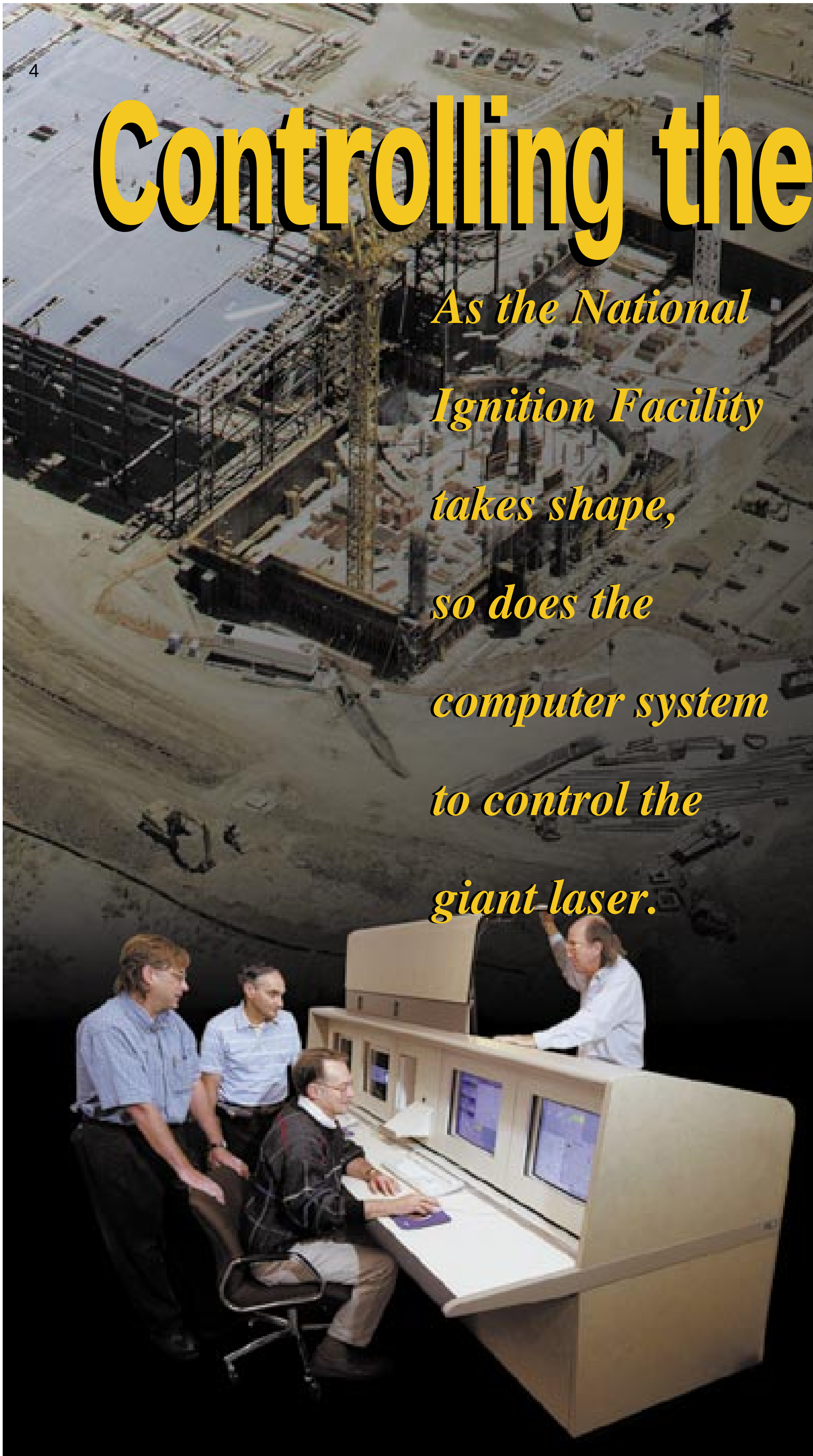
Being locked into an inflexible control system in which a hardware upgrade forces significant investment in new software simply does not make sense, either scientifically or economically. What's more, modern techniques are allowing us to build our software efficiently and to strict engineering standards, with a relatively small cadre of people, and in modular fashion for easy testing and upgrading.

So far, it looks as if we made the right choice as we review the first of five planned software iterations. Our American software industry partners are pleased, too, as they work to extend the market for their tools to make software more flexible, powerful, and easy to modify.

NIF's computer control system is likely to be the vanguard for other large scientific research facilities now being planned, especially those with expected long operational lifetimes. When the first experiments on NIF begin early in the next century, I am confident that the control system will be ready to expertly manage, monitor, and document our NIF experiments for many years to come.

■ E. Michael Campbell is Associate Director, Laser Programs.

Controlling the World's



As the National Ignition Facility takes shape, so does the computer system to control the giant laser.

THE extraordinary size, complexity, and goals for the National Ignition Facility, now under construction at Lawrence Livermore, make the project one of the most ambitious in high-energy-density physics history. No less ambitious is the computer control system being developed in parallel with the giant $1.2-billion facility. This system, distributed over an area roughly the size of two football fields, will choreograph the workings of thousands of parts to help ensure the reliability of America's nuclear stockpile and keep the United States the world leader in laser and inertial fusion research.

The Livermore engineering team assigned to design the NIF control system faces an immense challenge: every shot will require computerized monitoring and control of some 60,000 points, including mirrors, lenses, motors, sensors, cameras, amplifiers, capacitors, and diagnostic instruments. By working in computerized synchrony, the components will ensure that NIF's 192 beams propagate a 20-nanosecond-long burst of light along a 1-kilometer optical path, arriving within 30 picoseconds of each other at the center of a target chamber 10 meters in diameter. Here, they will strike—within 50 micrometers of their assigned spot—a target measuring less than one centimeter long.

In helping to ensure the success of each shot, the control system will supervise shot setup and countdown; oversee machine interlocks to protect hardware, data, and personnel; generate reports on system performance; provide operators with graphical interfaces for control and system status displays; perform alignment, diagnostics, and control of power conditioning and electro-optic subsystems; and monitor

Most Powerful Laser

the health of all subsystems and components, advising operators of any abnormal conditions. (The box at the right describes how the control system performs beam alignment.)

This system will operate around the clock and be able to control the firing of target shots every 8 hours or less (see the box on p. 9), with an allotted downtime of 7.5 days per year for unscheduled maintenance. Finally, as a major capital investment representing about 10 percent of the total facility cost, the entire system must be easy to maintain, extend, and upgrade.

Flexible Architecture

Paul VanArsdall, project leader for the NIF integrated control system, says the control system architecture is "a truly flexible design because we know, based on over a decade of experience with Nova, that the facility will evolve over the 30 years of its projected lifetime." Lead software architect John Woodruff says the team was well aware of the risks associated with controlling highly complex systems with inflexible system architectures.

The NIF control system is an event-driven control system, as opposed to a continuous system like those in many manufacturing plants or an airport baggage-handling system. Team members believe that the NIF control system will prove so flexible that control managers who are developing event-driven computer control systems for other facilities will be able to adapt the NIF system to their needs.

Project designers also understand that to control costs, they must purchase as many off-the-shelf components as possible. Although most of NIF's hardware is by necessity one-of-a-kind designs, the computer control system incorporates proven microprocessors, workstations, networks, interfaces, and other hardware. Finally, to assure NIF's long operational life, the team has elected to adopt concepts in software development and deployment that meet rigorous engineering standards.

The architecture for the NIF Integrated Computer Control System features two main layers: a lower layer of front-end processors (FEPs)

Deploying 10,000 Motors to Align NIF's Laser Beams

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 NIF engineers. The computerized alignment system, now under advanced development, must automatically point the beam through pinholes, center the beam on apertures of several optical sections, adjust the square beam's orientation, focus the beam onto the target, and adjust the angle of the KDP (potassium dihydrogen phosphate) frequency conversion crystals to match beam pointing, all in less than one hour.

Control system project leader Paul VanArsdall notes that the design of the alignment system reflects years of experience working on laser systems. The alignment control system is one of NIF's largest systems. It consists of 600 video cameras distributed at 20 points along the length of each of the 192 beamlines, 10,000 stepping motors, 3,000 actuators, 110 racks, 150 miles of cable, a high-speed network for transmitting digitized video images, and software to integrate all devices.

Says engineer Allyn Saroyan, "We realized that with 192 beams, we needed to automate as much as possible and have operator assistance only when we got into trouble." To determine an alignment error, a high-speed computer performs computations that analyze the digitized video images. Saroyan explains that the system compares the location of the observed beam with where it ought to be, requests a front-end processor (FEP) to move certain motors that precisely shift the beam, asks for another image, makes a second round of calculations, and if necessary, repeats the process. While normally automated, the process can also be performed by a NIF operator in the control room with joystick in hand and eyes trained on a video image.

In all, more than 4,000 devices are manipulated during the alignment process, including mirrors, pinhole wheels, waveplates, lenses, polarizers, shutters, light sources, reticles, and attenuators. The process continually readjusts itself over the course of the allotted time, during which some 48,000 messages are expected to be relayed between FEPs and the supervisory system.

Guiding the development of the system is the staff of the alignment concepts laboratory. This facility simulates a portion of the main laser segment of the NIF beamline, with prototype FEPs used to demonstrate automatic alignment.

interacting directly with laser and target equipment and a higher, supervisory layer to control and integrate the FEPs (Figure 1). The FEPs are distributed throughout the facility, while supervisory computers are located in the NIF central control room. Most FEPs will feature Power PC microprocessors running on the VxWorks operating system, while the supervisory system will be hosted on Sun workstations running a variant of UNIX.

The more than 300 FEPs constituting the bottom layer have been tailored for 19 applications, such as power conditioning and target diagnostics. FEPs will be installed in water-cooled, 19-inch racks and linked to thousands of components, such as laser energy sensors and motorized actuators, as well as to more complex precision instruments (Figure 2).

FEPs will report to seven supervisory control applications, each corresponding to a primary NIF subsystem such as alignment or power conditioning. The subsystems will incorporate several databases for both experimental data and data used during operations and maintenance. The subsystems are integrated by an eighth application, the shot director. In the control room, the system's nerve center, about a dozen operators will be assigned to consoles corresponding to each subsystem (Figure 3).

A distinct segment of the system contains industrial controls. A network of programmable logic controllers will be connected to the industrial control FEPs attached to devices governing, for example, vacuum systems for the target chamber and spatial filters. This segment also includes the Safety Interlock System, which monitors doors, hatches, shutters, and other sensors in order to display hazard levels and ensure personnel safety.

In addition to the 300 FEPs, the NIF computer system will consist of 16 dual-monitor workstations in the control room, several hundred embedded controllers, file servers, and two major data networks featuring both Ethernet and Asynchronous Transfer Mode (ATM) technologies (Figure 4). ATM, running at 155 megabits per second, will connect those systems requiring high throughput for tasks such as transmitting digitized video, timing signals, target diagnostics data, and optics inspection data. Ethernet, running at both 10- and 100-megabit-per-second speeds (depending on traffic requirements), will connect all other systems.

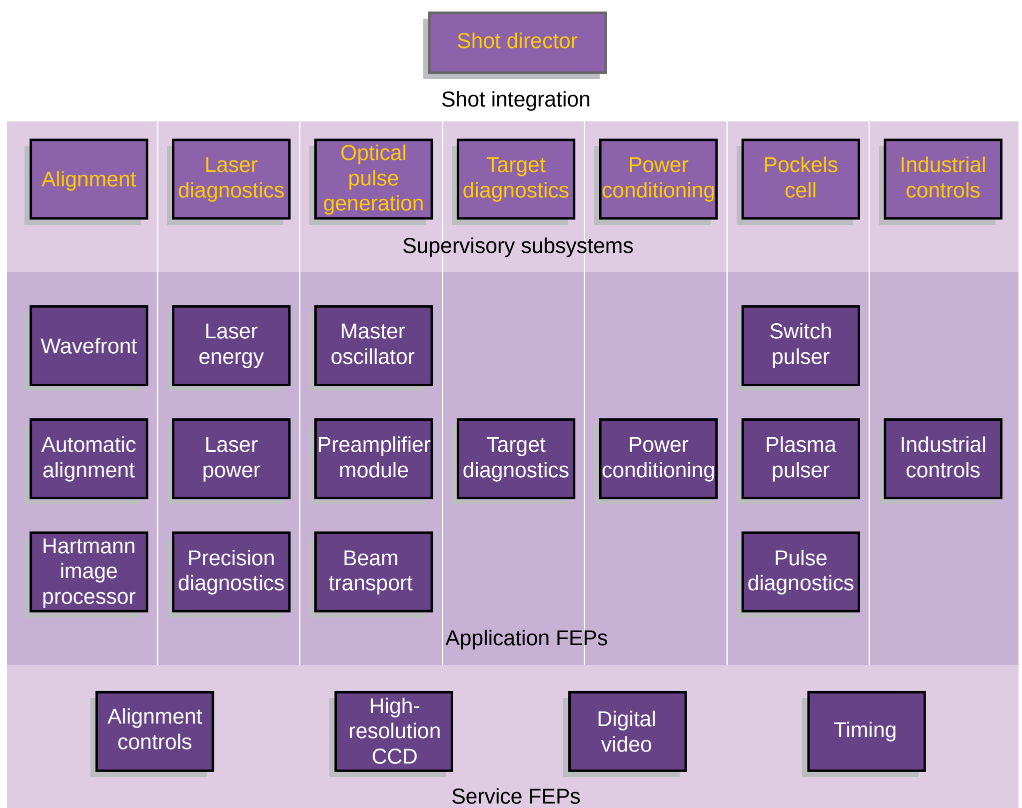


Figure 1. The architecture of the National Ignition Facility's integrated computer control system has four layers. The two main layers are the application front-end processor (FEP) layer (300 FEPs governing 11 applications) and the supervisory subsystems layer, which governs 7 applications. The FEP layer, distributed throughout the NIF laser, reports to the supervisory layer, located in the NIF control room, where all subsystems are integrated by the shot director application.

Owning the Software's "Soul"

The NIF control system, for all its complexity, is designed to "look like one amorphous computer," according to VanArsdall. He says that the development team considered contracting out the control system software, but industry consultants warned that Livermore needed to "own the soul" of the system. Hiring contractors would mean a steep learning curve for people not knowledgeable about lasers and the goals of the complex project. "The key to longevity of software is to own it and be able to replace parts of it as needed," VanArsdall says.

In that respect, he says, "We're building a system that has to last 30 years using a modest team of about 40 people." However, compared with nearby Silicon Valley firms, Livermore is unique because personnel turnover is low. The team also benefits from a wealth of experience with previous Livermore lasers. For example, Fred Holloway, manager of the FEP development effort, has been involved with every major Livermore laser, including the pioneering lasers of the 1970s such as Shiva.

VanArsdall also worked on the early machines, as well as on the automatic alignment system of Livermore's Nova,

(a)

(b)

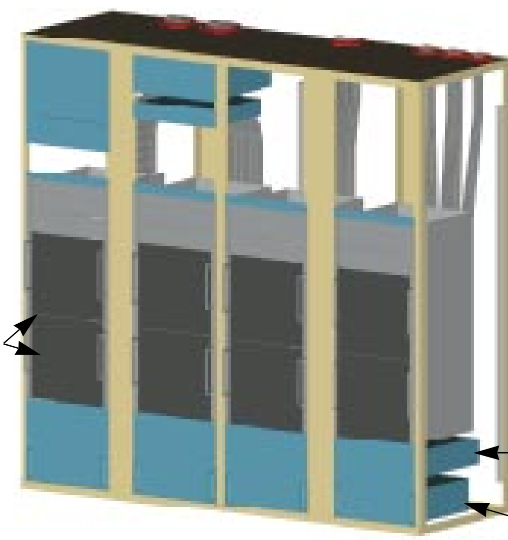


Figure 2. (a) Electronics engineer Bob Boyd inspects a pair of front-end processors (FEPs) in a water-cooled rack. (b) More than 300 FEPs make up the FEP layer of the NIF control system. They are linked to thousands of laser components and precision instruments governing applications such as alignment, power conditioning, and target diagnostics. (AutoCAD drawing by William Lew.)

Figure 3. (a) Artist's rendering of the National Ignition Facility's control room, the nerve center of the world's largest laser. Here, the Shot Director—both the person and the supervisory subsystem—will integrate each laser shot. (b) NIF control system developers (clockwise from left) John Woodruff, Paul VanArsdall, Fred Holloway, and Allyn Saroyan explore a prototype of a control console.

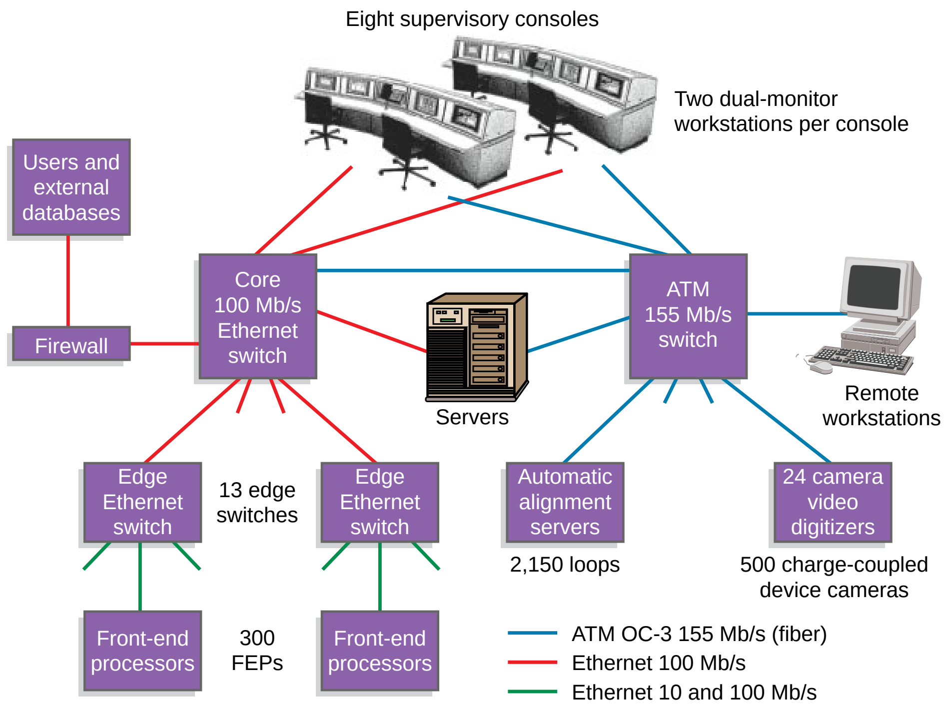


Figure 4. The control system's network employs both Ethernet and Asynchronous Transfer Mode (ATM) technologies to provide flexibility and high-speed data transfer.

for many years the most powerful laser in the world. He notes that Nova was designed in the early 1980s when there were no graphical-user-interface development tools, no fast networks, far less capable computers, and a poorly developed concept of software architecture.

Sustainability of the system over the NIF lifetime is key. Although Nova's control system was upgraded in the early 1990s, simply scaling up its system would not be effective because NIF will be vastly more complex, precise, and powerful. For example, NIF's power conditioning control subsystem (designed by Sandia National Laboratories, New Mexico) will monitor and control 384 high-voltage power supplies, 576 dump switches, 384 gas panels, 384 trigger systems, and 4,800 electrical current monitors distributed throughout four electrical capacitor bays.

Replacing Art with Engineering

Given the overwhelming number of components, the cost constraints, and the unforgiving schedule, the emphasis had to be on increased automation as well as a much greater degree of software development discipline. Woodruff explains, "We are replacing software 'art' with proven engineering techniques that will ensure that the software does what it is designed to do."

For example, the development team has incorporated many of the latest advances in software technology. These advances include CORBA, ADA 95, and so-called object-oriented techniques that together enhance the openness of the architecture and portability of the software from one application to another.

CORBA (Common Object Request Brokerage Architecture)—an international standard developed by the Object Management Group, a consortium of some 500 companies—makes it easy for components and operating systems from different vendors to work with one another. "We have over 400 computers, and they all have to communicate with each other. CORBA allows us to do that. Without it, we'd have to write a lot more software," says Woodruff.

VanArsdall says that the best way to think of CORBA is as a universal "software bus" that allows users to access data transparently, that is, without knowing on which software or hardware platform the data reside or where the platform is located on a network. Used in banking and telephone industries, CORBA hadn't been used in scientific control systems before. CORBA thus represented a certain risk. However, it has worked well in advanced NIF control simulations, and it is now considered the critical core of the architecture.

The team also chose the internationally standardized ADA 95 as the central software language. Ada is used in mission-critical applications such as air-traffic and military command and control systems. The major advantages of Ada are that it supports disciplined software engineering and has proven easier to maintain in the long term than other languages are.

Object-oriented design will assure significant reductions in system maintenance, especially in the face of

Counting Down to a NIF Shot

Preparation for a NIF shot will begin many weeks in advance of its occurrence, when a review committee selects experiments submitted by physicists that will be performed during the shot. An experiment may be scheduled for any number of shots, and one shot may support any number of experiments. One or more beams in a single shot may be set for different characteristics and paths than other beams. For example, even when the experiment's primary objective is target physics, it is also possible to fire 1 to 16 beams into calorimeters that measure laser energy, rather than fire them at the target.

All of the experiment's particulars, such as desired beam characteristics, target instrumentation, energy of the beam, and number of beams to be fired, will be entered into the control system software. The system will automatically issue a warning if certain operating parameters could damage key optical components. "NIF will be operating so close to its design limits that the control system has a number of operations to prevent damage," says control system project leader Paul VanArsdall. (Optical damage over time is inevitable, however, and the control system will catalog the damage and automatically schedule corrective maintenance.)

Several hours before the shot, the control system and operational staff will begin preparations of major NIF components—aligning the beamlines, testing diagnostic equipment, and verifying other parameters. Following these preliminary preparations, a formal countdown of 5 to 7 minutes will feature intricate choreography for sequencing all of the operations that must occur before the shot can take place (see figure below). To determine the countdown duration, the system queries each subsystem how long it needs to complete its final preparations. Because some operations may not be performed on every shot (late insertion of cryogenic targets, for example) and the time to complete these operations may vary, the control software will adjust the countdown optimally for each shot.

Many Fail-Safe Points

During the countdown, the supervisory subsystems controlling the plasma electrode Pockels cell, wavefront control, target, and target diagnostics will place a hold on charging of the main amplifiers and those for the preamplifier modules. The holds ensure that the laser will not be charged before all of its subsystems are ready and represent one form of many fail-safe points distributed throughout the countdown. Other fail-safe points, provided by industrial controls, are designed to monitor and control environmental and safety parameters. The industrial controls system will prevent the countdown from continuing if it detects an adverse condition such as high humidity in the KDP (potassium dihydrogen phosphate) crystals or low vacuum levels in the spatial filters.

"We only get three shots a day, so we've provided plenty of fallback positions," says VanArsdall. "It's better to delay a shot than get lower quality science."

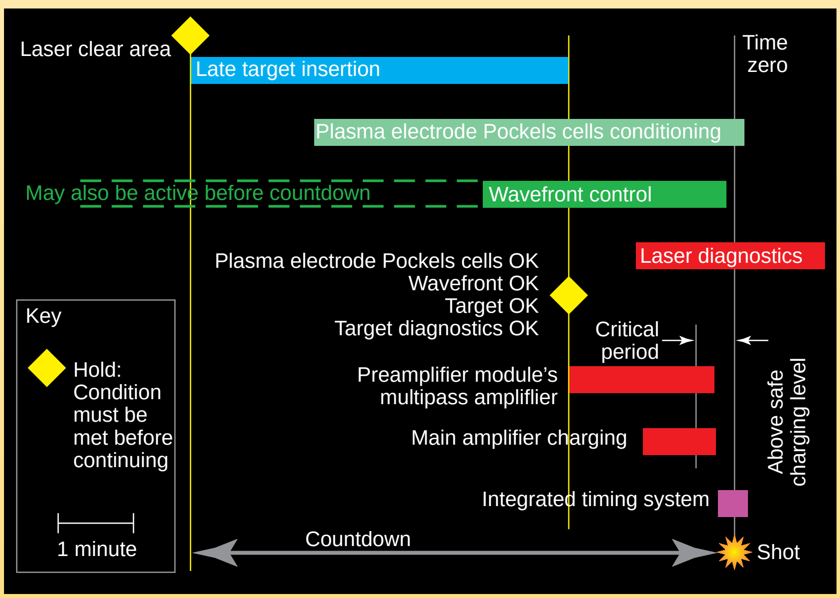
Once the holds are lifted, capacitor charging will begin. When the main amplifier capacitor banks reach full charge, the countdown will enter a critical period in which the laser must either be fired within a few seconds or the shot aborted and the capacitors' charge "dumped" to minimize capacitor aging.

For the final second before laser firing, some 360 "t–1" (one second before firing) devices will move into correct position. Many will have been involved in wavefront control and must be removed from the path of the laser. Others will be inserted at the last second to protect laser diagnostic instruments. Industrial controls will be monitoring the positions of every t–1 device; when all are in position, permission to fire will be given. If permission is withheld, the shot will be aborted.

Between t–1 and t-zero (firing of the laser), an avalanche of events will take place, all under the control of the integrated timing system. At t–zero, some 1,200 accurate firing triggers will be distributed, all synchronized to a single master clock source. After all of the months of planning and a painstakingly designed countdown, a NIF laser shot culminates in bombarding the target with a burst of light energy lasting only 20 billionths of a second.

Finally, the results of the shot will be gathered by the control system and turned over to the experimenter. The laser will return to the idle state and, following a cooldown period, will be automatically inspected by the control system for optical damage in preparation for the next shot.

Of course, the most challenging NIF countdown ends October 1, 2003, when the first full-system NIF experiment is scheduled to occur.



During the final 5- to 7-minute countdown before a NIF laser shot, all operations that must occur before the shot can happen are reviewed by the control system and precisely sequenced.

anticipated periodic replacement of computers and laser hardware. With object-oriented software, for example, supervisory software will not be affected by a change in the type or manufacturer of a motor that it is controlling. That level of detail is hidden in the FEP. With Nova, replacing a motor from a different company required rewriting software at all levels.

The control system software features the use of frameworks, or modular chunks of code. These chunks reduce the amount of coding necessary by providing prebuilt—and tested—components that can be shared for different applications as well as extended to accommodate additional requirements. Says VanArsdall, "With frameworks, we solve each problem once without needing to write huge amounts of detailed code. In effect, we build a software abstraction that we specialize 8 times up in the supervisory system and 19 times down in the FEP layer."

Holloway notes that in developing the FEPs, engineers first came up with a generic FEP with all the frameworks (12) needed for correct operation. For example, the status monitor, a framework reused in many different applications, observes devices (at a periodic rate ranging from 0.1 to 10 seconds) and notifies other elements of the system only when their status changes by a significant amount. This framework's flexibility reduces network traffic significantly.

Figure 5. Rita Bettenhausen and Larry Lagin write and test software in one of many development and simulation laboratories that are interconnected in the NIF control system testbed.

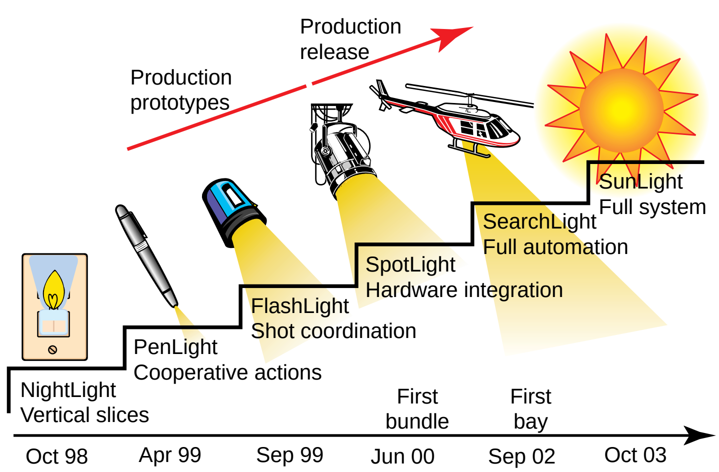


Figure 6. Incremental building of software reduces the risks over the life of the control system's development.

Building a Stairway to Success

Another key strategy to minimize risks is an iterative approach to software construction that has proven effective for projects whose final requirements are not fully known until late in the project. Because waiting to begin work on the control system until all NIF hardware designs are complete would add years to the project and large increases in the total cost, writing the code is being done in stages. Using this iterative approach, developers resolve increasingly smaller risks over the life of the project and add function as major NIF hardware designs are finalized.

As each iteration is built, it is tested and evaluated before the next cycle begins. In that respect, says VanArsdall, "Living with the customer (NIF shot operators) is a wonderful advantage as opposed to hiring a software vendor who goes off and then gives us a pile of code." For example, engineers receive immediate feedback on optimizing the displays on workstations and can begin to train NIF operators at the earliest possible date.

Aiding the software development effort is a web of simulation laboratories that include several FEPs, a small tabletop alignment system, and Ethernet and ATM networks (Figures 3b and 5). VanArsdall says that the laboratory has been particularly useful in modeling full-scale communications to answer questions such as "What happens when I have 5,000 devices chattering all at once to one another? Where are the bottlenecks in the system?"

Incremental building of software provides what NIF managers term a "stairway to success" (Figure 6). Within the first step are "vertical slices" of software that contain the supervisory system, appropriate FEPs, and frameworks for a single task using emulated or prototype hardware. For example, the vertical slice for transmitting video images demonstrates capturing an image of the laser beam and delivering that image to a display on an operator console.

In October 1998, the team delivered NightLight, the first step. "NightLight will probably prove to be the hardest," says Holloway, "because it presented the most risks. We had to show we could work as a team and build all the different applications from generic FEPs." In PenLight, scheduled for April 1999, engineers will apply what they learned in NightLight as they begin to build an integrated control system.

FlashLight is scheduled for September 1999 and will implement all parts of a shot life cycle, including shot coordination. For SpotLight (June 2000), the software will control the first bundle of eight laser beams. SearchLight will test full computer automation of 96 beams in September 2002. Finally, SunLight in October 2003 will operate the completed 192-beam machine.

SunLight is a particularly appropriate term for the final step for NIF's computer control system. After all, NIF will be igniting small fusion targets and creating, however briefly, miniature suns.

—Arnie Heller

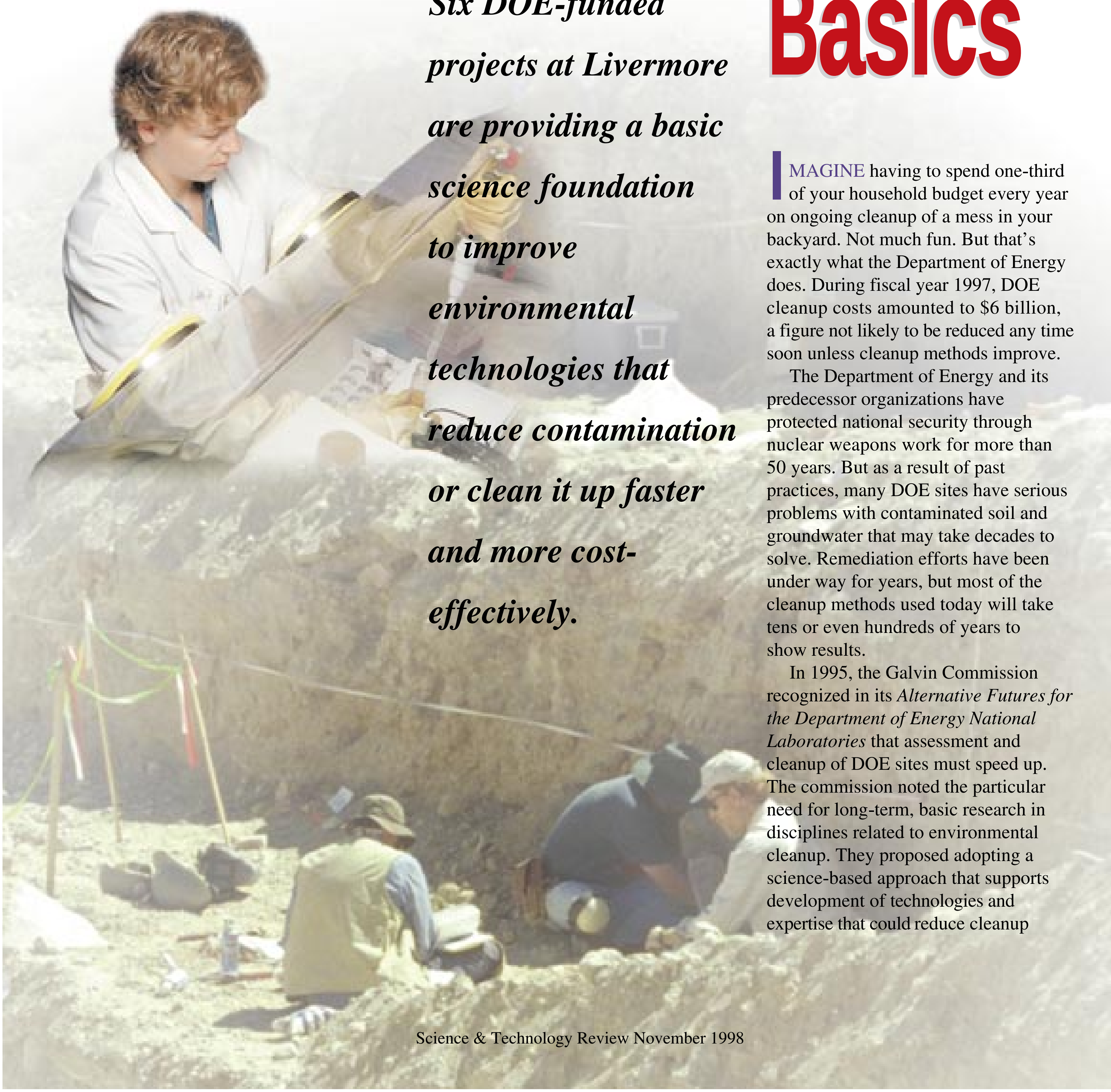
Key Words: ADA 95, Asynchronous Transfer Mode (ATM) networks, CORBA (Common Object Request Brokerage Architecture), distributed control system, front-end processor (FEP), National Ignition Facility (NIF), NIF integrated computer control system, Nova, object-oriented programming, software frameworks, Unix, VxWorks.

For further information contact Paul VanArsdall (925) 422-4489 (vanarsdall1@llnl.gov).

About the Engineer

PAUL J. VANARSDALL has been involved in the development of the National Ignition Facility since its inception. Currently, he is deputy system engineer for developing control systems for NIF and leads the unified effort to integrate computer controls from all levels in NIF's special equipment. He is also computer engineering group leader in the Electronics Engineering Department's Laser Engineering Division, which supplies many of the control engineers to the NIF project. Prior to his current assignment, he worked on internal confinement fusion (ICF) laser control systems, including Shiva and Nova, specializing in automatic alignment and supervisory controls. After gaining experience upgrading Nova's control system in 1991, VanArsdall led a development effort introducing object-oriented software technology to prepare engineers for the NIF task. He joined the Laboratory in 1976 after receiving his B.S. in computer engineering (1975) and his M.S. in electronics engineering (1976) from the University of Illinois, Urbana.

Getting Down to Environmental Cleanup Basics



Six DOE-funded projects at Livermore are providing a basic science foundation to improve environmental technologies that reduce contamination or clean it up faster and more cost-effectively.

IMAGINE having to spend one-third of your household budget every year on ongoing cleanup of a mess in your backyard. Not much fun. But that's exactly what the Department of Energy does. During fiscal year 1997, DOE cleanup costs amounted to $6 billion, a figure not likely to be reduced any time soon unless cleanup methods improve.

The Department of Energy and its predecessor organizations have protected national security through nuclear weapons work for more than 50 years. But as a result of past practices, many DOE sites have serious problems with contaminated soil and groundwater that may take decades to solve. Remediation efforts have been under way for years, but most of the cleanup methods used today will take tens or even hundreds of years to show results.

In 1995, the Galvin Commission recognized in its *Alternative Futures for the Department of Energy National Laboratories* that assessment and cleanup of DOE sites must speed up. The commission noted the particular need for long-term, basic research in disciplines related to environmental cleanup. They proposed adopting a science-based approach that supports development of technologies and expertise that could reduce cleanup costs, generate fewer environmental hazards at existing sites, and develop a scientific foundation for advances in environmental technologies.

The Department of Energy responded in 1996 by establishing an Environmental Management Science Program. It requested proposals from universities, national laboratories, and other research institutions for projects in basic science related to environmental management. That year, Lawrence Livermore received five grants for research and one more a year later. All are for three years of work and are under the direction of either Ken Jackson or Norm Burkhard, division leaders in the Earth and Environmental Sciences Directorate.

Five of the projects are geophysical and geochemical, with work ranging from a molecular view to a large-scale look at contaminant movement in the southeast corner of the Livermore site. The sixth is a chemistry project studying the vaporization of plutonium, uranium, and other radioactive elements when wastes containing them are burned. All six projects use experimental data to improve modeling codes and make them better predictive tools.

The payoff from these projects for DOE and other sites is expected to be long-term—basic research seldom pays off quickly. But over time, the benefits of this research will spread beyond the confines of Lawrence Livermore. And it is not just DOE sites that will benefit. Many other government and private sites are home to contaminated soil or groundwater or stored wastes that must be disposed of. The more environmental managers know about how contaminants behave, the smarter they can work to protect our environment.

The Water Table's Armor

One of the challenges for cleanup of contaminated soil and groundwater is learning more about how contaminants move in the area that lies between Earth's surface and the water table, a region known as the vadose zone. The vadose zone is critical because it is the only armor the water table has to protect it from contaminants on the surface. Yet the vadose zone is largely inaccessible to scientists except through core samples, monitor wells, other sampling methods, and a few underground imaging techniques.

The vadose zone is made up of soil, water, and air. It typically comprises more air and less water near the surface and is increasingly saturated closer to the water table. Depending on how deep the water table is, the vadose zone may be thin or nonexistent or up to hundreds of meters thick. Its soils may be sandy and gravelly and thus quite permeable, or they may contain dense clays that impede the downward movement of fluids.

Conventional wisdom says that a thick clay layer in the vadose zone should protect the water table from most contaminants near the surface. But even the most minute discontinuity in the soil layers—a chink in the armor, and there are many of them—provides an avenue for contaminants to migrate toward the water table.

What's Going on Down There?

Susan Carroll, Gregory Nimz, and Charles Carrigan are heading up projects to better understand the movement of contaminants in the vadose zone. Their projects cannot strengthen the armor, but they can fill some of the holes in our knowledge of this inaccessible region.

The Geochemistry of Strontium Movement. Carroll is seeking to determine the geochemical processes that govern the mobility of radioactive strontium in clays and iron hydroxides as a function of temperature, pH, and time. She notes, "Knowing more about strontium is important because strontium-90 is the fastest moving radionuclide except for tritium, and strontium has leached into soil and groundwater in places where nuclear weapons materials were manufactured, such as DOE's Hanford site in Washington."

Her objective is to obtain data needed to predict the behavior of strontium at temperatures and time scales typical for various thermal remediation processes. Her team is performing experiments on sorption/precipitation and desorption/dissolution that track changes in solution composition.

Batch sorption experiments were run at 25, 50, and 80°C, with pH ranging from 4 to 10. The experiments ran for 48 hours in various soil minerals using a nonradioactive strontium. As shown in Figure 1, temperature had no impact on sorption of strontium in goethite (an iron hydroxide) or in kaolinite. This figure also shows that sorption increased dramatically when the pH was greater than 7, with virtually no sorption when the pH was less than 7.

Carroll's research team is also looking at the molecular structure of strontium in its solid phase using x-ray absorption spectroscopy. Molecular spectroscopy experiments were performed over periods of 48 hours and two months to study how strontium bonds with various soil minerals and how those bonds change over time. For both time periods, it bonded only electrostatically with kaolinite and silica gel. With goethite, tight bonds were observed at 48 hours, but over time, the bonds disappeared.

Strontium's high mobility had been observed in the field, but these Livermore experiments were some of the first to confirm its mobility in the laboratory under a range of conditions. Strontium is so mobile because it does not sorb strongly to mineral surfaces; even its bond to goethite is short-lived and unstable.

"Our work is chemistry at its most basic," says Carroll. "We are working toward a geochemical model that will predict the right type of chemistry to mobilize or immobilize strontium. The model will also be able to predict the real hazard from the movement of strontium. Our data provide some very fundamental information about strontium's behavior, but they are only a small piece of the puzzle."

Radionuclide Movement in Undisturbed Soil. Gregory Nimz is also studying radionuclides in the vadose zone, specifically their migration in undisturbed soil. Says Nimz, "Detection of trace amounts of certain radionuclides—chlorine-36, strontium-90, zirconium-93, technetium-99, and iodine-129—was not possible prior to the development of accelerator mass spectrometry, a highly sensitive measuring technique. Without AMS, only a relatively high concentration of many radionuclides can be detected."

AMS is new enough that techniques did not exist when this project began for measuring strontium-90, zirconium-93, and technetium-99. Nimz's team developed them and also improved AMS methods for chlorine-36 and iodine-129. Livermore is home to one of the largest AMS facilities in the world and is at the forefront of AMS developmental work. (See *S&TR*, November 1997, pp. 4–11.)

Nimz's project is designed to fill two gaps in current knowledge about environmental management: how contaminant radionuclides move when they are far from the contaminant release point, and at what rate fluids move in unsaturated soils, a process known as moisture flux. The radionuclides he is studying were released into the atmosphere during aboveground nuclear testing in the 1950s and 1960s and have since settled into shallow soils, including permafrost, all over the world in a quite even distribution.

Nimz and his team are studying soil at the Nevada Test Site because it is handy, but they could have studied any desert location. They have trenched along a fault at the test site to get information about the shallow vadose zone (Figure 2). They trenched rather than bored to get as much information as possible about cracking and fracturing in the vadose zone—those chinks in its armor.

"Scientists now use the movement of chlorine as an indicator of moisture flux in low-moisture soil because it doesn't form compounds and stays in its ionic form in water," says Nimz. "But our field data indicate that nuclear test-related chlorine-36 is migrating faster than stable chlorine, casting doubt on the validity of using natural chlorine as an indicator of moisture flux."

The team is combining its new measurements of chlorine-36 and the other four radionuclides in the shallow vadose zone with NUFT, a Livermore flow-and-transport code, to develop a numerical model that simulates the movement of all five nuclides in the deep vadose zone. This model is designed to improve our understanding

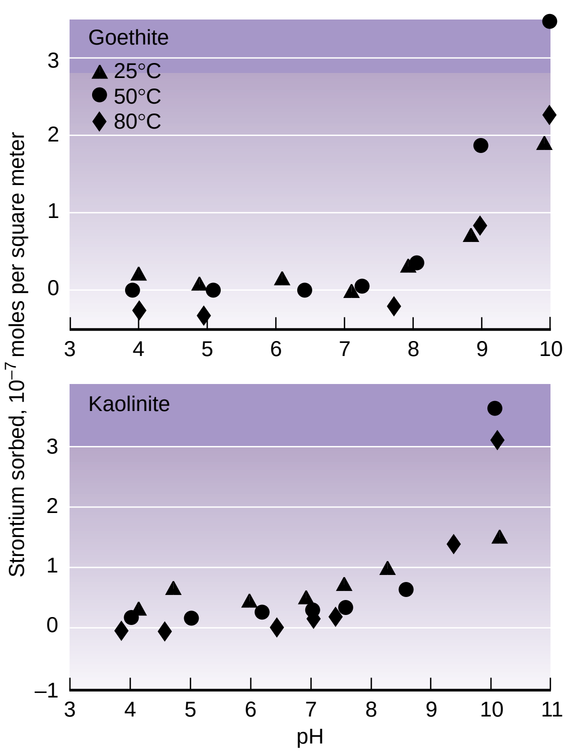


Figure 1. Experiments with strontium in two different types of clays showed that pH had a much greater effect on sorption than did temperature.

of the potential for radionuclide transport far from the contaminant release point and thus of the potential health risks in the far-field environment, where the public is most likely to come into contact with contaminants. The targeted radionuclides are not only common contaminants but also show migration behavior representative of radionuclides and heavy metals. The models developed in this research will thus furnish a foundation for a variety of contaminant migration assessments.

Contaminant Migration to the Water Table. Charles Carrigan's project is on a somewhat larger scale. He says, "We've set up a vadose zone observatory in the southwest corner of the Livermore site where we are monitoring the migration of contaminants to the water table. We're also looking at the 'partitioning' of liquid contaminants into gas. Once gas has formed, it may move laterally, downward, or upward to vent to the surface."

Complex interactions between the atmosphere and groundwater take place in heterogeneous vadose zones where fractures or other discontinuities contribute to permeability. Liquid or dissolved contaminants may flow down by gravity and capillary action. Because of changes in atmospheric pressure, all or part of the liquid may also become vapor. Carrigan's team is thus looking at both liquid- and gas-phase transport in the vadose zone. The goal is to have a model to predict liquid- and gas-phase distributions and downward fluxes of contaminants in the vadose zone.

The Vadose Zone Observatory has a center well for introducing a slightly saline solution as a "contaminant." The infiltration well is surrounded by wells for taking electrical resistance tomography (ERT) measurements to show liquid transport and by other wells for measuring gas-phase pressure changes.

ERT measures changes in resistance between two underground electrodes. These changes indicate changes in saturation in the vadose region. (See *S&TR*, May 1998, pp. 8–10.) Prior to "contamination" of the area, ERT measurements, lithologic logs, soil samples, and other data were used to characterize the site. Then 6,300 gallons of slightly saline water spiked with noble gas tracers were introduced into the center well at an average rate of 0.4 gallons per minute for 10 days at a depth of 15 feet. Figure 3 shows the changes in resistivity over time. Two isotopes of neon, neon-22 in air and neon-21 dissolved in water, were also introduced at different times into the center infiltration well to permit measurement of gas-phase transport and the coupling of gas and liquid phases, respectively. (See *S&TR*, November 1997, pp. 12–17.)

"At our observatory, the vadose zone is 70 feet thick, and we've found it to be highly permeable to gas- and liquid-phase infiltration," Carrigan says. In the experiments, contaminant infiltration occurred much faster than indicated by geologists' logs of the monitoring wells and by laboratory soil analyses. In fact, past data from this area give little or no indication of the magnitude of the observed infiltration rate, perhaps because the high permeability pathways are so localized that they are not well represented in any of the borehole observations.

To date, numerical models based on the NUFT flow-and-transport computer program have been compared with the ERT and gas-sampling observations. Several different models have been used to determine ranges of values for properties, such as permeability, that affect the relatively rapid infiltration of the plume.

A Better View

Electromagnetic induction tomography (EMIT), a technique that uses magnetic fields to image the

Figure 2. The trench at the Nevada Test Site for studying radionuclide movement in undisturbed soil is perpendicular to an earthquake fault. Two-inch cores were drilled horizontally about 24 inches deep. Samples were taken from six cores and from profiles, 15 to 30 feet apart. Two profiles are far from the cracked area, and the others are in the fracture area.

subsurface, was developed for use by the oil and gas industry to determine where reserves are located. Livermore's Jim Berryman has a team working to develop the code necessary to bring this powerful imaging tool to environmental management.

Says Berryman, "While electrical resistance tomography maps changes in resistance using electric current injection, EMIT does the same using magnetic fields. With EMIT, no electrodes need to be inserted into the ground. We just put induction coil transmitters and receivers on the surface or in a borehole" (Figure 4).

ERT as usually applied is two dimensional, measuring the electrical field on a plane between two boreholes. EMIT, however, is inherently a three-dimensional process, which makes the code for imaging the subsurface through magnetic fields more complicated. EMIT has been used by the oil and gas industry for several years, but these applications use a low-frequency field. With low frequencies and their long wavelengths, one gets a fairly smooth look at the subsurface. Higher frequencies and shorter wavelengths result in better resolution, which the environmental remediation community needs to accurately determine the makeup of a heterogeneous subsurface.

"Unfortunately," says Berryman, "the code used by the oil and gas industry cannot be used easily for these higher frequencies, so we chose to start from scratch."

Despite complications with the algorithms used to interpret the magnetic field data, the code is almost fully functional, a promising new tool in Livermore's kit for underground imaging. The EMIT imaging technique may soon be field tested at a Superfund site in Visalia, California, where compounds used to treat utility poles have contaminated the soil. Livermore is already assisting with cleanup of this site, working with SteamTech Environmental Services of Bakersfield, California, and the site owner, Southern California Edison. To date, Livermore has been using ERT for underground imaging on this project. (See *S&TR*, May 1998, pp. 4–11.)

Another Way to Look at It

Another improvement in subsurface imaging is in the works in the laboratories of Pat Berge and her team. Their new algorithm will allow "joint inversion" of several data sources—seismic (sound-wave) data, electrical properties, or magnetic data—to derive direct estimates of porosity and saturation.

Says Berge, "The current state of the art is to look at each set of data individually. Our goal is to combine multiple data sets and invert them together. It's like a crime: every witness tells a slightly different story, and some may even lie. We are like the detective, assembling all the information to come up with the truth. If all of the data

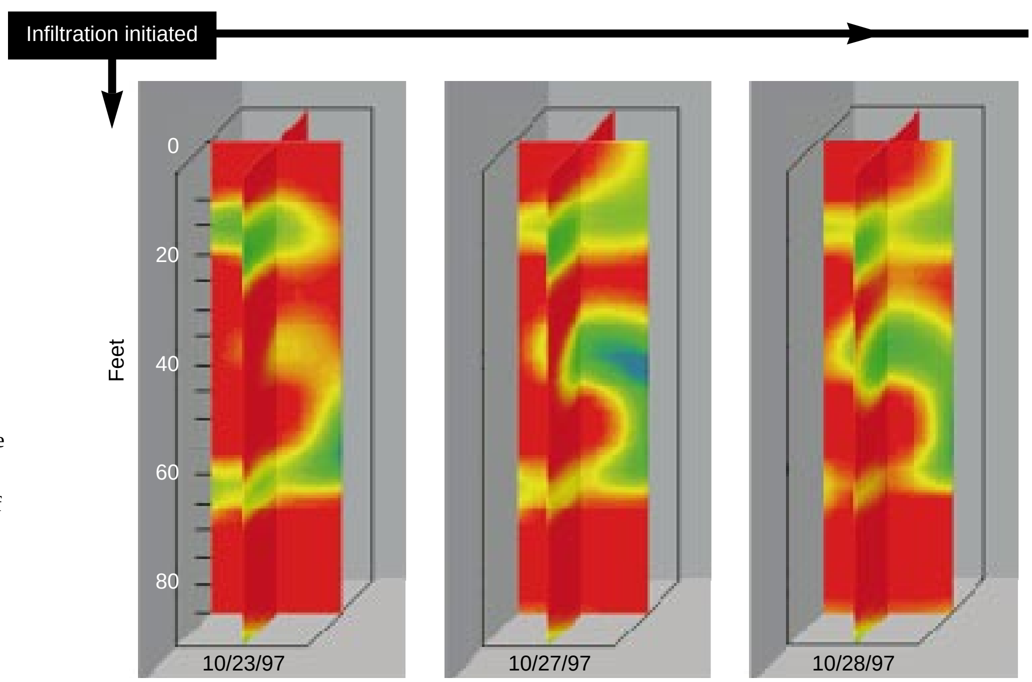


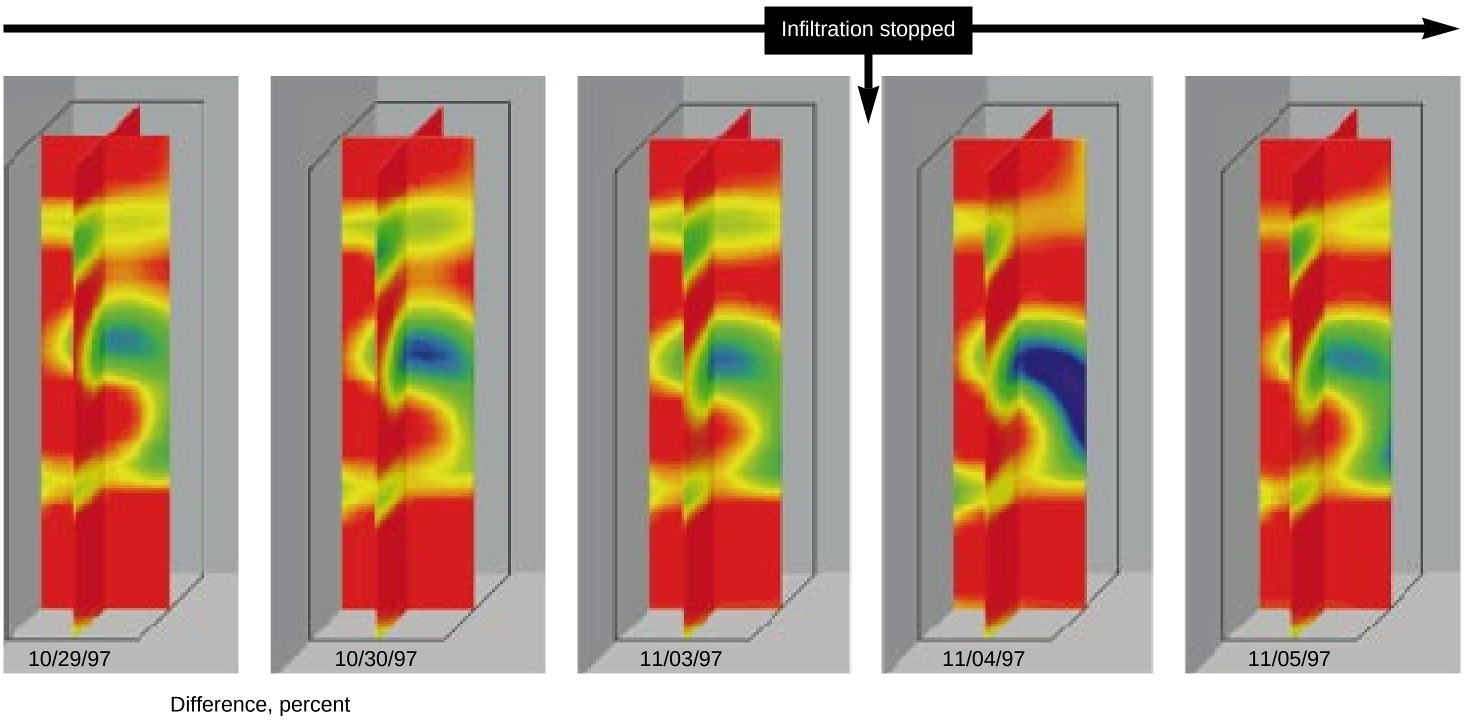
Figure 3. Several days following the start of the infiltration experiment, resistivity changes are apparent at the 40-foot level in the vadose zone. Oscillations in colors also occur (red = no resistivity change, blue = most negative resistivity change, or greater saturation). These changes in saturation result from the periodic upward flow of air in the vadose zone along permeable channels in a manner similar to the periodic flow of air through a narrow-necked, water-filled bottle turned upside down.

about the vadose zone are combined properly, environmental managers will have a more accurate picture of the subsurface for site characterization and remediation monitoring."

Before the joint inversion algorithm can be completed, however, a good deal of basic science research must be done on unconsolidated sediments (particularly for sediments containing clays) at the low pressures found in the near surface. To fill the need for sediment data, Berge and her colleagues are conducting numerous laboratory experiments to study a range of unconsolidated sand–clay mixtures (Figure 5).

Fully saturated samples are used for conductivity measurements. Dry and fully saturated samples are used for velocity measurements because partial saturation introduces a significant degree of complexity to the problem. Various clays are investigated as well as various mixing techniques because the microgeometry of the mix—the arrangement of sand grains, clay, and

Figure 4. From the location of a magnetic field transmitter in a borehole at Lost Hills, California, radial magnetic field receivers can be seen on the surface at 5, 10, 15, and 20 meters along a survey line.



fluid-filled pores—affects both elastic and electrical properties.

All of this information is key to developing relationships between geophysical properties and the hydrogeologic parameters that are most useful for environmental applications. Laboratory measurements suggest that microstructure controls the geophysical properties. Thus, studies of the microstructure assumptions used in empirical or theoretical methods may determine which methods are most successful in relating geophysical properties to porosity and saturation.

The necessary algorithms for the joint inversion are under development. Berge and her colleagues are assessing geostatistical methods, empirical techniques commonly used in borehole geophysics interpretation, and rock physics theories that describe how elastic wave velocities and electrical conductivities depend on porosity and saturation in porous materials with different microgeometries. The team is finding that methods developed in the oil industry generally cannot be applied to environmental applications because oil industry methods are optimized for consolidated rock at depths of one or more kilometers. Environmental site characterization focuses on depths of a few meters to a few hundred meters of mostly unconsolidated sediments.

Berge is quick to admit that a commercially usable joint inversion code will not be complete in the three years allotted for this project. "At that point, our results will still be a basic research tool. It would take perhaps 10 years to put together a code that can be used commercially."

Figure 5. Pat Berge works with team member Eric Carlberg in studying conductivity and wave velocity in a range of unconsolidated sand–clay mixtures. Her team's research seeks to discover relationships between geophysical properties and hydrogeology in the vadose zone. This basic science research is preparatory to developing a new joint inversion algorithm that environmental managers will use to directly estimate porosity and saturation in the vadose zone as part of site characterization and remediation monitoring.

Emission-Free Treatment

The DOE today is responsible for the disposal of a variety of wastes left from weapons production, operation of nuclear power plants, and other sources. Some can only be stored, but some organic-based mixed and radioactive wastes can be treated thermally to reduce or destroy them. Martyn Adamson and his team at Livermore are studying the vaporization of wastes containing uranium, plutonium, and other actinide elements under the high-temperature conditions of thermal treatment.

Notes Adamson, "The DOE lists emission-free destruction of organic low-level and mixed low-level wastes as a primary science need. They need to be able to dispose of these materials, but at the same time, the public is concerned about fugitive radioactive emissions during thermal treatment." His team's work on what happens to radioactive materials under high temperatures will contribute to the design of safe and effective treatment systems.

A number of mixed-waste thermal treatment processes are being considered, including conventional incineration, plasma arc technologies, pyrolysis, thermal desorption, gasification, molten salt oxidation, and hydrothermal oxidation, as well as vitrification of plutonium residues and ceramification of surplus plutonium oxides. Some of these processes are being studied or developed at Livermore and some elsewhere. Key to the success of all of them is assurance that radioactive elements will not escape into the atmosphere in significant amounts.

The team's work is a combination of experimental studies and thermodynamic modeling. Using conditions comparable to those found in various treatment processes, the team is making transpiration measurements, conducting thermal gradient transport experiments, and determining key thermodynamic parameters for gaseous actinide species. Figure 6 shows the setup for one type of experiment involving pressure measurements for actinide oxides.

Livermore is performing work on plutonium and neptunium (and possibly americium, if time permits), while Professor D. R. Olander and a small team at the University of California at Berkeley are doing work on uranium.

In parallel with the experimental effort, a complete thermodynamic database for expected gaseous actinide species is being developed from literature data, proposed measurements, and data predictions using bond energy correlation and statistical thermodynamic estimation methods.

Out of this work will come an understanding of the thermodynamics of actinide vaporization and partitioning/speciation behavior under conditions that exist during thermal treatment, which should help in predicting the behavior of radioactive and volatile metals during treatment.

A Quick Payoff?

These projects represent a blend of new measurement technologies and new processes, pieces of a large environmental management puzzle. Some of those pieces will likely be field tested in the not-too-distant future. Equipment and field operations for environmental cleanup are changing rapidly, as environmental managers learn more about how the vadose zone and the contaminants in it operate.

The cleanup of the Visalia pole yard is an example of rapid payoff from basic research. Two processes, dynamic underground stripping and hydrous pyrolysis oxidation, are being used to clean up the site. Dynamic underground stripping was born in the laboratories of Lawrence Livermore and the University of California at Berkeley in the early 1990s. Livermore scientists developed hydrous pyrolysis oxidation more recently. During the first six weeks of cleanup at Visalia in the summer of 1997, contaminants were removed from soil and groundwater at a rate of 46,000 pounds per week. The site's owner, Southern California Edison, had been using traditional pump-and-treat cleanup methods for 20 years, most recently removing about 10 pounds per week (earlier rates were higher). Thus, with the new cleanup techniques, 85 years of pump-and-treat at 1997 rates were accomplished in just six weeks. (See *S&TR*, May 1998, pp. 4–11.)

The Visalia cleanup is considered a big success by everyone involved. Not only have the processes proved to be

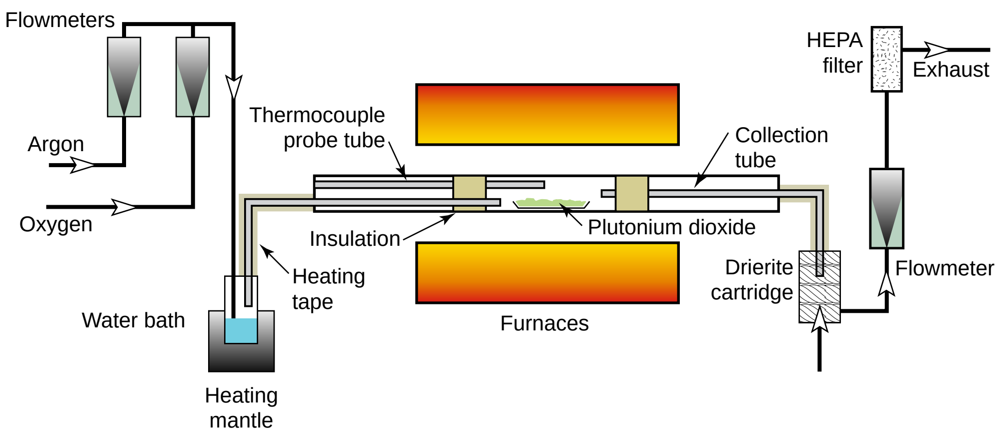


Figure 6. Schematic of the apparatus used for transpiration studies of plutonium dioxide vaporization in the presence of oxygen and steam.

remarkably effective, but the time between development and field use has been relatively short.

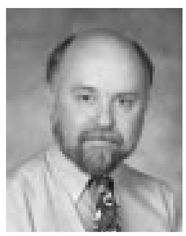
Right now, we can't know how or when these basic science projects will benefit environmental management, but it is fair to say that many of them will. Those with payoffs similar to the one at Visalia would make everyone at Livermore very happy indeed.

—Katie Walter

Key Words: accelerator mass spectrometry (AMS), electromagnetic induction tomography (EMIT), electrical resistance tomography (ERT), environmental geophysics, environmental management, joint inversion, mixed waste, modeling, moisture flux, Nevada Test Site, NUFT flow transport code, rock physics, rock properties, site characterization, thermal treatment, underground imaging, vadose zone.

For further information, contact Kenneth Jackson (925) 422-6053 (jackson8@llnl.gov) or Norman Burkhard (925) 422-6483 (burkhard1@llnl.gov). See also the Department of Energy's Environmental Management Science Project web site at **http://www.em.doe.gov/science/**.

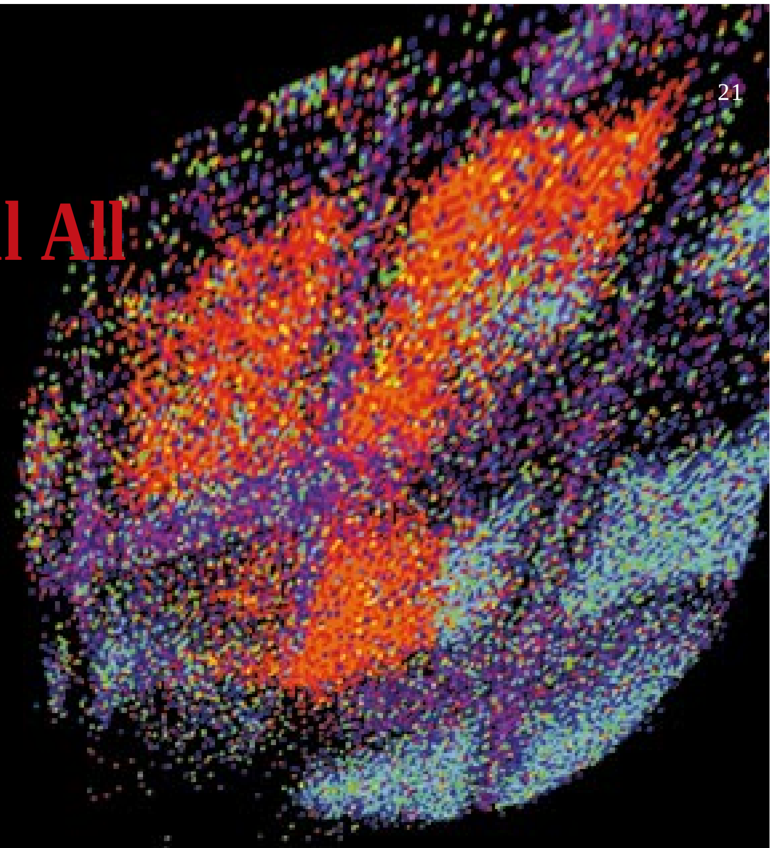
About the Scientists



KENNETH JACKSON joined the Laboratory in 1983 after graduating with a double major in geology and chemistry from the University of New Mexico, Albuquerque, in 1976 and completing graduate work in geology at the University of California at Berkeley (M.A., 1979; Ph.D., 1983). Beginning in 1986, he has filled a series of leadership positions for environmental geochemistry projects. Today, he is leader of the Geosciences and Environmental Technologies Division in the Earth and Environmental Sciences Directorate. His responsibilities include three of the environmental management basic science projects reported on in this article: electromagnetic induction tomography adaptation, joint inversion algorithm development, and organic-based mixed and radioactive waste treatment. Jackson's areas of research interest are aqueous solution chemistry, geochemistry modeling, organic geochemistry, and environmental geochemistry.

NORMAN BURKHARD is leader of the Earth and Environmental Sciences Directorate's Geophysics and Global Security Division. Among other duties, he is responsible for directing Livermore's three projects investigating contaminant movement in the vadose zone. He joined the Laboratory in 1977 after receiving his Ph.D. in physics from the University of California at Los Angeles. He also holds an M.S. in physics from UCLA (1973) and a B.A. in physics from Pennsylvania State University. Burkhard has extensive experience in supporting the Defense and Nuclear Technologies Directorate's work at the Nevada Test Site to address underground containment issues for subcritical experiments.

When Collisions Reveal All



As researchers focus on ever-smaller dimensions to engineer advanced materials, they increasingly demand new tools to scrutinize these materials. The need is particularly acute for semiconductor chip makers as they continue to shrink the size of chips and their internal features. Lawrence Livermore researchers also want a better way to image and characterize the all-important surfaces of critical materials.

Now a team from Livermore's Physics and Space Technology, Chemistry and Materials Science, and Engineering directorates has developed a diagnostic instrument called a time-of-flight secondary ion mass spectrometry (SIMS) emission microscope. For the first time, the instrument simultaneously provides extremely sensitive surface analysis, high-resolution imaging, and chemical determination of surface constituents. Recent tests on a variety of materials show that the new microscope may well prove valuable in solving vexing surface analysis problems in fields as diverse as precision optics and amino acid sequencing.

SIMS is a widespread technique in which a stream of energetic, primary ions bombards the surface of a material under investigation. Upon impact, these ions generate positively and negatively charged secondary ions, which are gathered by electrically charged lenses, imaged, and identified. (Neutral atoms and molecules are also given off but are not detected.)

NASA scientists used the first SIMS instrument in the 1960s to analyze moon rocks. Today, SIMS is widely used for analyzing trace elements and contaminants in solid materials, especially semiconductors and thin films.

Traditional SIMS instruments employ a stream of single-charged primary ions (for example, xenon +1) to bombard a sample. With this technique, about a thousand bombardments are needed to produce one secondary ion, a slow process during which a spectrum of surface constituents is gradually built up.

Greater "Pop"

The new Livermore instrument uses not single-charged, but multiple-charged ions (for example, gold +69), which produce a thousandfold increase in secondary ions. "Highly charged ions make our instrument unique," says materials scientist Alex Hamza. "The higher the charge, the greater the 'pop,' the more ions that come off." More ions mean more—and faster—information about the composition of the surface layer, including any contaminants.

Hamza says studies at Livermore show that during the first few femtoseconds (quadrillionths of a second) of impact, the highly charged ions deposit a huge amount of potential energy into a surface area several nanometers (billionths of a meter) square. In contrast, single-charged ions deposit large amounts of kinetic, not potential, energy. This kinetic energy transfer is not localized at the surface but is distributed more deeply into the sample.

Although the exact mechanism of highly charged ion energy transfer isn't fully elucidated, Hamza says it is probable that electrons from nearby surface atoms are attracted to the strongly positive primary ion. The resulting electron transfer removes the "glue" that once held the nearby atoms in place, allowing them to fly off. As they leave the surface, they are attracted to the electrostatic lens of the microscope and accelerated to a detector located about a half meter from the sample. Finally, an image of the surface magnified at from 40 to 400 times is created (Figure 1).

The chemical determination of the secondary ions is performed through time-of-flight techniques in which the time a secondary ion takes to arrive at the detector is directly related to the mass. Histograms of the arrival times are built up to form mass spectra of the secondary ions emitted from the sample (Figure 2). With a collision rate of about a thousand per second, the Livermore instrument takes roughly 15 minutes (corresponding to about a million events) to build up a useful image such as that in Figure 1.

Because of the number of secondary ions produced per collision and the small area being investigated, the microscope is particularly useful in determining the location of secondary ions through coincidence counting. By seeing what molecules come off together from the impact of primary ions, the instrument can reveal impurities in the location of interest. This feature is particularly important as chips shrink and can be contaminated by fewer impure atoms or molecules, which, nevertheless, must be detected.

Focusing on Sensitivity, Resolution

The new Livermore instrument can detect 10 parts per million, a sensitivity equal to that found in a typical SIMS instrument. Resolution of feature sizes has been demonstrated at 6 micrometers. The development team is confident it can achieve resolutions down to 10 nanometers within a year through better lens design and improved detector resolution.

The instrument uses beams of highly charged ions generated by the electron-beam ion trap (EBIT), developed by a Lawrence Livermore research team a few years ago. With this device, the charge, energy, and mass of the primary beam can be varied independently. Electrostatic lenses and apertures control the intensity and width of the primary ion beam.

Conceived, designed, and fabricated by Livermore physicist Alan Barnes with the assistance of mechanical engineer Ed Magee, the SIMS emission microscope features a novel "acorn-shaped" objective lens used to image the secondary ions while a sensitive detector determines the up–down position and time of arrival of the secondary ions at the microscope image plane. Contrast in the image can be based on the intensity of the electrons detected or the presence of particular secondary ions.

Because of this technology's potential importance to the semiconductor industry, the team has used it to analyze the deposition of tungsten on patterned silicon wafers, a common step in computer chip manufacturing. Figure 1 is an image collected from a wire-mesh-covered sample of a silicon wafer patterned with silicon dioxide and tungsten. The colors in the image indicate the type of secondary ion observed, as measured by time of flight: red indicates a tungsten-related region and blue a silicon dioxide–dominated region.

By selecting events from the blue and red regions, researchers can provide a spatially resolved analysis of the surface composition. Figure 2a shows the time-of-flight spectrum of the blue region, while Figure 2b is the spectrum from the red region. Both spectra reveal the outstanding sensitivity of the instrument.

According to Hamza, an impressive array of instruments is available to image materials with very high resolution—examples include transmission electron microscopy, scanning electron microscopy, and scanning tunneling microscopy. An equally impressive array of instruments and techniques is available to determine material composition (Auger electron spectroscopy, photoelectron spectroscopy, and SIMS). However, no other technique combines high-resolution images, high sensitivity to trace elements, and the chemical structure of the secondary ions, all in one package.

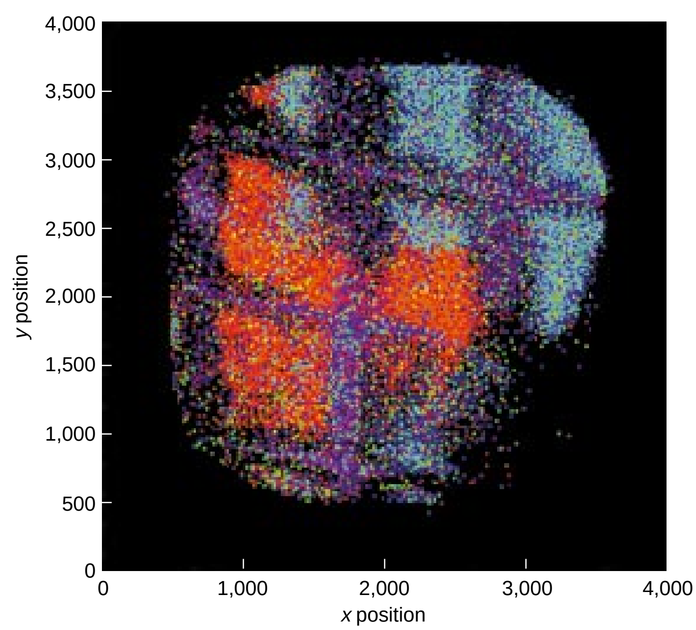


Figure 1. Image of a 70-line-per-inch copper grid over a silicon wafer. The colors indicate the mass of the secondary ions measured. Blue and green indicate silicon dioxide features of the material, while red and orange indicate tungsten features. Purple is chlorine and carbon contamination. The lines are 360 micrometers apart, and the smallest observed feature is 6.4 micrometers wide.

An Eye on the Future

The first Livermore instrument was built to demonstrate the concepts necessary to construct more powerful versions. Plans for the next two years include improved resolution, data collection, and primary beam focusing. To image smaller areas, the team will experiment with using ion streams chilled to low temperatures.

Hamza reports significant interest from Semitech, a national semiconductor industry forum. Semitech officials have suggested that semiconductor companies could send samples to a central location housing several of the Livermore microscopes.

As for other applications, the research team sees significant potential wherever chemical structure must be determined at high resolution. A natural fit is stockpile surveillance activities such as investigating corrosion in metals and inspecting high explosives to determine their reliability. In fact, the research team has already used the new microscope to examine the distribution of high-explosive molecules in their binding material—a factor affecting reliability.

Another important application is the investigation of possible links between glass failure and polishing residue in optical components used in powerful lasers such as Lawrence Livermore's forthcoming National Ignition Facility. One intriguing application is analyzing biological materials. By using a highly charged ion stream to break molecular bonds, the microscope could be used to determine the sequence of amino acids forming proteins and thereby become a powerful tool used in molecular biology as well as forensics.

If planned refinements succeed, the instrument could well become a mainstay in research laboratories everywhere.

—Arnie Heller

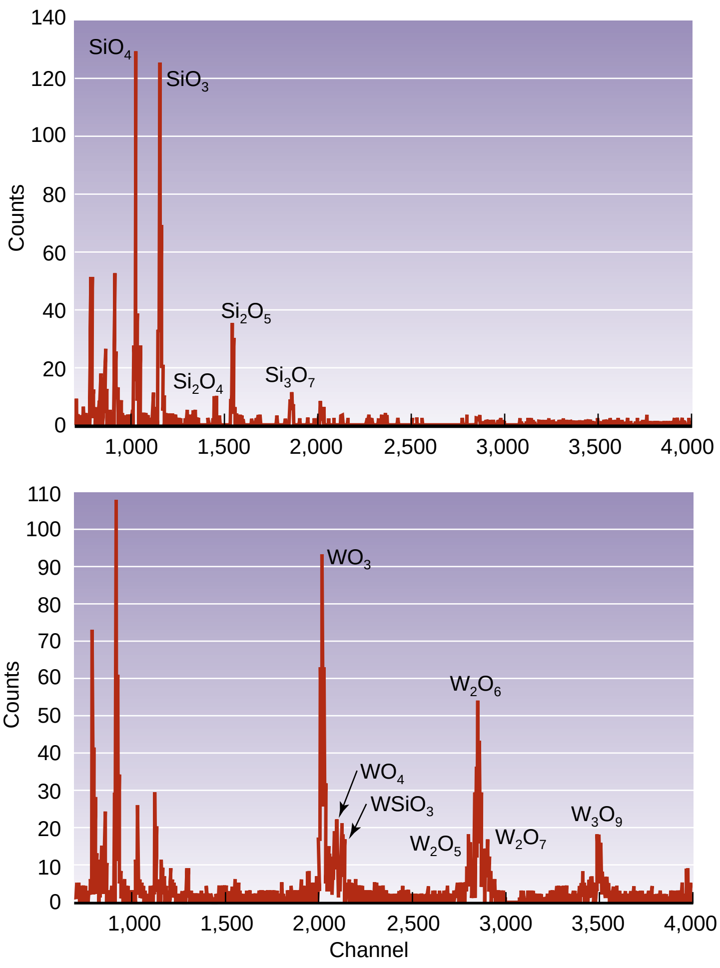


Figure 2. (a) The time-of-flight spectrum of the blue region in Figure 1 dominated by silicon compounds (SiO_x). (b) The time-of-flight spectrum from the red region in Figure 1 dominated by tungsten compounds (WO_x).

Key Words: highly charged ions, SIMS (secondary ion mass spectrometry), time-of-flight secondary ion mass spectrometry (SIMS) emission microscope.

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Collaboration Opens Door to Understanding Genetic Kidney Disorder

THE search for genes—just as for gold—may be long and arduous, but the rewards are great. Genes and the proteins they produce hold the keys that unlock the mysteries of genetic diseases and allow the development of gene and drug therapies. The worldwide Human Genome Project has the ultimate goals of finding all the genes in the DNA sequence, developing tools for using this information to study human biology and medicine, and improving human health.

The task of locating a particular gene in the human genome can be more daunting than searching for a vein of precious ore underground. For perspective, the human body has 100 trillion cells, each of which contains 23 pairs of chromosomes. Each chromosome carries a complete set of DNA. If the DNA of one cell, which contains about three billion nucleic acid units or “base pairs,” were formed into a single continuous strand, it would stretch six feet long. (The four chemical “bases”—adenine, thymine, guanine, and cytosine—bind together to form base pairs that are the building blocks of DNA.) About 3 percent of this DNA forms working genes. The task facing gene hunters is to search through the “genetic junk” of the human genome to find that one string of DNA that comprises the gene in question.

It’s a task that makes digging for gold in a mountain of dirt and rock look easy.

The Search for a Kidney Disease Gene

For many years, researchers from the Karolinska Institute in Stockholm, Sweden, and the University of Oulu in Finland had been seeking the gene for congenital nephrotic syndrome, an inherited kidney disease that causes massive amounts of proteins to be excreted by the kidneys. The disorder, which occurs primarily in families of Finnish origin, develops shortly after birth and usually causes death within a year. The only alternative for this progressive disease is a kidney transplant.

By 1993, the researchers, led by medical chemistry professor Karl Tryggvason from Karolinska Institute’s Department of Medical Biochemistry and Biophysics, had narrowed their search to chromosome 19. Because Lawrence Livermore is well known for its mapping and sequencing of chromosome 19, Tryggvason contacted Livermore biomedical scientist Anne Olsen for assistance.

“Other laboratories and institutions are sequencing pieces of 19, but we are the only one addressing the entire chromosome,” Olsen explained. (For more information about the Laboratory’s work in DNA sequencing, see *S&TR*, November 1996, pp. 24–26, and July/August 1997, pp. 18–20.)

When the European researchers contacted Livermore, they knew where the gene resided on the genetic linkage map, but not on the physical map of chromosome 19. (See the box on p. 25.) In 1993, the physical map of chromosome 19 was less developed than it is today. Olsen and other biomedical scientists worked for more than a year to complete a physical map of the genetic region in question, providing the European team with well-characterized DNA fragments or clones. The collaborators used those cloned pieces of chromosome 19 to further narrow down the site of the fatal gene, tracing it to an area containing 150,000 base pairs.

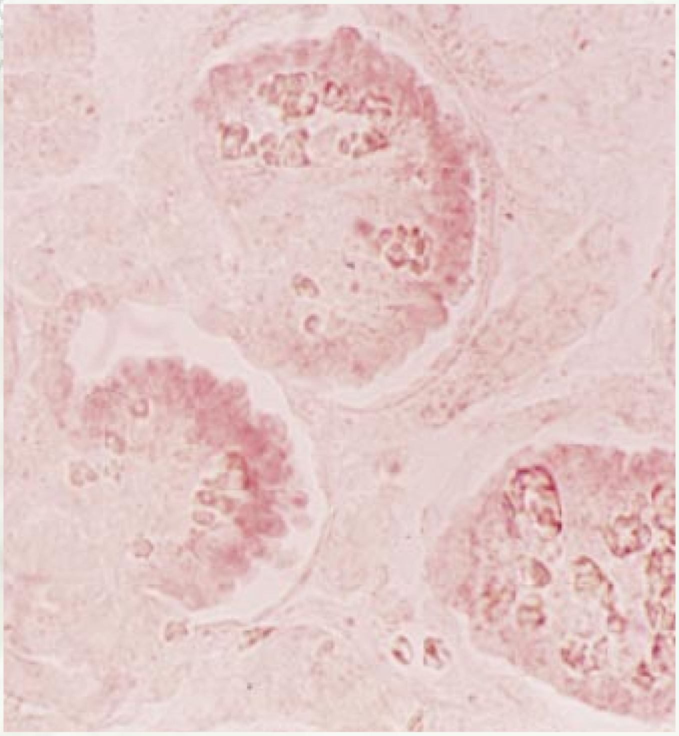
Narrowing Down the Search

At this point, the teams had gone as far as they could go with physical mapping, and it was time to sequence the individual base pairs to determine their exact order on the chromosome. Jane Lamerdin and Paula McCready led another Lawrence Livermore team that sequenced the bases using the Laboratory’s high-throughput sequencing machines. The Finnish collaborators used the clones provided by Livermore for biological analysis and located 11 likely genes in the candidate region.

Of those genes, they finally narrowed it down to one. That particular gene was mutated in the families carrying the disease, and the protein associated with the gene was well-expressed in the kidneys.

“Even though our part is done, the story is just beginning,” said Olsen. “Since the main symptom of this disease—protein excreted in the urine—appears in other conditions, this work may offer insights into other kidney ailments as well.”

The breakthrough was announced in March 1998 when a paper on the research appeared in the journal *Molecular Cell*



Expression of the congenital nephrotic syndrome kidney gene (Nephrin) in the cellular material from a blood vessel in the kidney of a human embryo. Nephrin was discovered by Karl Tryggvason and his team of Finnish and Swedish researchers with the assistance of Livermore genetic scientists Anne Olsen, Jane Lamerdin, and Paula McCready. (Image courtesy of Karl Tryggvason of the Division of Matrix Biology, Department of Medical Biochemistry and Biophysics, Karolinska Institute, Stockholm, Sweden, and the Biocenter and Department of Biochemistry, University of Oulu, Oulu, Finland.)

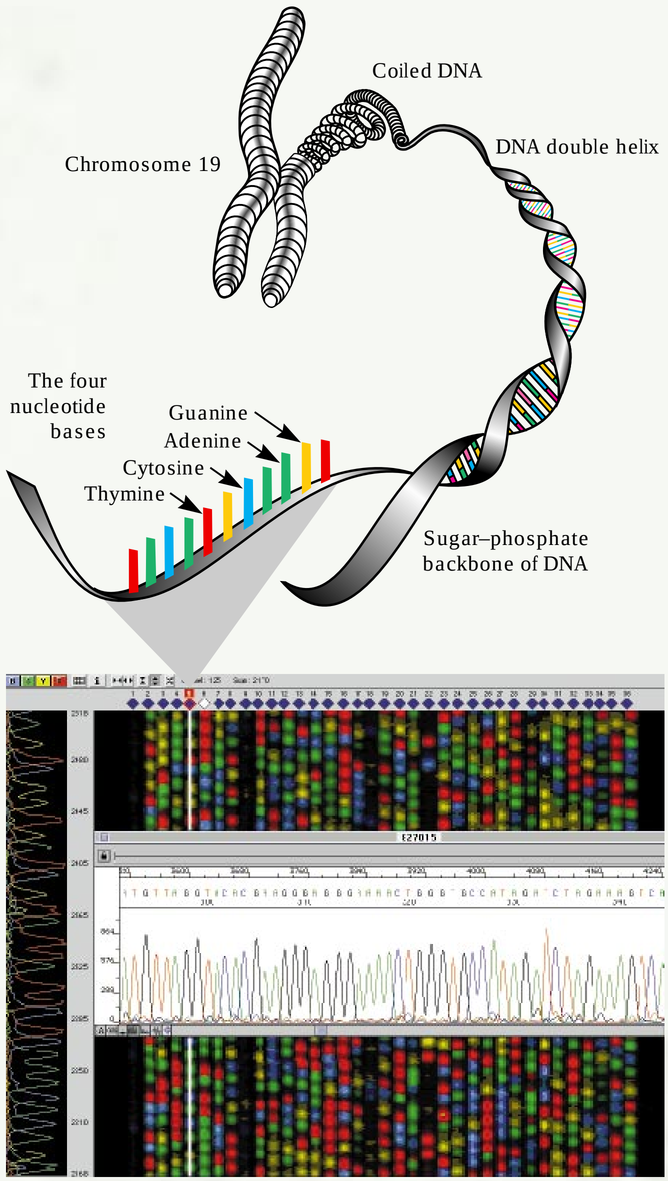
A Primer on Maps, Markers, and Sequencing

A genome map describes the order of genes or other markers and the spacing between them on each chromosome. Human genome maps are constructed on several different scales or levels of resolution. At the coarsest resolution are genetic linkage maps, constructed by observing how frequently two markers are inherited together. These maps depict the relative chromosomal locations of DNA markers (genes and other identifiable DNA sequences) by their patterns of inheritance. Two markers near each other on the same chromosome tend to be passed together from parent to child. During the normal production of sperm and egg cells, DNA strands occasionally break and rejoin in different places on the same chromosome or on the other copy of the same chromosome. This process— called meiotic recombination— can result in the separation of two markers originally on the same chromosome. The closer the markers are to each other, the more tightly linked they are, making it less likely a recombination event will separate them. Recombination frequency thus provides an estimate of the distance between two markers.

The value of the genetic map is that an inherited disease can be located on the map by following the inheritance of a DNA marker, even though the responsible gene is not yet identified.

Physical maps, in contrast, provide a finer resolution of the absolute location of a gene. A physical map lays out the order of all the base pairs on a chromosome. The ultimate physical map of the human genome is the complete DNA sequence, or the determination of all base pairs on each chromosome.

For more information about basic genetics as well as mapping and sequencing techniques, see the U.S. Department of Energy’s “Primer on Molecular Genetics” on the World Wide Web at *http://www.ornl.gov/TechResources/Human Genome/publicat/primer/intro.html*.



At the lower left is a portion of a sequencing gel produced recently at Lawrence Livermore using the latest mapping and sequencing technology. Rapid advances in mapping and sequencing techniques and technologies are enabling researchers to find specific genes faster than they could just a few years ago when Livermore researchers collaborated with Swedish and Finnish colleagues in their search for the kidney disorder gene Nephrin.

(March 1998, pp. 575–582). This announcement came hot on the heels of another genetic discovery involving a rare hereditary susceptibility to a variety of cancers—the Peutz–Jeghers syndrome. Pinpointing the location of the Peutz–Jeghers gene took only one year.

"The difference in time indicates how far we've come with mapping and sequencing techniques and technologies over the past few years," Olsen said. "When Karl Tryggvason first contacted us about the kidney disease gene, we didn't have a highly developed physical map for that region. Three years later, when we were asked to collaborate on the search for the Peutz–Jeghers gene, our map was much better developed, and that search went more quickly. Better, more detailed maps mean the search for genes will only accelerate in the future."

—Ann Parker

Key Words: chromosome 19, congenital nephrotic syndrome, DNA clones, DNA mapping and sequencing, Human Genome Project, kidney disease, Peutz–Jeghers syndrome.

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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
Alan F. Jankowski Jeffrey P. Hayes	**Process System and Method for Fabricating Submicron Field Emission Cathodes** U.S. Patent 5,746,634 May 5, 1998	A method for fabricating submicron field emission cathodes over relatively large substrate surface areas.The deposition source divergence is controlled to produce field emission cathodes with height-to-base aspect ratios that are uniform over large substrate surface areas while using very short source-to-substrate distances. The rate of hole closure is controlled from the cone source. The substrate surface is coated in well-defined increments. The deposition source is apertured to coat pixel areas on the surface past the deposition source. Either collimated sputtering or evaporative deposition sources can be used The position of the aperture and its size and shape are used to control the field emission cathode size and shape.
Daniel M. Makowiecki Alan F. Jankowski	**Magnetron Sputtered Boron Films** U.S. Patent 5,766,747 June 16, 1998	A method for the production of thin boron and titanium–boron films by magnetron sputter deposition. The magnetron sputter deposition method requires the use of a high-density crystalline boron sputter target prepared by hot isostatic pressing. Thin boron films prepared by this method are useful for producing hardened surfaces or for surfacing machine tools and for making ultrathinband pass filters as well as the low-radioactive element in low-radioactive/high-radioactive optical components. They contain no morphological growth features, which are found in thin films prepared by various physical vapor-deposition processes.
Thomas E. McEwan	**Light Beam Range Finder** U.S. Patent 5,767,953 June 16, 1998	A laser “tape measure” capable of measuring the distance to a target with a resolution of less than 1 millimeter and a precision of better than 0.1 percent. A transmitter (including a laser diode) transmits a sequence of electromagnetic pulses in response to a transmit-timing signal. A receiver samples reflections from objects within the field of the sequence of visible electromagnetic pulses with controlled timing in response to a receive-timing signal. In response to the samples, the receiver generates a sample that indicates distance to the object causing the reflections.
Thomas E. McEwan	**Short Range Micro-Power Impulse Radar with High Resolution Swept Range Gate with Damped Transmit and Receive Cavities** U.S. Patent 5,744,091 June 30, 1998	A radar range finder and hidden-object locator based on ultrawideband radar with a high-resolution swept-range gate. The device generates an equivalent time–amplitude scan with a typical range of 4 inches to 20 feet and an analog range resolution limited by a jitter of about 0.01 inch. A differential sampling receiver eliminates ringing and other aberrations induced by the near proximity of the transmit antenna, so a background subtraction is not needed, which simplifies the circuitry while improving performance. Clutter in the receive signal is reduced by decoupling the receiver and transmit cavities by placing a space between them, using conductive or radiative damping elements on the cavities, and placing terminating plates on the sides of the openings. Uses include fluid-level sensing, automotive radar, hidden-object location, and collection of vehicle count and speed data for traffic control.

(continued on p. 28)

(continued from p. 27)

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Abraham P. Lee Peter A. Krulevitch M. Allen Northrup Jimmy C. Trevino	**Micromachined Actuators/ Sensors for Intratubular Position/Steering** U.S. Patent 5,771,902 June 30, 1998	Micromachined thin-film cantilever actuators with the means for individually controlling the deflection of the cantilevers, valve members, and rudders for steering the actuators through blood vessels or positioning them within a blood vessel. The cantilever actuators include tactile sensor arrays mounted on a catheter or guide-wire tip for navigation. They also include tissue identification, shape-memory-alloy-film-based catheter/guide-wire steering mechanisms, and rudder-based steering devices that allow the selective actuation of rudders that use flowing blood to help direct the catheter through the blood vessel. While particularly adapted for medical applications, these cantilever actuators can be used for steering through piping and tubing systems.
Kurt H. Weiner	**Method for Producing Silicon Thin-Film Transistors with Enhanced Forward Current Drive** U.S. Patent 5,773,309 June 20, 1998	A method for fabricating amorphous silicon thin-film transistors (TFTs) with a polycrystalline silicon surface channel for enhanced forward current drive. The method is particularly adapted for producing top-gate silicon TFTs, which have the advantages of both amorphous and polycrystalline silicon TFTs, but without the problem of leakage current of polycrystalline silicon TFTs. The method uses a pulsed excimer laser to create a thin polycrystalline silicon layer at the amorphous silicon/gate–insulator surface. This layer has an increased mobility compared with that of the amorphous silicon during forward device operation so that increased drive currents are achieved. In reverse operation, the polysilicon layer is relatively thin compared to the amorphous silicon, so that the transistor exhibits the low leakage currents inherent in amorphous silicon. Silicon TFTs can be used as pixel switches in an active-matrix liquid crystal display to improve display refresh rates.
Daniel M. Makowiecki Robert S. Rosen	**Limited-Life Cartridge Primers** U.S. Patent 5,773,748 June 30, 1998	A cartridge primer using an explosive that can become inactive in a predetermined period of time. The primer's explosive or combustible material is an inorganic reactive multilayer (RML). The reaction products of the RML are submicrometer grains of noncorrosive inorganic compounds that have no harmful effects on firearms or cartridge cases. Unlike primers containing lead, primers with RMLs do not present a hazard to the environment. Physical structure and stored interfacial energy determine the sensitivity of an RML. The sensitivity lowers with time because of a decrease in interfacial energy resulting from interdiffusion of the elemental layers. Time-dependent interdiffusion is predictable, thereby enabling the functional life time of an RML primer to be predetermined by the materials selected for the reacting layers and their thickness.
Robert L. Druce Hugh C. Kirbie Mark A. Newton	**Light-Weight DC to Very High Voltage DC Converter** U.S. Patent 5,774,348 June 30, 1998	A dc–dc converter capable of generating output of 100 kilovolts without a transformer composed of a silicon-opening-switch (SOS) diode connected to allow a charging current from a capacitor to flow into an inductor. When a specified amount of charge has flowed through the SOS diode, it opens up abruptly, and the consequential collapsing field of the inductor causes a voltage and current reversal that is steered into a load capacitor by an output diode. A switch across the series combination of the capacitor, inductor, and SOS diode closes to periodically reset the SOS diode by inducing a forward-biased current.

Awards

Paula Trinoskey, a certified health physicist and radiation protection technologist in the Laboratory's Hazards Control Department, has been inducted into the 1998 **Fellow Class of the Health Physics Society**. This distinguished award honors senior members of the society who have made significant administrative, education, or scientific contributions to the profession of health physics. Trinoskey, who joined the Laboratory in 1989, has been active in the society since 1979.

In 1997, Trinoskey was presented with the **Jack M. Brewer Award of Excellence**—the highest award in the Department of Energy Training Community. She was also the first recipient of the **American Nuclear Society Training Excellence Award** in recognition of achievement, excellence, and innovation in nuclear training given in 1994.

Abstracts

Controlling the World's Most Powerful Laser

The National Ignition Facility's (NIF) control system will supervise experiment setup and countdown; oversee machine interlocks to protect hardware, data, and personnel; generate reports on system performance; provide human operators with graphical interfaces for control and system status displays; perform alignment, diagnostics, and control of power conditioning and electro-optic subsystems; and monitor the health of all subsystems and components, advising operators of any abnormal conditions. The system has been designed to be easy to maintain, extend, and upgrade over the course of the giant laser's projected 30-year lifetime. The system's architecture features two main layers: a lower layer of front-end processors (FEPs) interacting directly with laser and target equipment and a higher, supervisory layer to control and integrate the FEPs. In designing the control system, engineers have used proven engineering techniques as well as modern software techniques such as object-oriented programming, ADA 95 software language, and the CORBA (Common Object Request Brokerage Architecture) international standard. One key strategy to minimize risks is an iterative approach to software construction in which increasingly smaller risks are resolved as the control system is developed and function is added after major NIF hardware designs are finalized.

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Getting Down to Environmental Cleanup Basics

The Department of Energy has established an Environmental Management Science Program to sponsor projects in basic science related to environmental management. The purpose of the program is to reduce the cost of environmental cleanup and make it faster over the long term. Since the program's inception in 1996, Lawrence Livermore has received grants for six of these basic science projects. This article describes them and presents progress reports on the research. Three of the projects are studying the movement of contaminants in the vadose zone, the area between Earth's surface and the water table. Two projects are adapting existing computer code or developing new code for imaging the subsurface for environmental management purposes. The sixth project is investigating processes for thermally treating some organic-based low-level radioactive and mixed low-level wastes to reduce or destroy them with no or insignificant releases to the environment.

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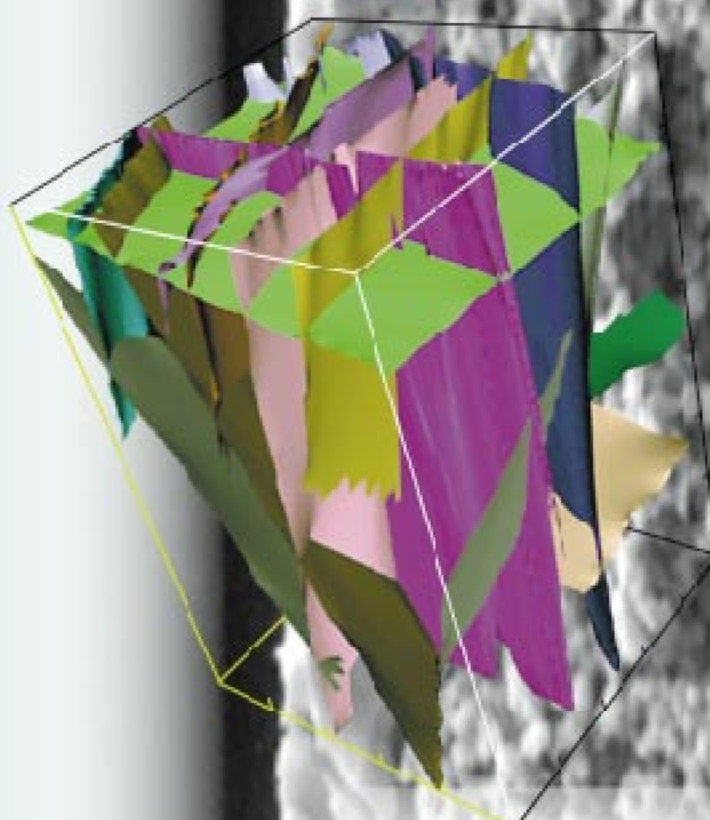
Norman Burkhard (925) 422-6483 (burkhard1@llnl.gov).

U.S. Government Printing Office: 1998/783-051-60058

Coming Next Month

The December *S&TR* will feature a report on how the Laboratory's energy technology research is addressing the nation's energy needs in the areas of

- Fuel cells
- A repository for nuclear waste
- Electric power storage devices
- Carbon management



Also in December

- Using antimatter with the positron microprobe to study materials in the nuclear stockpile
- Modeling the San Francisco Bay Bridge for seismic safety
- The Forensic Science Center's latest sleuthing technologies: thin-layer chromatography screening and solid-phase microextraction

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