November 2000

Science & Technology Review

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

At the Forefront of Environmental Modeling

Also in this issue:

- **Proton Radiography as a Stockpile Stewardship Tool**
- **Creating the Stuff of Stars in an Ion Trap**
- **Imaging Deep beneath Skin with Light**

About the Cover

Massively parallel supercomputers similar to those used to assure the safety and reliability of the U.S. nuclear deterrent are also aiding environmental research. Lawrence Livermore researchers are using this high-powered computing capability to produce models of natural events in a fraction of the time that similar but less complex simulations once took. The cover image—a three-dimensional model of the geology underlying part of the Orange County Water District in Southern California—illustrates how scientists are using supercomputers to understand, predict, and safeguard the environment. The article beginning on p. 4 reports on recent advances in modeling groundwater movement, earthquakes, climate change, and atmospheric release emergencies.

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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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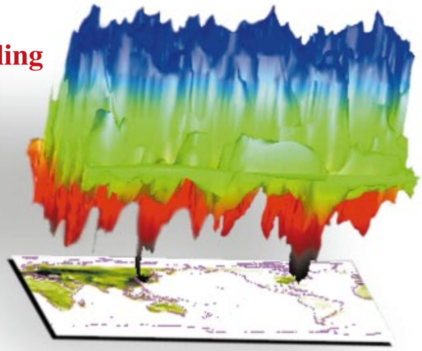

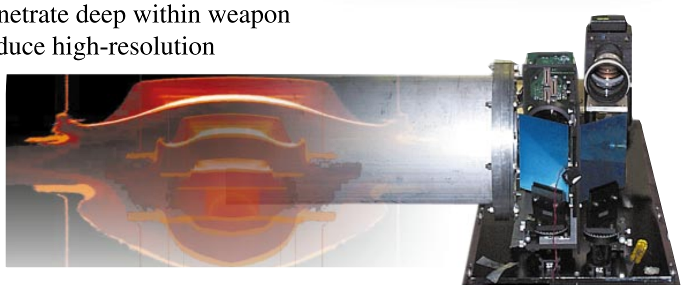

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B Factory announces first results

In May 1999, the B Factory electron–positron collider and its massive, high-resolution BaBar detector came on line at the Stanford Linear Accelerator Center (SLAC) in Stanford, California. Recently, the experiment's collaborators—SLAC and Lawrence Livermore and Lawrence Berkeley national laboratories—announced their first results at the International Conference on High-Energy Physics in Osaka, Japan.

Although these preliminary results are too inconclusive to confirm or overturn long-held theories about why the universe contains far more matter than antimatter, the collaborators have much to celebrate. According to Doug Wright, principal investigator for the Laboratory's B Factory team, both the accelerator–collider and the detector have run well from the moment they were turned on. Says Wright, "The really great thing is that we're getting significant results in our very first year of operation." Most new accelerators need years of fine-tuning to perform at full potential.

The B Factory—and the similar B-meson experiment (KEKB) in Japan—provides scientists with a means of detecting and measuring with greater precision than ever before the differences, or asymmetries, between the laws of physics for matter and those for antimatter. Although scientists have had experimental evidence of subtle asymmetries since 1964, they have had no way to explain how the effect originates. The B Factory and KEKB provide a way to measure asymmetry and either confirm or challenge current theories about the preponderance of matter over antimatter following the big bang that is believed to have brought the universe into being.

"At this stage, we're still developing the tools to extract the asymmetry from the data," explains Wright. Despite the limited preliminary data, Wright says that with both the B Factory and KEKB gearing up their accelerators and fine-tuning their detectors, more definitive results with a lower margin of error are inevitable. And regardless of the outcome, both experiments are win–win for cosmological theory. For Wright, "If we see an asymmetry, that's a huge discovery. If we see no asymmetry, that would be big news as well."

Lawrence Livermore scientists and engineers have been involved in every aspect of the B Factory from conception and design to construction and operation. For more information on Livermore's contributions to the B Factory, see *S&TR*, January/February 1997, pp. 4–13, and January/February 1999, pp. 12–14.

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Lab successfully implements safety system

After more than a week-long in-depth review, a Department of Energy verification team recently informed Laboratory management that an Integrated Safety Management (ISM) system has been successfully implemented at Lawrence Livermore. The positive report is the culmination of a three-year program to institute ISM throughout the Laboratory.

According to the verification team's final report, "LLNL has demonstrated a consistent, top-to-bottom commitment to develop and implement a satisfactory ISM system."

"We are very pleased with the DOE team's conclusion," said Director Bruce Tarter. "Implementing ISM and preparing for verification required a true Lab-wide effort. Hundreds of people dedicated themselves to our success. I want to congratulate all Lab employees for what we have accomplished together."

The successful verification process began in November 1999 with a DOE review of all Laboratory environment, safety, and health (ES&H) documentation and interviews with senior management. The next phase came in May 2000, when a DOE verification team focused on implementation of ISM in the Site Operations and Engineering directorates and in a number of facilities.

The third and final phase of verification began September 11, 2000, when a team of 26 DOE experts verified ISM implementation in four additional directorates, inspected 25 facilities across the Laboratory, and reviewed 700 ES&H documents. To complete the verification, the team interviewed over 200 employees, ranging from associate directors to programmatic workers.

According to Bob Kuckuck, Deputy Director for Operations, the implementation of ISM has been the most intensive and substantial Laboratory-wide effort he has seen in his 37-year career at Livermore.

The next step is to continue to strengthen the ISM program by addressing the opportunities for improvement offered by the DOE verification team and by solidifying the ES&H enhancements that have been put into place as a result of ISM implementation.

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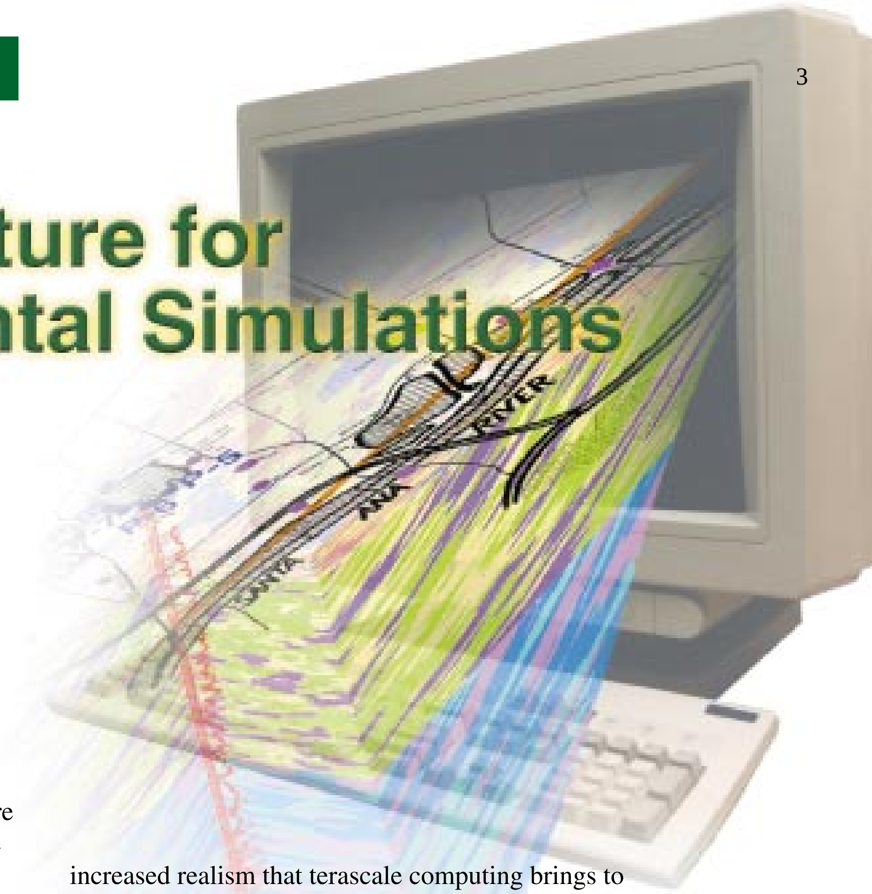
Commentary by Lee Younker

A Bright Future for Environmental Simulations



THE world faces an array of daunting environmental and energy challenges that are not going away any time soon. Nuclear materials continue to pile up worldwide, posing national security and environmental threats. Some nuclear materials already released to the environment are continuing to spread. Greenhouse gases accumulating in the atmosphere may threaten the environment and the world economy. The adequacy, security, and reliability of energy sources for personal and industrial needs are uncertain.

These knotty issues are too large for any one institution or government to solve. But environmental scientists at Livermore are giving it their best shot, using their long-standing expertise in computer simulation to find new and better ways to address them. Simulations are ideal not only for visualizing a problem as a whole but also for examining the profusion of details.

Computer modeling has been an integral part of the work of the Laboratory's environmental programs from their beginning. Codes we have developed over the years for analyzing groundwater flow, seismic signals, geochemical processes, and activity in the atmosphere and oceans—such as NUFT, PARFLOW, E3D, SAC, EQ 3/6, IMPACT, and APDIC/LODI—are in wide use by academia, industry, and other national laboratories. Today, Livermore is among the few institutions in the world that can couple scientific expertise and laboratory and field measurements with sophisticated software engineering and high-performance computing techniques to produce state-of-the-art scientific simulations.

The Accelerated Strategic Computing Initiative (ASCI) has brought the largest computers in the world to bear on classified research at Livermore. Since ASCI began, our environmental programs have developed partnerships with the Computation Directorate and made the financial investment necessary to bring big computers to environmental research, too. When the Livermore Compaq Teracenter and the Visualization Theater were developed to display the vast quantities of data produced by the ASCI computers, four of the first six projects to use them were environmental simulations.

The article beginning on p. 4 focuses on several projects using this expanded computational capability. Research on groundwater contamination, seismic waves, atmospheric emergencies, and climate modeling is benefiting from the increased realism that terascale computing brings to environmental simulations.

Where do we go from here? Computers will certainly become more powerful. Over a decade ago, Moore's law predicted a doubling of computing capacity every 18 to 24 months. Recent advances in terascale computing are far surpassing that prediction. In a few years, simulations of dynamic, large-scale environmental systems will grow to a level of sophistication barely imaginable now.

Wireless communications and sensing devices for recording environmental data are evolving, too—almost as fast as computers—becoming smaller and cheaper and easier to use. Sensors feeding real-time data to advanced simulation models will not just monitor environmental processes; instead, an accumulation of real and simulated data over time may allow scientists to predict the unusual.

These technologies are key elements of the Virtual Valley project that Livermore is developing with the forthcoming University of California campus at Merced. In the not too distant future, sensors all over the Central Valley and the nearby Sierra Nevada mountain range, an area of about 155,000 square kilometers (38 million acres), will begin feeding environmental data to a huge, ongoing simulation of a rapidly developing part of California.

While we cannot solve the world's environmental problems alone, Livermore continues to be a leader in tackling the toughest challenges with the best and most advanced scientific and computational tools.

■ Lee Younker is acting Associate Director, Energy and Environment.

Cutting-Edge Environmental Modeling

Terascale supercomputers are the springboard to a new level of environmental simulation of natural events.

THERE is only one way to "watch" groundwater move. Likewise, the only way to "see" our changing climate, the shaking of an earthquake, or the dispersion of a toxic cloud—other than by living through the event—is by simulating it on powerful computers. By simulating these dynamic events with their many chemical constituents and physical changes, scientists can begin to understand why our environment operates as it does.

Livermore researchers have been modeling the environment for years, often in one and two dimensions. Researchers began modeling the flow of groundwater to solve problems caused by contaminants in the ground. They modeled the atmosphere to learn where a radiation cloud from a nuclear accident would move. With increasing computer power came better codes and more realistic models. Three-dimensional models were an improvement because our world is, after all, three dimensional. But the complex chemical and physical processes were computationally overwhelming. A simulation might take hours or even days to run.

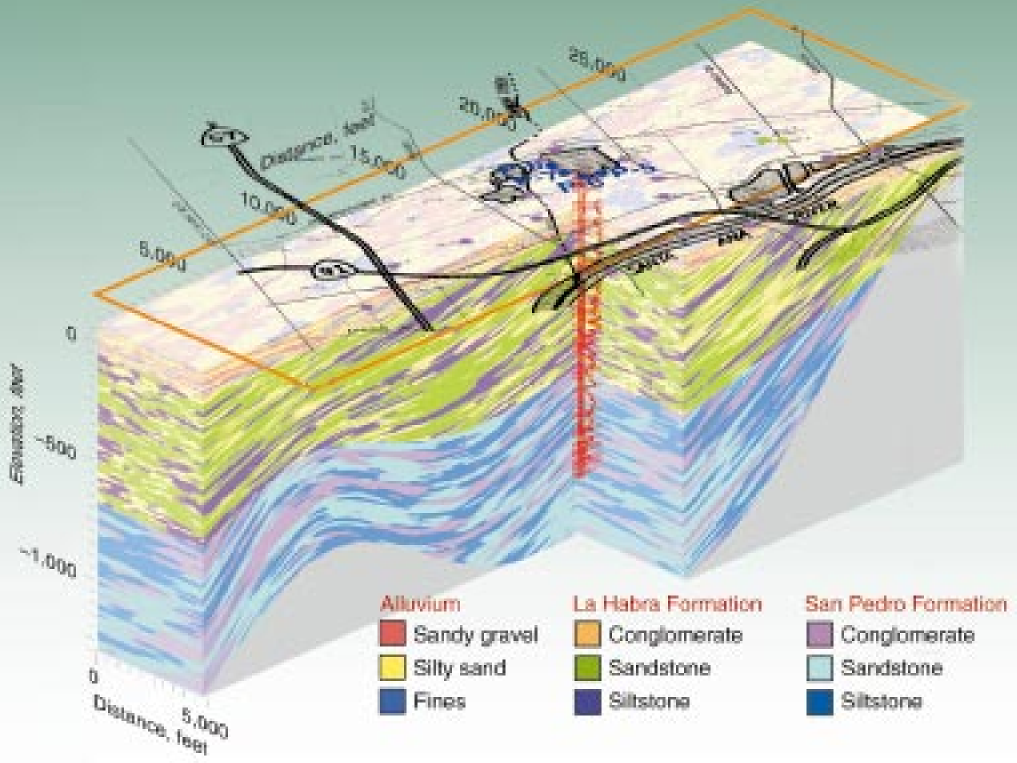
Then came high-performance supercomputing with the Accelerated Strategic Computing Initiative (ASCI), the Department of Energy's program to increase computational power to 100 teraops (trillion floating-point operations per second) by 2005. ASCI computers are developed and acquired to simulate the aging of nuclear weapons and predict their performance. But the arrival of the first ASCI computers in 1996 and the accompanying computing know-how has influenced all Livermore programs, spreading massively parallel computing throughout the Laboratory. Livermore's Multiprogrammatic and Institutional Computing Facility have enabled much of this activity.

The changes wrought by terascale computing are significant. Until recently, it took as long as 18 hours to run a global climate model. With the newest computers, that time is reduced to seconds. Not only are the computers fast, but their many processors, working in parallel, can also handle more variables and solve extremely complex problems. (See *S&TR*, June 2000, pp. 4–14.)

Today's simulations are far more realistic. At the Livermore site, groundwater contamination was discovered in 1983, and Livermore was declared a Superfund site in 1987. The contamination consists of widely distributed plumes of several volatile organic compounds, tritium, fuel hydrocarbons, and some dissolved heavy metals. The first simple model, in 1990, showed that to meet current regulatory standards, cleanup would take 80 years. By the mid-1990s, when some of the first three-dimensional models were being developed, we better understood the state of the contamination and were better able to clean it up. Estimated cleanup time was reduced to about 30 years, or to just 10 to 15 years if risk-based remediation was used. Today, with even better models and several innovative remediation technologies at work, the estimated time to complete regulatory cleanup is even less. Researchers now have models of the subsurface whose level of complexity—and hence realism—were unthinkable just a few years ago.

Atmospheric scientist Bill Dannevik of Livermore's Energy and Environment Directorate notes that all environmental simulations have many features in common. "For one thing, they are all 'data-starved,'" he says. "We have only so much information about our atmosphere, our oceans, and especially the ground beneath us. We can't possibly drill enough boreholes to detail every square inch of the geology of our planet. So our models have to be stochastic, which means that they involve a certain amount of probability."

He goes on to say, "To be meaningful, environmental models must incorporate



A three-dimensional image of the geology underlying part of the Orange County Water District.

chemistry, physics, and all three dimensions plus time, which makes them very demanding computationally. Incorporating full dimensionality has been perhaps the biggest challenge. Until large, terascale computers came along, we simply could not include everything.”

Throughout science, simulation models have been used largely as a diagnostic tool, as an adjunct to theory and experiment. Supercomputers are now the springboard to a new level of simulation that can provide a multidimensional, evolving model of natural events. As the speed of computation continues to increase even faster than predicted by Moore’s law, Livermore scientists will be able to perform truly predictive, three-dimensional simulations. Then simulation will emerge as a peer to theory and experiment, revolutionizing the way science and engineering are done.

In the past, observations of natural events have been used to validate environmental simulation models. According to Dannevik, “Today’s mostly one-way relationship between observation and model will, in the not too distant future, be transformed into a interactive relationship through which models and sophisticated, mobile sensors are constantly being mutually updated and made ‘smarter.’”

Making the Subsurface Visible

Knowing the sources of groundwater contamination might be simple, but knowing where and how quickly the contaminants are traveling in subsurface soil and rock is another matter. Simulation models provide a window into this otherwise unseen, underground world.

Livermore codes are among the first to realistically account for variations in groundwater flow caused by complex geologic differences. Although the mix of varying types of rock and soil has long been known to influence the flow of water and the spreading of contaminants, such natural complexity has typically not been well represented in computer models. A Livermore team led by hydrologist Andy Tompson is using a geostatistical method to handle complex geology in groundwater models.

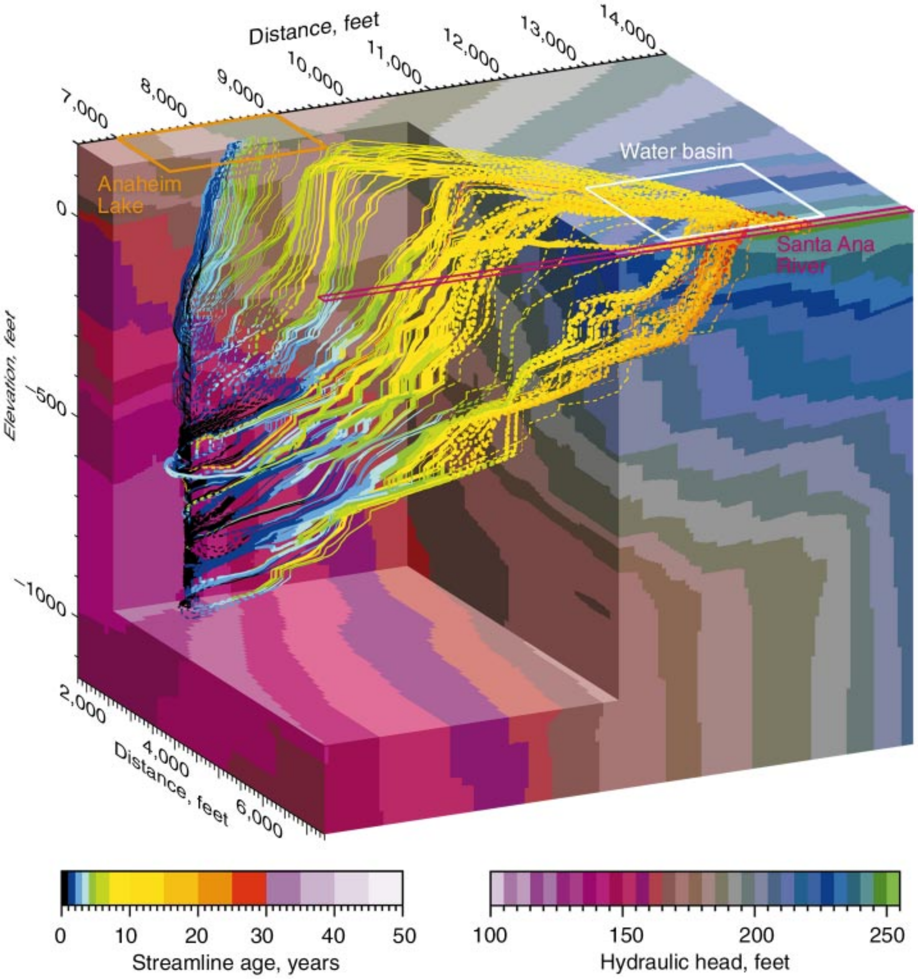
The Orange County Water District in southern California plans to artificially recharge its aquifer with reclaimed water from a treatment plant. Because this water must be underground for at least a year before being used, the district wants to know how long the water is staying underground and where it travels in the subsurface before being withdrawn through a production well (See also *S&TR*, November 1997, pp. 12–17.)

One three-dimensional image of the area’s geology from a highly resolved model is shown in the figure above. The figure on p. 6 shows one simulation of water flowing to a production well. The paths taken by the water from three recharge basins to the well indicate that no water less than a year old comes from the basins. A recent experiment using xenon gas as a tracer was consistent with modeling results. These and other data indicate that small-scale variability in the geologic structure can produce major differences in where water flows. Geologic heterogeneity must be considered in groundwater models.

Work at the Nevada Test Site is another example of the importance of high-resolution computer models. The Underground Test Area (UGTA) project is evaluating the extent of contamination that resulted from 828 underground tests, some of which released radionuclides to the groundwater.

A Livermore team has produced a model that, for the first time, accounts for heat produced by a nuclear test in studies of groundwater flow. An underground nuclear test generates huge amounts of energy, vaporizing everything around it. Rock and soil above the resulting cavity eventually collapse, forming a “chimney” of rubble. Data obtained after the Cheshire test in 1976 showed that significant heat continued to exist in the underground cavity and chimney for as long as 6.5 years after the test. The team used these temperature data to calibrate a nonisothermal model of fluid flow, which suggested that more than 50 years would be needed for conditions to return to normal.

Modeling results indicate that the high temperatures associated with a test persist for several decades and may push water from the cavity area to the upper chimney in 10 to 20 years. This movement contrasts with movement under normal conditions, which takes 100 years or more. The quick upward flow means that the contaminated water has reached a highly permeable geologic zone surrounding the upper reaches of Cheshire’s chimney and has a pathway from the test location to a broader area of the test site.



A close-up perspective of the “backward travel” of water between production well P-6 and three Orange County Water District recharge basins on the surface. Streamlines are color coded to indicate travel time. Dashed lines indicate portions of streamlines “hidden” within a background block, which is also color coded to indicate hydraulic head, or the water pressure in the block arising from the pressure in it.

And the Heat Goes on

Another scientific team at Livermore also has concerns about heat underground. It is studying the Yucca Mountain site in Nevada that is the nation’s candidate for an underground repository for high-level nuclear waste. According to geochemist Bill Glassley, “One of the biggest challenges of the Yucca Mountain project is determining how the mountain will respond to the tremendous amount of heat generated by the buried waste and if any of those geologic responses will result in the waste packages getting wet.” (See *S&TR*, March 2000, pp. 13–20.)

Livermore’s supercomputers and newly developed software have allowed a team of Livermore scientists to construct a code to simulate the geologic evolution of the repository for an anticipated lifetime of 100,000 years or more. The code is being used to predict the temperature evolution surrounding buried waste and the possible means by which water will enter the repository’s tunnels over the eons.

Most of the preliminary simulations have focused on a hypothetical waste emplacement tunnel more than 300 meters below the surface. Different types of waste are separately packaged and generate temperatures ranging from

60°C to as much as 200°C. After about 500 years, significant and irreversible changes to the rock near the waste are apparent. Water that has condensed above the tunnel causes a dome of dissolved minerals to form and partially seal the rock fractures. The hotter waste packages cause more extensive sealing than the cooler packages. Moreover, the partially sealed domes occur farther away from the hot waste than from the cooler waste.

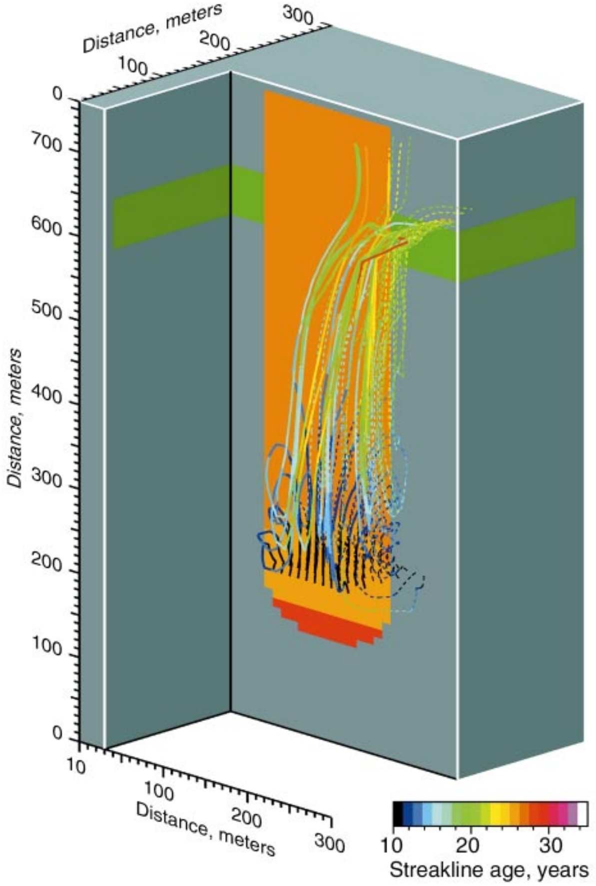
More recent simulations are depicting multiple tunnels, with each tunnel containing waste packages generating different amounts of heat. These simulations are examining how arrays of waste packages will interact over time.

Shake, Rattle, and Roll

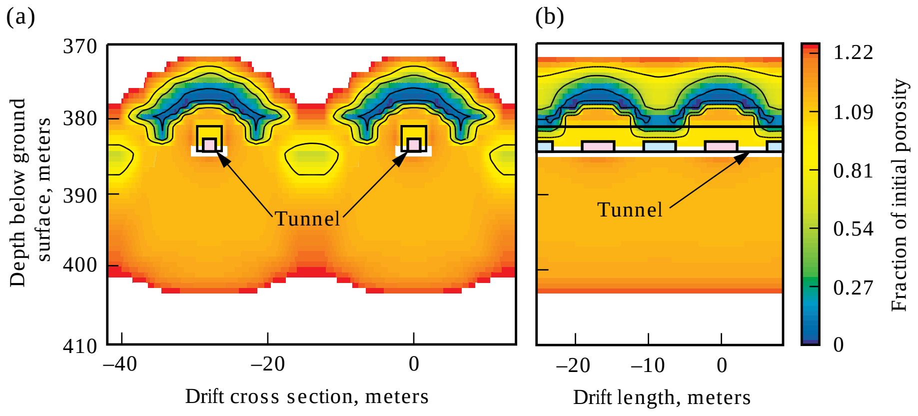
A powerful seismic code developed by Livermore geophysicist Shawn Larsen is helping to tell us what the San Francisco Bay Area's next big earthquake might look like. His E3D code incorporates three-dimensional information about the propagation of seismic waves—how they are radiated from the earthquake's source to the surface and how they interact with the geology and topography in their path.

The next big one may well occur on the Hayward Fault, which runs through the densely populated cities of Oakland and Berkeley, among others. Scientists give this fault a 50 percent probability of producing a magnitude 7 to 7.5 quake in the next 30 years. Seismologists believe that it could cause destruction comparable to that of the 1995 quake in Kobe, Japan, which resulted in 6,000 fatalities and over $100 billion in damage. The figure on p. 8 shows how E3D and high-performance computing are being used to determine seismic hazards on the Hayward Fault.

E3D is a considerably more powerful seismic code now that it can run on massively parallel computers. For some time, E3D has modeled the effects of



One simulation for heat generated by the 1976 Cheshire test at the Nevada Test Site shows the movement of tagged parcels of water. Over the geologic units are "streaklines" that represent the motion of water over the course of the simulation. They are color coded to represent time of travel and may be used to estimate the residence time of a conservative (nonsorbing and nonreactive) tracer in the cavity–chimney system. Circulation patterns near the cavity that develop early in the simulation are clearly visible.



(a) Two-dimensional cross section through two tunnels at Yucca Mountain shows the formation of domes overlying the "hot" (pink) waste packages from spent nuclear power plants. (b) A lengthwise cross section of a single tunnel simulates both "cool" (blue) waste packages from defense production and hot waste packages. The hot waste clearly causes more extensive sealing than does the cool waste. Also, the domes occur farther away from the hot waste. After about 3,000 years, the domes have been formed, but a small amount of water is beginning to approach the cool packages.

compressional (sound) waves as well as shear waves, which move sideways. Shear waves are particularly important for effectively modeling earthquakes. But they are complex and, says Larsen, "computationally overwhelming. We could do three-dimensional models before but only for much smaller problems."

The code is also being used for oil and gas exploration, medical imaging, and structural response studies. For treaty verification, it is being used inversely. Livermore experts are using E3D to determine whether explosions measured elsewhere in the world are the result of seismic activity, a weapon test, or some other cause.

Atmospheric Emergencies

Livermore's Atmospheric Release Advisory Capability (ARAC) was founded in the late 1970s to predict the dispersion of radioactivity into the atmosphere from nuclear accidents or attacks and terrorist incidents. Today, ARAC is one of many emergency response organizations sponsored by the U.S. government to counter dangers and threats to the nation. Over the years, its charter has expanded to include working with all manner of toxic and hazardous atmospheric releases. ARAC scientists can predict the transport and fate of material released during disasters, whether natural or caused by human activity. It makes predictions not only during actual atmospheric releases but also for contingency planning purposes.

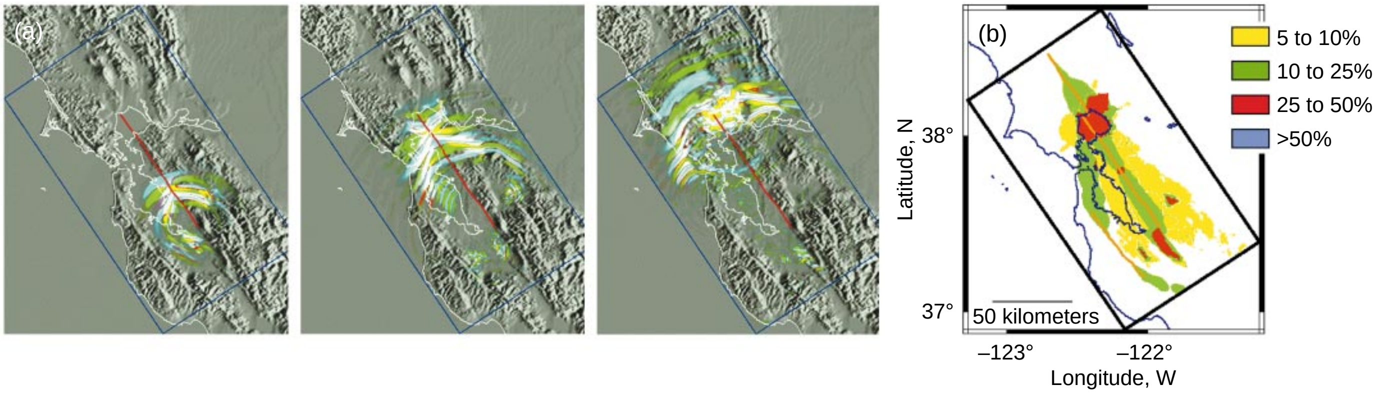
ARAC scientists use several codes to handle the many variables involved in an atmospheric dispersion—for example, wind speed and direction, turbulence, local wind systems such as sea breezes, terrain, and precipitation that might wash toxic material out of the atmosphere. With this knowledge, they have accurately modeled the radiation cloud resulting from the Chernobyl nuclear plant disaster, the eruption of Mount Pinatubo in the Philippines, a release of cesium in southern Spain, and many other toxic and hazardous releases in this country and around the world.

ARAC's response time to these accidents is continually being shortened thanks to better model resolution, with faster computer speed. In addition, ARAC has been able to increase the breadth of its capabilities and the accuracy of its predictions. These improved capabilities are enabling ARAC to meet emerging risks that are not yet formally required in the

The Virtual Valley

Cutting-edge computers, communication systems, and sensors will combine forces in the Virtual Valley that Lawrence Livermore and the University of California at Davis and Merced plan to create as part of their California Institute for Environmental Informatics and Technologies. A variety of sensors and simulation models will monitor the land, air, and structures of California's Central Valley and Sierra Nevada mountain range to supply information on everything from soil and subsurface properties to atmospheric conditions, land use, hazardous materials distribution and emission inventories, wildfire fuel conditions, ecosystem stresses, power and transportation grid loading, population distribution, seismic activity, and engineered structure inventory.

In the Virtual Valley, historical data, current conditions, and model-generated forecasts will be in a common format. At the same time, a common set of analysis, visualization, and geographic information system tools will be available to explore the myriad interrelationships among the many datasets. The data system will be accessible from multiple viewpoints with various layers designed to suit the needs of everyone from urban planners, to environmental research scientists, to the public at large.



(a) One scenario of seismic waves from an earthquake on the Hayward Fault is shown at 15, 30, and 45 seconds after the quake's start. (b) The results of all scenarios come together in this look at the probability of ground motion above 50 meters per second in the San Francisco Bay Area from 2000 to 2030.

emergency readiness role defined by sponsors. (See *S&TR*, June 1999, pp. 4–11.)

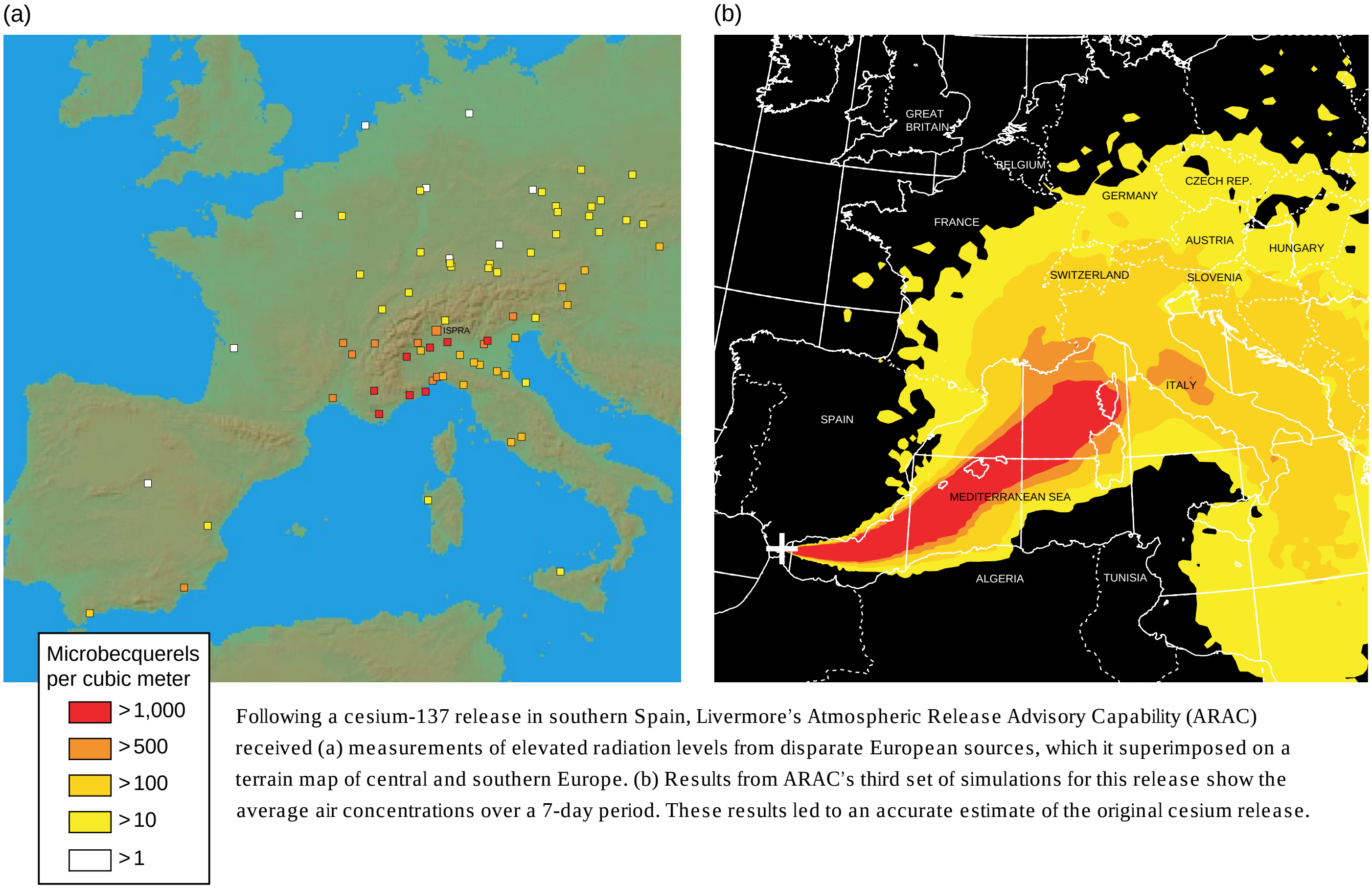
A Global Look at Climate

An offshoot of Livermore's early research and modeling of our atmosphere was an interest in global climate. Thirty years later, Livermore is one the world's premier institutions for the study and simulation of global climate change. Of particular interest are the changes in Earth's climate that may be caused by human activities. The principal source of potential climate change may be the greenhouse gas carbon dioxide (CO_2) produced from burning fossil fuels. Humans are introducing 6 billion tons of fossil-fuel-derived CO_2 into the atmosphere every year. This and previous emissions have resulted in an increase in the concentration of atmospheric CO_2 from about 280 parts per million during the mid 19th century to about 370 parts per million today.

However, not all CO_2 generated by human activity stays in the atmosphere. Only about half of the emissions accumulate there, while the rest is taken up by the oceans or vegetation and soils as part of the carbon cycle. The capacity of these "sinks" is expected to change as climate changes. Scientists are estimating the amount of CO_2 that will accumulate in the atmosphere by modeling the carbon cycle with its many sources and sinks.

As part of this process, separate models of the various strata of the atmosphere and the oceans have been developed over the years. Now, for the first time, Livermore has the computational strength to bring these models together interactively to answer these questions about CO_2 and global climate.

One such first was a coupling of tropospheric (up to 12 kilometers) and stratospheric (12 to 60 kilometers) models to examine the greenhouse gas ozone. Atmospheric chemistry models analyze how natural and human-made emissions of chemical species (for example, via energy production) may alter the distribution of ozone in the stratosphere and troposphere, and more importantly, how these two regions of the atmosphere interact. The figure on p. 10 shows a 100-parts-per-billion concentration of ozone, which is typical at lower stratospheric levels. As the figure shows, at various geographic locations, stratospheric ozone is being

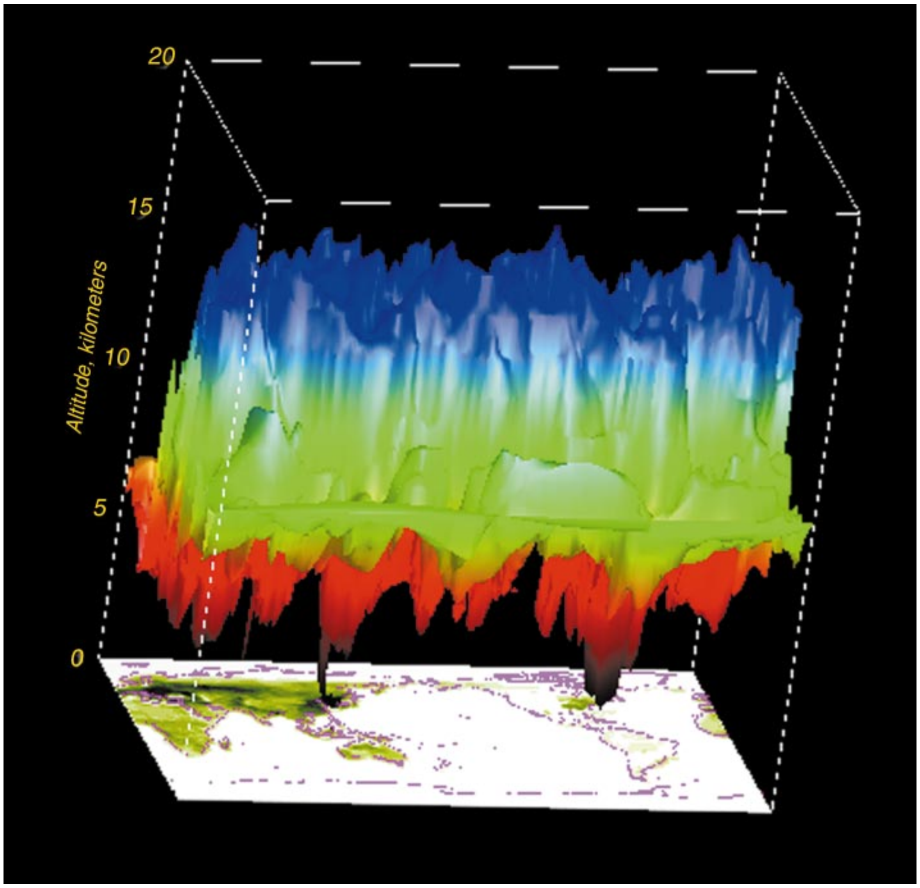


Following a cesium-137 release in southern Spain, Livermore's Atmospheric Release Advisory Capability (ARAC) received (a) measurements of elevated radiation levels from disparate European sources, which it superimposed on a terrain map of central and southern Europe. (b) Results from ARAC's third set of simulations for this release show the average air concentrations over a 7-day period. These results led to an accurate estimate of the original cesium release.

transported to altitudes near Earth's surface. In this example, it is occurring in the northeastern United States and eastern China. These results indicate that global ozone chemistry must be considered in any quantification of surface ozone distributions.

To study the effects of CO_2, researchers have combined a detailed atmospheric model with a simplified ocean model. They predicted that the surface temperature would change should the amount of CO_2 in the atmosphere double in the future. They found that because of feedback in the climate system, more warming occurs at high latitudes. The most important contributor to this feedback is the sea ice in the Arctic and Antarctic regions, which reflects radiation back to the atmosphere. The CO_2 captures more outgoing radiation at low latitudes, so there is less warming.

Livermore's atmospheric models are just now beginning to include aerosols, such as sulfur emissions, and sooty particulate matter, which are also produced when fossil fuels are burned. Scientists now think that aerosols are producing some significant cooling, which may be largely canceling the expected global warming from increased CO_2 during the 20th century.



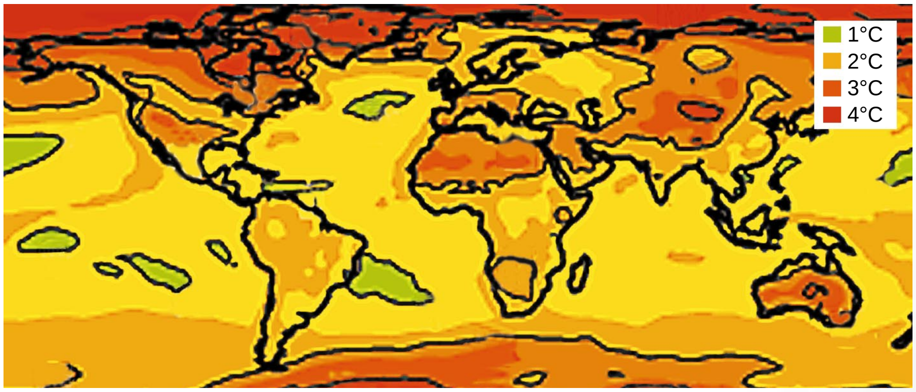
The 100-parts-per-billion concentration level of ozone is typical of lower stratospheric levels. As the model results show, at various geographical locations, this stratospheric ozone is being transported to near-surface altitudes. To quantify surface ozone distributions requires the inclusion of global ozone chemistry.

Into the Future

Besides the ever-increasing capability of supercomputers, two other technology trends will make environmental simulations more realistic. These are in the areas of wireless communication systems and sensing devices, both of which are becoming smaller and cheaper. Wireless communication is being seamlessly connected into the Internet and other communication channels. At the same time, environmental sensors are becoming smarter, less invasive, and more mobile so that the information they transmit is more readily usable.

The confluence of these trends will result in an unprecedented ability to measure the environment and to link these measurements instantaneously to advanced simulation models. Together these systems will monitor, characterize, and predict complex environmental processes. Timely collection and insertion of sensor data into live simulations will enable models to "learn" about the details of environmental media and to adapt to and reconfigure themselves for changing conditions. With sensors tied into a global positioning system, the models will also "train" smart, mobile sensors to collect information where and when it is needed, thereby maximizing the quality of incoming information and of the resulting model.

By analyzing real-time environmental data from fixed and mobile sensors, researchers can quickly detect a hazardous material spill or other event, characterize it, supply a quick-response team with needed information, and assess consequences. The Virtual Valley (see the box on p. 8), planned for California's Central Valley and Sierra Nevada mountain range, is just one example of the way that networked sensors located in the land, air, water, structures, and transportation systems will be able to work together to feed data to a



This simulation shows by how many degrees surface temperature would increase if atmospheric carbon dioxide content were to double. A detailed atmospheric model was coupled with a simplified ocean model to produce this result. The reflectivity of sea ice in the Arctic and Antarctic regions creates feedback in the climate system, increasing warming at high latitudes.

supercomputing center, where models can be built for a range of users.

The Virtual Valley is one of several endeavors that are part of a great leap forward at Livermore in environmental computing. An Environmental Simulation Center to bring all environmental modeling work under a single organizational umbrella is in the planning stages. Computational experts continue to devise new ways of representing the environment in models. Geostatistical methods and new ways of evaluating risk are just two such examples.

Bill Glassley notes, “There are so many factors to consider when we study fluid moving in Earth’s crust. But with the powerful computers we have now, we can incorporate virtually everything and actually watch water move. Then if we change one thing, we can see the results. If we run many simulations adjusting lots of variables, we can begin to learn what really matters, what the important issues are.” The same can be said of all modeling—that the purpose is to learn what really matters.

—*Katie Walter*

Key Words: atmospheric modeling, Atmospheric Release Advisory Capability (ARAC), global climate modeling, groundwater modeling, hydrology, Nevada Test Site, seismic modeling, Underground Test Area, Virtual Valley, Yucca Mountain.

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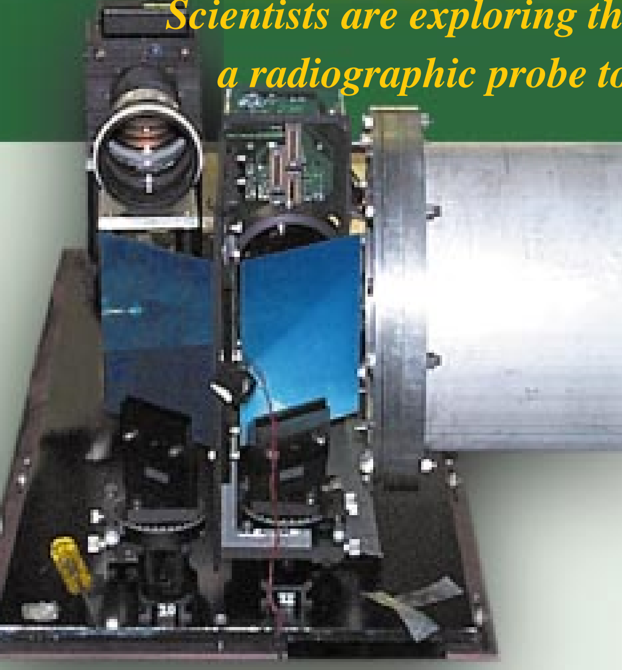
About the Scientist

WILLIAM P. DANNEVIK leads the Laboratory’s Atmospheric Sciences Division and is the acting Deputy Associate Director for Energy and Environment. He came to Livermore in 1988 as a member of a weapons code group in the Defense and Nuclear Technologies Directorate. He received his B.S. in engineering science from the University of Texas in 1969 and his Ph.D. from St. Louis University in atmospheric science in 1984. In previous positions, he led an engineering consulting firm from 1974 to 1980 and was on the research staff of the Princeton University program in applied and computational mathematics from 1984 to 1988. He has published numerous articles on computational fluid dynamics, boundary-layer meteorology, high-performance climate simulation, and turbulence theory and modeling.

Protons Reveal the Inside Story

Scientists are exploring the advantages of using protons instead of x rays as a radiographic probe to study the performance and aging of weapons.



ONE of the most important scientific breakthroughs in the past century was the discovery that a beam of x rays could penetrate matter and produce a radiograph that revealed the inside of objects.

X-radiography is today an indispensable tool for medicine, industry, and science. Scientists at Lawrence Livermore have long used x-radiography to obtain information about fleeting events that occur in experiments using high explosives to mimic the operation of a nuclear device. The resulting images yield important information on the hydrodynamic behavior, performance, and aging characteristics of weapon components.

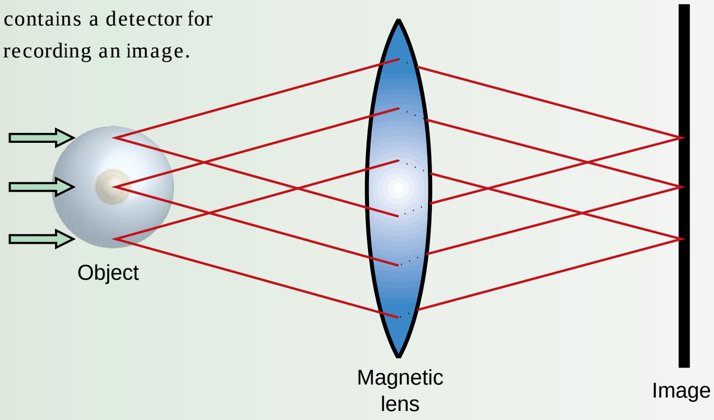
While x rays have many favorable attributes, current x-ray technology will have difficulty meeting the long-term requirements of stockpile stewardship, the Department of Energy's program to assure the safety and reliability of the nuclear stockpile without underground nuclear testing. In particular, providing views from multiple angles and at different times during one experiment will be a challenge for x rays.

For some time, physicists have considered using protons, the positively charged constituents of atomic nuclei, as a way to penetrate thick materials more effectively than x rays. Proton radiography has been used for medical imaging and to treat some types of cancer. Early tests with protons as a radiographic probe were not promising: the radiographs were blurred, an effect caused by the scattering of protons as they move through an object because of their electrical charge. The quest was largely abandoned until 1995, when physicists at Los Alamos National Laboratory came up with the idea of using a magnetic lens to focus the scattered protons into a clear image.

A team of Lawrence Livermore scientists soon joined their Los Alamos colleagues in a broad effort to determine if beams of high-energy protons focused with magnetic lenses could be used for stockpile stewardship to image deep inside dynamic systems. Over the past five years, the researchers have conducted a series of tests at Los Alamos and Brookhaven national laboratories.

The tests have centered on extending basic proton science and gauging proton

Proton radiography depends on magnetic lenses that focus scattered protons onto an image plane that contains a detector for recording an image.



radiography's ability to image and differentiate materials in both static and explosive situations. While more experiments are under way, the researchers have gained confidence that proton radiography offers a viable technology to meet future stockpile stewardship needs.

Seemingly Simple Technology

"At first glance," says Lawrence Livermore physicist Edward Hartouni, "proton radiography seems simple and obvious. High-energy protons are used directly as a radiographic probe to illuminate an object, are absorbed and scattered by the object, and then are brought to a focused image by a magnetic lens system for recording by an imaging detector."

Hartouni heads a research team drawn from Livermore's Physics and Advanced Technologies, Defense and Nuclear Technologies, and Engineering directorates, with funding by the Laboratory Directed Research and Development program. He notes that the Laboratory is well positioned to assess proton radiography because of its expertise in accelerators and detectors obtained in nuclear and high-energy physics research.

Hartouni says protons offer several advantages over x rays for studying the dynamics of imploding systems. For example, about 10,000 times fewer protons than x rays are needed to make

A Proton Radiography Primer

Protons are positively charged particles that, along with electrons and neutrons, comprise all matter. Protons interact with matter by way of strong and electromagnetic interactions. Because the strong interaction has a short range (about 1 fermi, or 10^{-15} meters), protons interact with other protons and neutrons by colliding with them. The probability of collision with the nuclei is indicated by a material's cross section and is dependent upon the number of protons and neutrons in the nucleus.

A proton interacting with a nucleus via the strong interaction can do so either elastically or inelastically. If the interaction is elastic, the proton scatters at some angle, retaining its identity as a proton and maintaining most of its original momentum. If the interaction is inelastic, the proton is "absorbed" in the interaction. That is, it transfers most of its energy to breaking up the nucleus, in the process producing subatomic particles called pions.

Because protons carry an electrical charge, they also interact with matter through long-range electromagnetic forces. This interaction takes two forms: with the electric field of nuclei and with the atomic electrons orbiting nuclei. The effects are quite distinct. Interacting with nuclei's electric field is termed elastic scattering and produces a small change in the proton's direction. The effects of each of the small scatters can accumulate, a phenomenon called multiple coulomb scattering. The consequence of multiple scattering for proton radiography is important, especially for dense materials, because ultimately it blurs a radiograph.

The proton interactions with atomic electrons are generally inelastic; that is, the proton loses a small amount of energy by ionizing atoms (kicking an electron out of its orbit). These interactions generally do not result in much change to the proton direction, but many scatters do reduce the proton energy. With dense materials, the energy loss can be quite large (100 to 500 megaelectronvolts). The amount of energy loss can be important, depending on the energy of the beam.

Protons travel a few centimeters to tens of centimeters through matter before they undergo a significant interaction with the object either through strong or electromagnetic forces. These so-called interaction or attenuation lengths are optimum for radiographing objects to extract precise physical characteristics such as density. In contrast, x rays have a maximum attenuation length of about 1 centimeter. For a 10-centimeter-thick slab of material, a beam of x rays is reduced by roughly one million (one in a million x rays makes it through the slab), whereas one in three protons makes it through. Because many more protons make it through than x rays, scientists say that protons are more penetrating.

the same quality radiograph. The greater penetrating ability of protons gives a much higher signal-to-noise ratio, which translates to higher resolution. Protons also have a better capacity to discriminate between two similar materials. X rays are sensitive to density only, so if the densities of two dissimilar materials are close, the radiograph will fail to differentiate the two clearly.

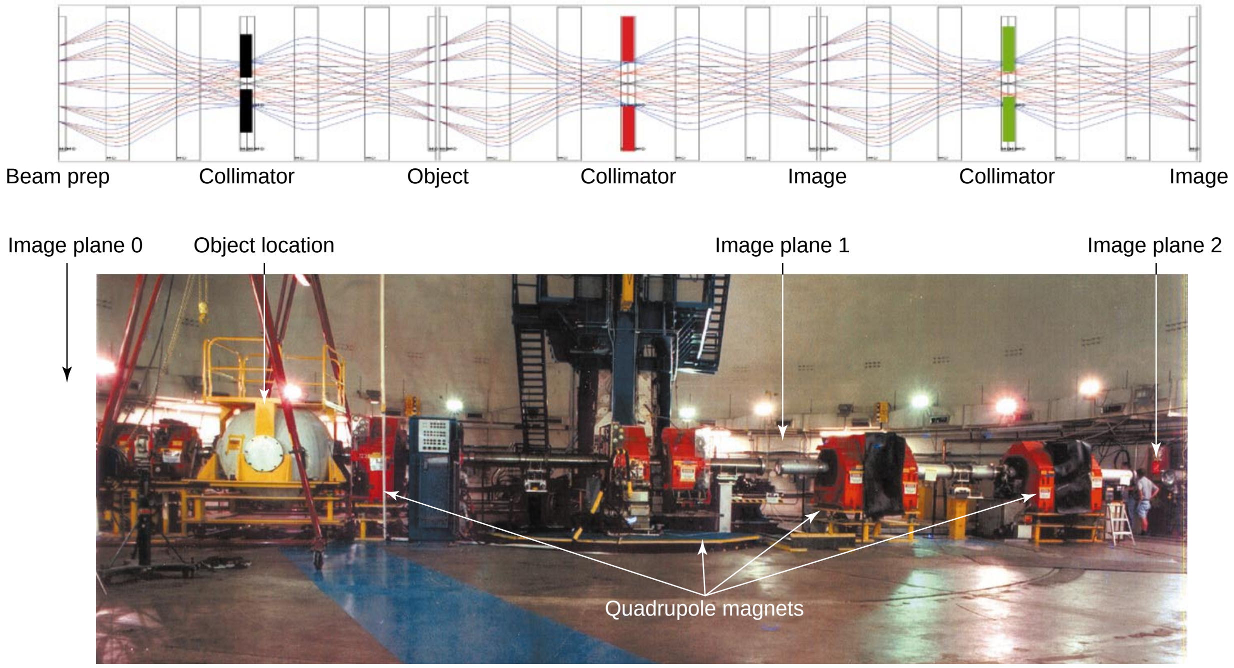
What's more, Hartouni says, using magnets to focus beams of charged particles is an established practice at accelerator laboratories. If is quite easy to split a single proton beam into a large number of separate beams for penetrating an object from different angles. Also, because protons are naturally pulsed in the accelerator, it is easy to produce pulsed beams that would permit multiple, stop-action radiographs to be taken during a single dynamic experiment.

Finally, x rays are produced by first creating and accelerating a beam of electrons. These electrons are directed onto a target, where they decelerate, damaging the target in the process. The deceleration produces photons with a broad energy spectrum and with only some of the photons in the x-ray band. Protons offer a more efficient direct source of penetrating radiation.

Leading Candidate for New Facility

Because of these strong attributes, proton radiography is a leading candidate for the proposed next-generation stockpile stewardship hydrotest facility, called the Advanced Hydrotest Facility (AHF). Imaging a mock primary detonation at multiple vantage points and at various times to form a three-dimensional movie will provide scientists more data to help verify the supercomputer codes that model the performance of a nuclear weapon.

Livermore scientists joined the proton radiography research effort shortly after Los Alamos physicists in 1995 successfully tested the concept of a magnetic lens. The Los Alamos scientists used a beam of 800-megaelectronvolt protons produced at the Los Alamos Neutron Science Center (LANSCE). The success at LANSCE encouraged tests using a much higher-energy (24-gigaelectronvolt) proton beam at Brookhaven National Laboratory's Alternating Gradient Synchrotron facility in New York. (A proton radiography facility would require



Explosive proton radiography experiments are conducted at the Los Alamos Neutron Science Center facility. In these experiments, a proton beam traveling inside a tube penetrates a target placed in a spherical vessel (left) to contain the explosion. Quadrupole magnets (orange) focus the scattered protons onto imaging detectors. This particular setup uses three imaging stations, including one installed in front of the target to examine the profile of the incoming proton beam. Collimators are located inside the beam tube.

Radiography Remains the Top Tool

In the absence of nuclear testing, advanced radiography is the most important experimental tool currently available to help maintain the nation's aging nuclear stockpile. Hydrotests use high explosives and surrogate nuclear materials to make up a mock primary (the first stage of a nuclear weapon). During the test, explosive pressures become so great that materials flow like liquids, that is, hydrodynamically. X-radiographs taken during the experiment allow physicists to study what happens to the different materials on very short time scales and deep within the mock primary.

Livermore's newly upgraded Flash X-Ray (FXR) machine, located at the remote Site 300 test center, will continue to be one of the premier flash x-ray capabilities once the Contained Firing Facility is completed in 2001. The upgraded machine will be able to take two radiographs along the same vantage point about a microsecond apart.

Los Alamos National Laboratory's Dual Axis Radiographic Hydrodynamic Test (DAHRT) facility, when fully operational, will offer higher resolution radiographs than FXR. The first arm of the facility, which uses a single-phase accelerator, is scheduled to become fully operational in the late fall of 2000. A second arm (for which Livermore scientists provided most of the design) will be situated 90 degrees to the first and is scheduled for completion in about two years. Although additional arms can be added, the expense would be considerable and the number of pulses per view is severely limited.

To meet the goals of the DOE's Stockpile Stewardship Program, scientists require much more information about the functioning and aging of primaries than either facility can provide. The work of the last five years by physicists from Lawrence Livermore and Los Alamos national laboratories has helped to advance proton radiography to the point where the technology is a serious candidate for the Advanced Hydrotest Facility (AHF).

Planning the Next-Generation Facility

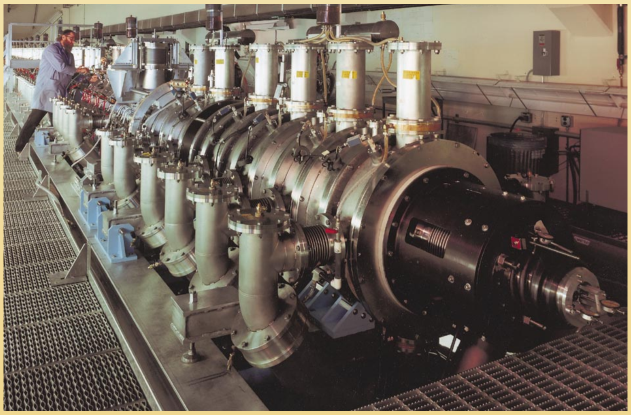
Still in the conceptual stages, the AHF would be an important long-term goal of the Stockpile Stewardship Program. The facility would better reveal the evolution over time of a weapon primary under normal conditions and in accident scenarios. The AHF would be constructed at either Los Alamos or DOE's Nevada Test Site (NTS).

The facility would provide radiographs from between 8 and 16 directions and between 5 and 12 fleeting pulses per experiment. In this way, it would create a three-dimensional tomographic movie of the object as it implodes. Each image would last 50 nanoseconds, with 200-nanosecond to 2-millisecond intervals between images. A high spatial resolution of 0.5 to 1 millimeter would allow experimenters to identify the amounts and types of material at each location inside the object. Says Livermore physicist Edward Hartouni, "Only three-dimensional radiographs can fully answer stockpile stewardship questions and verify our computer codes."

Hartouni says that the AHF would also provide a research and development base for industrial applications. Some of these applications might include the investigation of combustion in automobile engines and various nondestructive testing procedures, such as material identification.

Different approaches to achieving an AHF capability have been considered by the laboratories. Livermore physicists have studied ways of developing limited proton radiography capabilities quickly and at minimum cost by recycling components from the decommissioned main ring of the Fermi National Accelerator Laboratory.

At the same time, conceptual work is being done by Los Alamos scientists on the design of a complete AHF sited at Los Alamos and using the Los Alamos Neutron Science Center facility as the proton injector for the main accelerator ring. Some of their designs have drawn on concepts developed at Livermore for minimizing the cost of the facility and for producing, along the path to a full AHF radiography facility, more limited proton radiography. With this interim capability, scientists could conduct classified high-explosive-driven dynamic experiments using bursts of energetic protons, magnetic lenses, and particle detectors to produce radiographic images. Currently, because of classification, material, and safety issues, no suitable facilities exist in the U.S. to perform these experiments.



Livermore's upgraded Flash X-Ray machine will be one of the most capable radiographic facilities in the world.

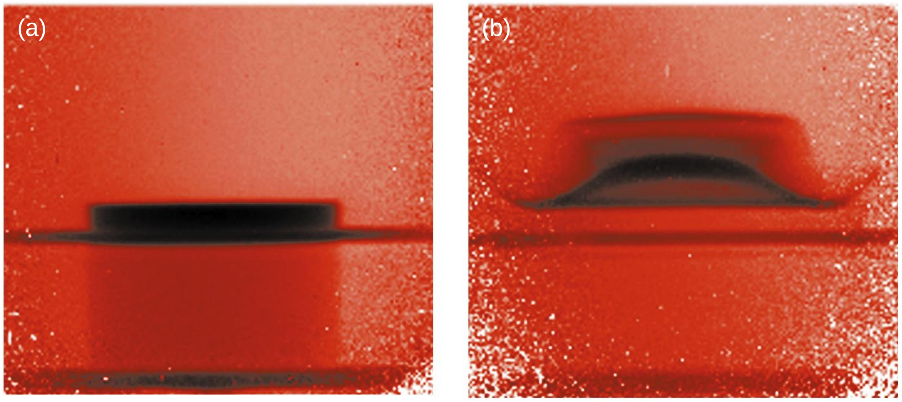
20- to 50-gigaelectronvolt proton beams.) "The ease with which the experiment at Brookhaven was set up and run showed us that new technology does not have to be developed; current accelerators easily provide a source of protons for radiography use," says Hartouni.

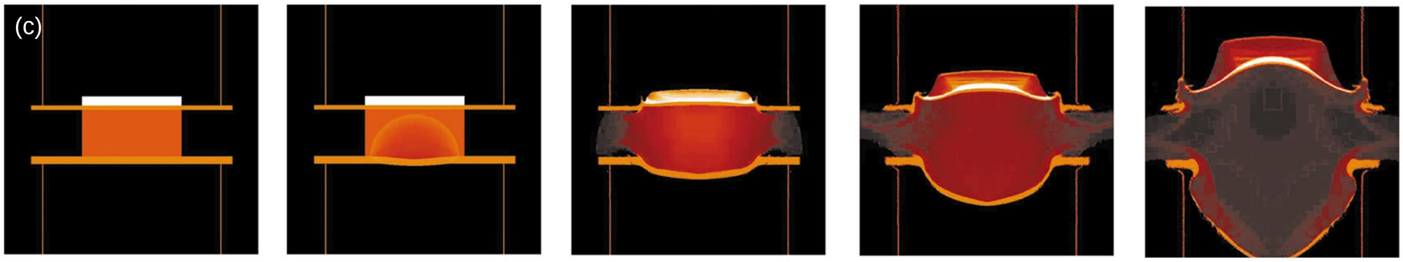
The early experiments were followed by increasingly more complex tests. Livermore weapons physicist Lloyd Multhauf notes that the experimental program has been essential to learning the capabilities and limitations of proton radiography. "We can't argue just on theory that proton radiography works," he says. "There are always lots of practical problems and experimental details that can prevent achieving needed accuracy." But Multhauf points out that the research team "has learned with each experiment."

Basic science experiments, conducted largely at Brookhaven, have focused on understanding better how proton beams interact with different materials. In studies on a variety of materials and at proton energies from 1 to 10 gigaelectronvolts, a parameter was established for the cross section of a proton–nuclear interaction. Other experiments studied the momentum of scattered protons as well as the subatomic particles (namely pions) that inevitably are created when protons collide with nuclei.

Experiments also have been conducted on developing the systems to image objects with protons and refining components such as magnets and detectors. In the summer of 1999, a Livermore–Los Alamos experiment at Brookhaven radiographed static objects using a 20-gigaelectonvolt beam of protons and an advanced magnetic lens. The images were of static objects chosen to provide data on the density

Livermore physicists Doug Wright (foreground) and Hye-Sook Park and technician Eric Parker monitor experiments at the Los Alamos Neutron Science Center control room.





Some experiments have investigated the hydrodynamic properties of shocked metal. (a) A 4-centimeter-diameter tin disk sits on a block of high explosive that is sandwiched between two layers of aluminum. (b) Some 10 microseconds following the blast, a radiograph reveals how the top aluminum plate is bent by the blast and how the tin falls apart from the explosive shock wave. The radiographs also reveal how gas and small chunks of matter intermix. (c) A computer simulation of the proton radiography experiment in (a) and (b).

and composition of objects containing different materials.

Static, Explosive Systems Tested

In tandem with the Brookhaven experiments, tests have been conducted on both static and explosive systems at LANSCE using 800-megaelectronvolt protons. The collaborative experiments have helped scientists develop lenses and detectors and provided information on the hydrodynamics of the interfaces between shocked metals and gases.

One series of experiments involved pulsed protons aimed at a target of high explosives and tin. The bursts probed the exploding object by producing a series of images lasting from 40 to 100 nanoseconds, separated by about 1 microsecond, and with a resolution better than 500 micrometers.

In follow-on experiments at LANSCE, a Livermore team measured the hydrodynamic properties of tin when shocked by high explosives. In particular, the team examined the small pieces, or ejecta, that fly off the surface and the way the tin fails by spalling because a tension wave propagates through the tin from the high explosives. Ejecta and spall are important phenomena for stockpile stewardship because they describe how plutonium can behave in a nuclear weapon's primary stage.

Dynamic experiments at LANSCE are expected to continue through next year. In early 2001, a Livermore–Los Alamos experiment at Brookhaven will perform three-dimensional tomography of objects and develop material composition analysis tools. Later in the year, experiments at Fermi National Accelerator Laboratory in Illinois will measure high-energy cross sections of protons interacting with various materials.

Magnetic Lens Focuses Protons

A major emphasis of the research effort is improving the all-important magnetic lenses that overcome the blurring of proton radiographs. Not only do these lenses focus scattered protons, but they also reduce the obscuring effect of secondary particles that cause an overall haze on proton radiographs.

Just as our eyes combine two images into one, so the magnetic lens reconverges diverging rays onto an image plane. When the lens is in focus, protons emerging from the object and traveling in different

Lawrence Livermore physicist Hye-Sook Park checks an imaging station at the end of the proton beamline at the Los Alamos Neutron Science Center. At the right are Livermore-designed detectors that record the differences in the focused proton beam's intensity through the target. One of the detectors is a charge-coupled device that images the experiment in two dimensions. The other detector is a one-dimensional streak camera that images the exploding target at 180-nanosecond intervals. A scintillating screen converts the proton beam intensity into visible light that is diverted by the turning mirrors onto the detectors.

directions are bent by the magnet to reconverge onto an image plane containing a detector, where a permanent image is recorded.

The simple magnets (quadrupole magnets) used for this purpose have four poles alternating in sign. The magnetic lens system allows for the addition of collimators, which can restrict the presence of protons scattered multiple times within the object. The spread in scattering angles depends on the material type, so by adding different collimators, a user can dial in the contrast for the object's region of interest.

Another critical element is the detector system, which records the spatial distribution of the protons that are transmitted through the object. Early experiments used traditional radiography detectors such as phosphor plates that act like photographic film (exposed when the protons penetrate the plate). Newer, more efficient electronic detectors take advantage of the protons' electrical charge. Hartouni notes that detectors for charged particles are commonly used in nuclear and high-energy physics experiments.

The new detectors have little effect on the proton beam so that multiple detectors can be placed in the beam downstream from the object being radiographed. In this way, sets of lenses and detectors can be used in tandem to allow researchers to obtain several simultaneous radiographs, each with a different angular "cut." By combining these images, it is possible to distinguish and identify different materials in the radiograph. For example, Livermore physicists have observed the expected differences in materials at LANSCE in a test object containing Teflon, graphite, Lexan, and aluminum layers.

Livermore's detector development program is adapting the well-known charged-coupled device (used in home video cameras) for high-resolution images. These devices have a screen that scintillates when protons pass through it and can take measurements such as the proton intensity per area and the average energy of the protons. Images from the screen are stored in a computer file. The ultimate goal is to have a camera that allows multiple time frames of an image to be recorded during one experiment, with a frame-duration of 120 nanoseconds and a frame-to-frame spacing of 180 nanoseconds. Livermore engineers have also developed a solid-state streak camera for making proton radiographic movies of dynamic objects.

As the Livermore research team prepares for another year of experiments, its members are increasingly confident that they understand the science of proton radiography and its capabilities for stockpile stewardship. In short, says Hartouni, "We know enough to build a facility and run it. Proton radiography's scientific underpinnings are on solid ground."

—Arnie Heller

Key Words: Advanced Hydrotest Facility (AHF), Brookhaven National Laboratory's Alternating Gradient Synchrotron, Dual Axis Radiographic Hydrodynamic Test Facility (DAHRT), Fermi National Accelerator Laboratory's Main Ring, Flash X Ray (FXR), hydrotests, Los Alamos Neutron Science Center (LANSCE), multiple coulomb scattering, Nevada Test Site (NTS), proton radiography, quadrupole magnets, stockpile stewardship, x-radiography.

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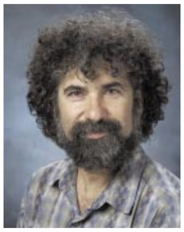
About the Scientist



EDWARD HARTOUNI received a B.A in physics from the University of California at Berkeley in 1976 and an M.A., M.Ph., and Ph.D. from Columbia University in 1978, 1979, and 1984, respectively. He was a postdoctoral fellow at the University of Massachusetts from 1985 to 1988 and an assistant professor there from 1985 to 1994. He joined Lawrence Livermore in 1995 as a physicist involved in high-energy physics research. He is currently group leader of the Proton Radiography Group within the Physics and Advanced Technologies Directorate.

Matter That Matters

CREATING the stuff of stars—this was the goal of a team of experimental researchers from Lawrence Livermore and Texas A&M University.

Using the Laboratory's electron-beam ion trap (EBIT) as an ion source and a cryogenic Penning ion trap (RETRAP) to capture, confine, and cool the ions, these experimenters produced a form of matter that is the thermodynamic analog of the matter found in white dwarf stars. "This development has exciting astrophysical ramifications," says Dieter Schneider, EBIT program leader. "Understanding the cooling process of white dwarf stars will help us determine their age and the age of the universe."[1]

Making Ions to Order

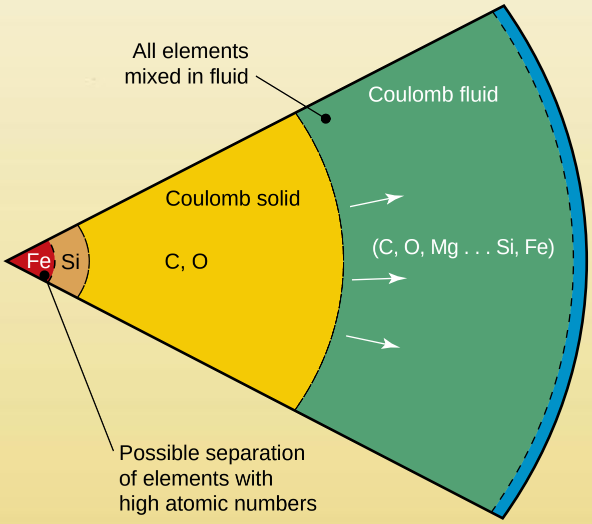
Originally developed and built at Lawrence Livermore by physicists Mort Levine and Ross Marrs in 1985, EBIT uses a tightly focused and energy-tunable electron beam to create and trap highly charged ions. (An ion is an atom or molecule that has become charged by gaining or losing one or more electrons. A completely ionized atom is one stripped of all of its electrons.) Virtually any charge state of any element in the periodic table can be studied using EBIT. It is the only ion source in the world that can create the highest charged ions at rest; other sources able to produce such highly charged ions involve accelerators that increase the velocity of the ions to extremely high energies.

The Livermore EBIT consists of a high-current-density electron beam (up to 5,000 amperes per square centimeter) passing through a series of three drift tubes that hold in place ions of the element being studied. These positively charged ions are confined radially by being attracted to the center of the electron beam and are trapped axially by voltages applied to the end drift tubes. As the electrons in the beam collide with an ion, they strip electrons off the ion until the energy required to remove the next electron is higher than the beam energy.

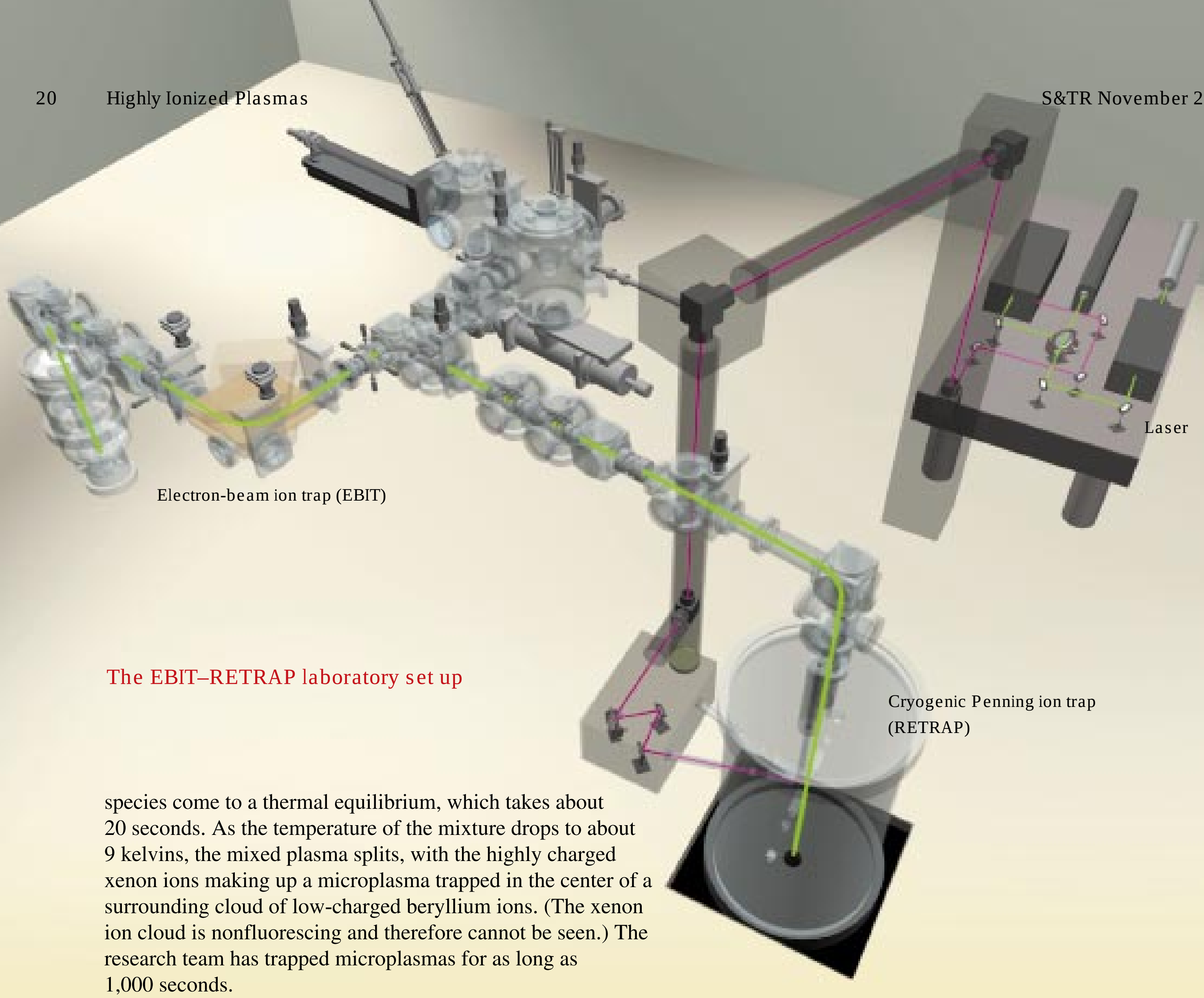
The original EBIT had a peak electron-beam energy of about 30 kiloelectronvolts, enough to make uranium ions with the same number of electrons as neon (U^{82+}). The Super-EBIT can achieve an electron beam energy of 220 kiloelectronvolts, enough to make bare uranium (U^{92+}). Uranium has the highest atomic number among the naturally occurring elements, and therefore, Super-EBIT is sufficiently powerful to serve as the ion source for all of these elements.

Once the highly charged ions are created in EBIT, they are extracted to RETRAP, where they are cooled, stored, and studied. (One of several types of ion traps, the Penning trap uses static electric and magnetic fields to hold the ions.) RETRAP allows researchers to control the temperature and the relative position of the ions. In particular, it allows cooling the ions (reducing their kinetic energy by slowing down their random motion) to the near-zero temperatures needed to create strongly coupled, crystallized plasmas.[2]

The cooling is accomplished in a two-step cooling scheme developed at Lawrence Livermore. (See the figure on p. 21.) First, the cloud of light, singly charged beryllium ions (Be^+) in the ion trap is illuminated with laser beams whose frequency has been selected so that only those ions moving away from the beam absorb the laser light. As the ions reemit the light in a random direction and return to their ground state, they (on average) lose kinetic energy. The process cools the ion cloud to temperatures of a few kelvins. Highly charged xenon ions (Xe^{44+}) are extracted from EBIT and moved to the RETRAP. The beryllium ions, which continue to be cooled by the laser, sympathetically cool the xenon ions, slowing them down. The temperature (energy) of the xenon ions drops until both ion



Structure of the interior of a white dwarf star, showing how the elements are distributed. EBIT–RETRAP recreates the thermodynamic conditions shown in the yellow section, where the ion plasmas crystallize.



The EBIT–RETRAP laboratory set up

species come to a thermal equilibrium, which takes about 20 seconds. As the temperature of the mixture drops to about 9 kelvins, the mixed plasma splits, with the highly charged xenon ions making up a microplasma trapped in the center of a surrounding cloud of low-charged beryllium ions. (The xenon ion cloud is nonfluorescing and therefore cannot be seen.) The research team has trapped microplasmas for as long as 1,000 seconds.

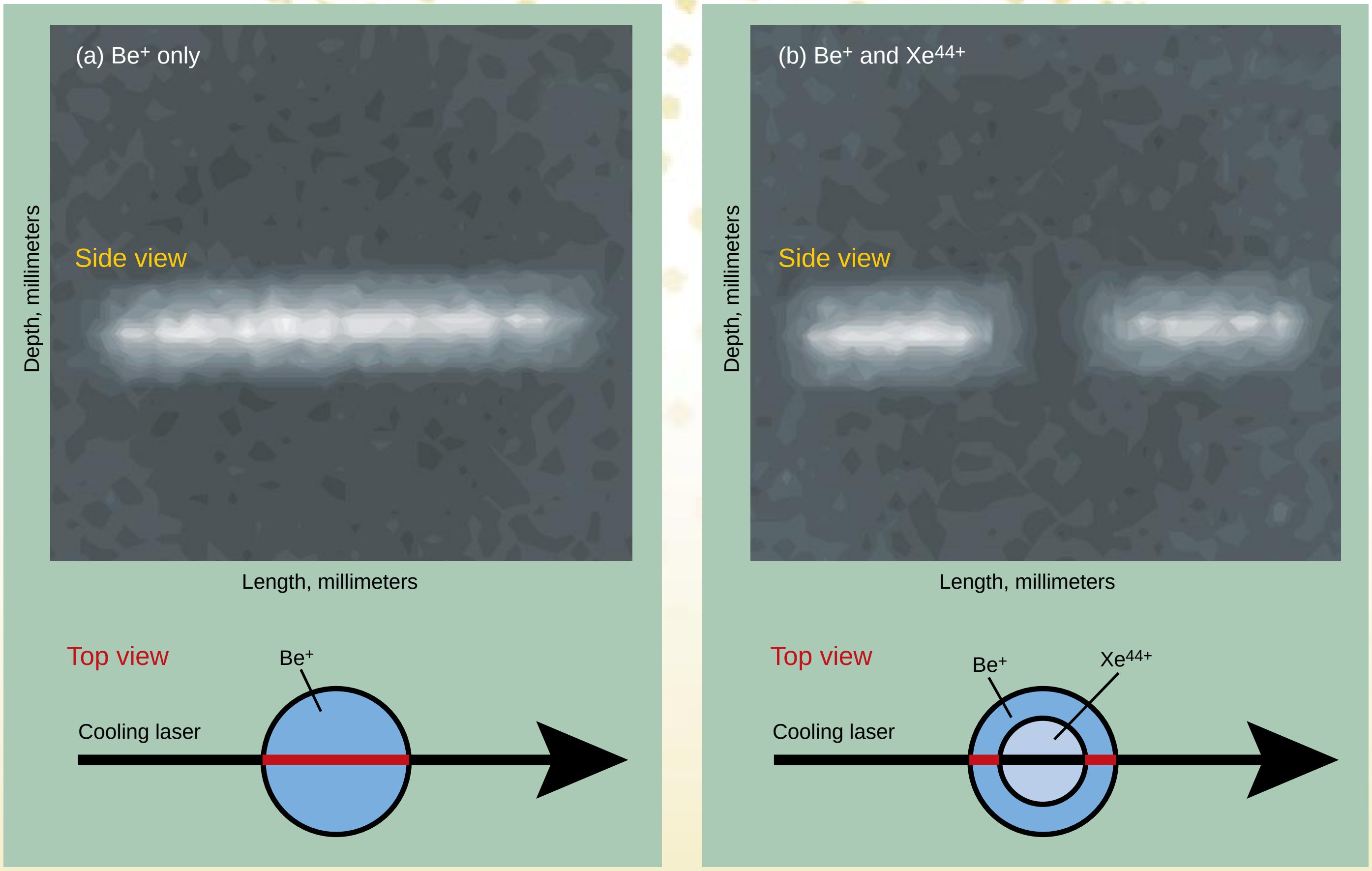
The densities of the microplasmas created with EBIT and RETRAP reach about 100 million (10^8) ions per cubic centimeter, with the distance between the ions being a few micrometers. (Normal, room-temperature liquids and solids have densities of about 10^{23} atoms per cubic centimeter and distances between atoms of a few nanometers.)

Cool and Thin Equals Hot and Dense

At these ultracold temperatures and at certain densities, the microplasmas condense to form an ionic crystal in which the individual ions lock into place relative to each other yet retain their individual identities. “Unlike a noncharged or neutral plasma,” says Schneider, “these highly charged plasmas can exist at thermal equilibrium.”

What’s more, these microplasmas are thermodynamically equivalent to certain exotic high-density plasmas found in white dwarf stars. That is, these two plasmas, at opposite ends of the temperature and density spectrums, have the same thermodynamic properties—for example, specific heat and phase transitions. The reason for this strange parallelism lies in the definition of a single, dimensionless parameter called the Coulomb coupling parameter. This parameter is determined by the density and temperature of the plasma as well as the amount of attraction or repulsion felt by neighboring ions because of their charge (the Coulomb force). Schneider says, “In the EBIT–RETRAP system, we create a strongly coupled, highly charged plasma that crystallizes and has the same Coulomb coupling parameters as those found in the plasmas of white dwarf stars. As long as the parameter is the same, the thermodynamic properties of the plasmas are analogous, even though, in the trap, the ion densities are 20 orders of magnitude and the temperatures 9 orders of magnitude lower than those found in white dwarf stars.”

The extreme conditions in white dwarf stars lead to highly ionized plasmas that are essentially bare nuclei of mostly carbon and oxygen, stripped of all their electrons. The electrons form a uniform background of negative charge, confining the star plasma much as the microplasma is confined by electric and magnetic fields in the RETRAP. Another big plus for researchers who seek to understand these plasmas better is that the EBIT–RETRAP system can be used to create microplasmas consisting of a mix of ion species,



(a) Side view and top-down diagram of a cold (about 9 kelvins) beryllium ion cloud illuminated by a laser beam passing through the center of the cloud. (b) Side view and top-down diagram of the cold beryllium ion cloud displaced radially by a microplasma of highly charged xenon ions, which are chilled by the cold beryllium ions using a sympathetic cooling scheme developed at Livermore. (The xenon ions cannot be seen because they are nonfluorescing.)

just like those in the stars themselves. The system is unique because not only can researchers choose the concentration of different ion species they want in the plasma mix, but they also can control the density and the temperature of the plasma. "This capability exists nowhere else in the world," says Schneider.

Future in the Stars

Studies of these exotic plasmas are helping researchers understand and model the cooling of hot, dense stars and the evolution of our galaxy.

Other intriguing research directions are possible, notes Schneider, including the possibility of creating quantum-computing gates based on ions in crystals stored in traps. A quantum computer could exponentially reduce the time required to complete a complex computation.

—Ann Parker

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Key Words: Coulomb coupling parameter, cryogenic Penning ion trap (RETRAP), electron-beam ion trap (EBIT), highly ionized plasmas, microplasmas, white dwarf stars.

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New Imaging Technique Gets under the Skin . . . Deep

USING a combination of simple optical techniques, plain old white light, and image processing, two Lawrence Livermore researchers and a colleague from the City College of New York (CCNY) have developed a technique for imaging tissue structures—tendons, veins, tumors—deep beneath the skin. The ultimate goal of this research is to dramatically improve the ability to perform minimally invasive cancer detection.

“With a technique called spectral polarization difference imaging [SPDI], we use different wavelengths of light to reach different depths. We also use the polarization properties of the light to help us select the light that penetrates into the tissue and is reflected back out of the tissue as opposed to the light that bounces off the tissue surface,” says Livermore physicist Harry Radousky, acting Director of University Relations. “We then image the tissue structures at the different depths, based on how these structures absorb, scatter, and depolarize light. This technique, combined with fiber optics, charge-coupled-device cameras, and image enhancement calculations, allows us to image up to 1.5 centimeters inside tissue, far deeper than the millimeter depths managed by other existing optical techniques.”

The basic research to develop this technique was funded by the Department of Energy through one of its centers of excellence in laser medicine—the DOE Center for Laser Imaging and Cancer Diagnostics directed by Robert Alfano, M.D., at CCNY. A branch of this center is hosted at the Laboratory within the Materials Research Institute.

Optical Trickery

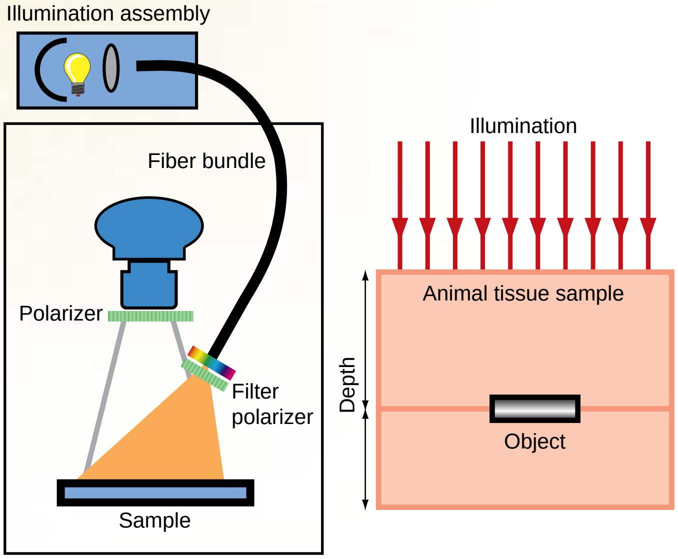
The SPDI system developed by the Livermore–CCNY team depends on simple and inexpensive instrumentation, including a white light source, fiber optics, a filter, two polarizers, and a camera lens coupled to a charge-coupled device (CCD).

The low-power, white-light source is coupled to a fiber-optics bundle that delivers the light to a filter. This filter selects the desired wavelength of light. With this setup, the research team conducted experiments using different bandwidths at the visible to near-infrared portion of the white-light spectrum.

“Longer wavelengths penetrate tissue more effectively,” explains physicist Stavros Demos. “Think of what you see when you hold an ordinary white-light flashlight to your hand. The light that shines through your hand is red, which is at the longer wavelength end of the visible spectrum; the other wavelengths in the visible spectrum are scattered and absorbed within the tissue. For even longer wavelengths—those in the near-infrared spectral region—scattering and absorption of the photons is even further reduced.”

The light that passes through the filter then passes through a polarizer. The light that finally hits the tissue sample is thus not only of a given wavelength but also of a selected polarization. As photons penetrate the tissue, they interact with various tissue structures that may have optical properties different from those of the host tissue. Finally, some of the injected photons emerge from the tissue in the backscattering direction. The intensity of the backscattered light depends on the optical characteristics of the tissue at the sample’s surface as well as below its surface at a particular location.

Light that reflects from the surface (known as a spectral reflection) is polarized and can be removed with a second polarizer set to reject this light. This phenomenon is similar to the way sunglasses work to remove the polarized glare from surfaces, such as the water surface in a swimming pool. The light that backscatters from somewhere below the surface of the tissue is depolarized and consequently can pass through this second polarizer. This remaining light passes through a 50-millimeter camera lens, which is coupled to a CCD detector that captures the image in an exposure of a few milliseconds.

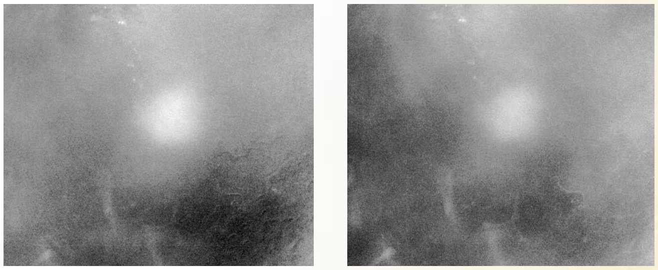


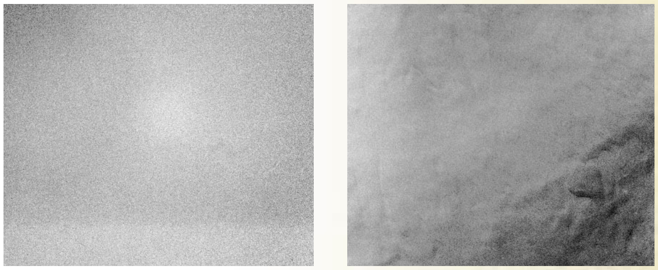
Schematic diagram of the spectral polarization difference imaging setup.

First Chicken, Then Beef

To prove their technique, the researchers attempted to image a small ceramic disc buried in a chicken breast (tissue) bought from a local supermarket. The disc—about the size of a small slice of pencil eraser (4 millimeters in diameter and 1 millimeter thick)—was placed on top of a 1-centimeter-thick slab of chicken breast and topped with an equally thick slab. This “chicken sandwich” was placed between two glass plates and slightly compressed to a uniform thickness.

Four images were recorded using light at 600, 690, 770, and 970 nanometers. The exposure time of the CCD camera was adjusted so the intensity of each image at an arbitrary point was about the same. The researchers took pairs of these digital images—one from a longer wavelength that reaches the disc, the other from a shorter wavelength—and digitally subtracted one from the other. By combining this subtraction technique with the elimination of specular reflections, researchers can remove the image information from the outer tissue layers. In the resulting images, structures deep within the tissue are more visible than they would be if the images were made with light at a single wavelength. “It’s like looking for stars in the daylight,” explains Radousky. “By ‘subtracting’ light from the sun, you’re able to see the stars.”


(a) 970 nm minus 600 nm (b) 970 nm minus 770 nm


(c) 770 nm minus 690 nm (d) 690 nm minus 600 nm

Four final images of an object 1 centimeter below the surface produced by the spectral polarization difference imaging technique. The images were produced by digitally subtracting images derived from photons at different illumination wavelengths (in nanometers, nm) that reach different depths within the tissue. Using the right combination of wavelengths of light is important to the clarity of the resulting image. The wavelength combinations in (a) and (b) allow the subsurface object to be seen with better contrast than in (c) and (d).

“Once we proved the basic technique,” adds Demos, “we imaged the tendons in bovine tissue as well as the veins in the arm of one of the researchers.”

More Details Coming

All in all, the researchers say, SPDI looks to be a promising technique that, once refined and developed into a system, could help the medical community in its fight against cancer.

The next step in this DOE-sponsored project, notes Radousky, is to develop mathematical models that will reconstruct the object in more detail and also provide the object’s precise size, something that isn’t yet possible. “We’re going to work to enhance the images and get as much information out of them as possible. That, of course, is the goal of any cancer-detection system used in a clinical setting—to get as much information about the tumor to the clinicians as possible, in real-time.”

—Ann Parker

Key Words: cancer detection, Center for Laser Imaging and Cancer Diagnostics, Materials Research Institute, spectral polarization difference imaging (SPDI).

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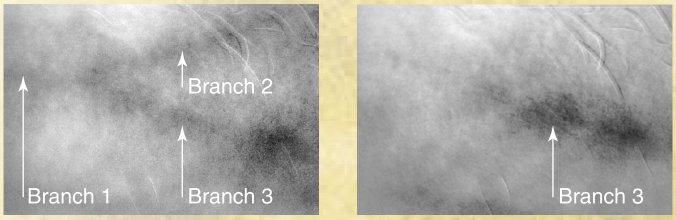
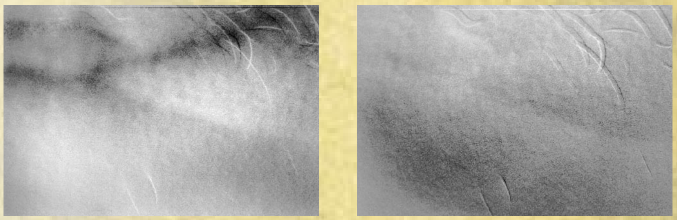


(a) 850 nm minus 600 nm (b) 690 nm minus 600 nm


(c) 850 nm minus 690 nm (d) 690 nm minus 640 nm

Four subsurface views of the arm of a human male with well-developed muscle structure and deep veins. The different nanometer-wavelength combinations reveal different details of the subsurface. For example, (a) the image created by subtracting the 600-nanometer (nm) wavelength from the 850-nm wavelength reveals three vein branches, while (b) the 690-nm minus 600-nm subtraction shows only one vein branch, which is closer to the surface than the other two.

Patents and Awards

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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Stephen A. Payne Ralph H. Page Kathleen I. Schaffers Michael C. Nostrand William F. Krupke Peter G. Schunemann	**Low-Phonon-Frequency Chalcogenide Crystalline Hosts for Rare Earth Lasers Operating beyond Three Microns** U.S. Patent 6,047,013 April 4, 2000	The invention comprises an RE-doped, MA_2X_4 crystalline gain medium, where RE represents the trivalent rare earth ions; M includes a divalent ion such as magnesium, calcium, strontium, barium, lead, europium, or ytterbium; A is selected from trivalent ions including aluminum, gallium, and indium; and X is one of the chalcogenid ions sulfur, selenium, and tellurium. The MA_2X_4 gain medium can be employed in a laser oscillator or a laser amplifier. Possible pump sources include diode lasers. The laser wavelengths generated are greater than 3 micrometers, which is possible because of the low phonon frequency of this host medium. The invention may be used to seed optical devices such as optical parametric oscillators and other lasers.
Ai-Quoc Pham P. Henrik Wallman Robert S. Glass	**Natural Gas–Assisted Steam Electrolyzer** U.S. Patent 6,051,125 April 18, 2000	An efficient method of producing hydrogen by high-temperature steam electrolysis that will lower electricity consumption by an estimated 65 percent compared to usage by previous steam electrolyzer systems. This reduction of electricity consumption is accomplished with a natural gas–assisted steam electrolyzer, which replaces one unit of electrical energy with one unit of energy content in natural gas at one-quarter the cost. It is possible to vary the ratio between the electricity and the natural gas supplied to the system in response to fluctuations in relative prices for these two energy sources. In one approach, an appropriate catalyst on the anode side of the electrolyzer will promote the partial oxidation of natural gas to carbon monoxide (CO) and hydrogen (called Syn-Gas). The CO can also be shifted to carbon dioxide to give additional hydrogen. In another approach, the natural gas is used in the anode side of the electrolyzer to burn out the oxygen resulting from electrolysis, thus reducing or eliminating the potential difference across the electrolyzer membrane.
Lisa A. Tarte Wayne L. Bonde Paul G. Carey Robert J. Contolini Anthony M. McCarthy	**Process for Protecting Bonded Components from Plating Shorts** U.S. Patent 6,051,493 April 18, 2000	A method that protects the region between a component and the substrate onto which the component is bonded. It uses an electrically insulating fillet of photoresist. The fillet protects the regions from subsequent plating with metal, thereby shorting the plated conductors that run down the sides of the component and onto the substrate.
Karla G. Hagans Robert E. Clough	**Optical Key System** U.S. Patent 6,055,079 April 25, 2000	An optical key system comprises a battery-operated optical key and an isolated lock. The optical key has a light-emitting diode or laser diode for transmitting a bit-serial password. The key user operates the lock by entering the code to transmit directly or an index to a pseudorandom number code. (Such personal identification numbers can be retained permanently or can be ephemeral.) When a send button is pressed, the key transmits a beam of light modulated with the password information. At the corresponding optical lock, a photo–voltaic cell produces enough power from the beam of light to operate a password-screen digital logic. In one application, an acceptable password allows a 2-watt power laser diode to pump vehicle ignition and timing information over a fiber-optic cable into a sealed engine compartment. The receipt of a good password allows a vehicle's fuel pump, spark, and starter systems to operate. Otherwise, the vehicle remains thoroughly disabled. Bypassing the lock mechanism to steal a car is pointless.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Abraham P. Lee Joseph P. Fitch Daniel L. Schumann Luiz Da Silva William J. Benett Peter A. Krulevitch	**Microfabricated Therapeutic Actuators and Release Mechanisms Therefore** U.S. Patent 6,059,815 May 9, 2000	Microfabricated therapeutic actuators are made using a shape memory polymer (SMP), a polyurethane-based material that undergoes a phase transformation at a specified temperature (T_g). At a temperature above T_g, material is soft and can be easily reshaped into another configuration. As the temperature is lowered below T_g, the new shape is fixed and is locked in as long as the material stays below T_g. When the material is reheated to above T_g, it will return to its original shape. Microtubing made with SMP material can be used as a retaining/release actuator for the delivery of material, such as embolic coils, through catheters into aneurysms, for example. The microtubing can be manufactured in various sizes and the phase-change temperature T_g is the determinate for an intended temperature target and intended use. The SMP microtubing can be positioned around or within an end of a deposit material. Various heating arrangements can be used with the SMP release mechanism, and the SMP microtubing can include a metallic coating for enhanced light absorption.
David A. Goerz Michael J. Wilson	**Ultracompact Marx-Type High-Voltage Generator** U.S. Patent 6,060,791 May 9, 2000	An ultracompact Marx-type high-voltage generator includes individual high-performance components that are closely coupled and integrated into an extremely compact assembly. In one embodiment, a repetitively switched, ultracompact Marx generator includes • Low-profile, annular-shaped, high-voltage, ceramic capacitors with contoured edges and coplanar extended electrodes used for primary energy storage. • Low-profile, low-inductance, high-voltage, pressurized gas switches with compact gas envelopes suitably designed to be integrated with the annular capacitor. • Feed-forward, high-voltage, ceramic capacitor attached across successive switch-capacitor–switch-capacitor stages to couple the necessary energy forward and thus sufficiently overvoltage the spark gap of the next in-line switch. • Optimally shaped electrodes and insulator surfaces, both to reduce electric field stresses in the weakest regions where dissimilar materials meet and to spread the fields more evenly throughout the dielectric materials, allowing them to operate closer to their intrinsic breakdown levels. This embodiment uses manufacturing and assembly methods to integrate the capacitors and switches into stages that can be arranged into a low-profile Marx generator.
Layton C. Hale	**Three-Tooth Kinematic Coupling** U.S. Patent 6,065,898 May 23, 2000	A kinematic coupling based on having three theoretical line contacts formed by mating rather than six theoretical point contacts. The geometry requires one coupling half to have curved teeth and the other to have flat teeth. Each coupling half has a relieved center portion that does not affect the kinematics, but as the face width approaches zero, three line contacts become six point contacts. As a result of having line contact, a three-tooth coupling has greater load capacity and stiffness. This kinematic coupling can be used for precision fixturing of tools or work pieces, as a registration device for a work or tool changer, or for optics in various products.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Conrad M. Yu	**Microminiature Gas Chromatograph Column Disposed in Silicon Wafers** U.S. Patent 6,068,780 May 30, 2000	A microminiature gas chromatograph column is fabricated by forming matching halves of a circular, cross-section spiral microcapillary in two silicon wafers and then bonding the two wafers together using visual or physical alignment methods. Each wafer has heating wires deposited on its outside surface, in a spiral or serpentine pattern large enough to cover the whole microcapillary area inside the joined wafers. In the visual alignment method, one wafer has an alignment window etched in it, and the other has a precision-matching alignment target. The two wafers are bonded together using the window and target. The physical alignment method consists of etching vertical alignment holes in both wafers and then using pins or posts through corresponding vertical alignment holes to force precision alignment during bonding. The pins or posts may be withdrawn after the bond is cured. Once the wafers are bonded together, a solid phase of ultrapure silicone is injected in a solution of ultrapure chloroform into one end of the microcapillary. The chloroform lowers the viscosity of the silicone enough that a high-pressure hypodermic needle with a thumbscrew plunger can force the solution into the whole length of the spiral microcapillary. The chloroform is then evaporated out slowly to leave the silicone behind in a deposit.
Alexander R. Mitchell Philip F. Pagoria Robert D. Schmidt	**Amination of Electrophilic Aromatic Compounds by Vicarious Nucleophilic Substitution** U.S. Patent 6,069,277 May 30, 2000	Process to aminate electrophilic aromatic compounds by vicarious nucleophilic substitution of hydrogen using quaternary hydrazinium salts. The use of trialkylhydrazinium halide (for example, trimethylhydrazinium iodide) as well as hydroxylamine, alkoxylamines, and 4-amino-1,2,4-triazole to produce aminated aromatic structures, such as 1,3-diamino-2,4,6-trinitrobenzene (DATB), 1,3,5-triamino-2,4,6-trinitrobenzene (TATB), and 3,5-diamino-2,4,6-trinitrotoluene (DATNT), is described. DATB and TATB are useful insensitive high explosives. TATB is also used for the preparation of benzenehexamine, a starting material for the synthesis of novel materials (optical imaging devices, liquid crystals, ferromagnetic compounds).
Abraham P. Lee Michael D. Pocha Charles F. McConaghy Robert J. Deri	**Microbenchtop Optics by Bulk Silicon Micromachining** U.S. Patent 6,071,426 June 6, 2000	Bulk silicon has the characteristic of being etched in parallel planes. By integrating this parallel etching with the silicon wafer bonding and impurity doping techniques, on-chip optics can be fabricated with in situ, aligned etched grooves for use in optical fibers, microlenses, photodiodes, and laser diodes. Other optical components that can be microfabricated and integrated include semitransparent beam splitters, microoptical scanners, pinholes, optical gratings, and microoptical filters. Micromachining of bulk silicon, taking advantage of its parallel etching characteristics, can be used to develop miniaturized bioinstrumentation for wavelength monitoring by fluorescence spectrometers, miniaturized Fabry–Perot interferometry for filtering of wavelengths, tunable cavity lasers, microholography modules, and wavelength splitters for optical communication systems.
Russell M. Hudyma	**High Numerical Aperture Projection System for Extreme Ultraviolet Projection Lithography** U.S. Patent 6,072,852 June 6, 2000	An optical system that is compatible with extreme ultraviolet radiation and comprises five reflective elements for projecting a mask image onto a substrate. The five optical elements are characterized in order from object to image as concave, convex, concave, convex, and concave mirrors. The optical system is particularly suited for ring field, step-and-scan lithography methods. The invention uses aspheric mirrors to minimize static distortion and balance the static distortion across the ring field width, which effectively minimizes dynamic distortion. This invention allows for higher device density because the optical system has improved resolution that results from the high numerical aperture, which is at least 0.14.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Joe N. Lucas	**Method for Isolating Chromosomal DNA in Preparation for Hybridization in Suspension** U.S. Patent 6,077,671 June 20, 2000	A method for detecting nucleic acid sequence aberrations using two immobilization steps. A nucleic acid sequence aberration is detected by identifying nucleic acid sequences having both a first nucleic acid sequence type (for example, from a first chromosome) and a second nucleic acid sequence type (for example, from a second chromosome). The presence of both types on the same nucleic acid sequence indicates the presence of a nucleic acid sequence aberration. Immobilization of a first hybridization probe is used to isolate a first set of nucleic acids in the sample that contains the first nucleic acid sequence type. Immobilization of a second hybridization probe is then used to isolate a second set of nucleic acids from within the first set of nucleic acids that contain the second nucleic acid sequence type. The second set of nucleic acids is then detected, indicating the presence of a nucleic acid sequence aberration. Chromosomal DNA in a sample containing cell debris is prepared for hybridization in suspension by treating the mixture with RNace. The treated DNA can also be fixed prior to hybridization.
Charles G. Stevens Norman L. Thomas	**Immersion Echelle Spectrograph** U.S. Patent 6,078,048 June 20, 2000	A small spectrograph containing no moving components and capable of providing high-resolution spectra of the mid-infrared region from 2 to 4 micrometers in wavelength. The resolving power of the spectrograph exceeds 20,000 throughout this region and at an optical throughput of about 10^{-5} square centimeters steradian. The spectrograph incorporates a silicon immersion echelle grating operating in high spectral order combined with a first-order transmission grating in a cross-dispersing configuration to provide a two-dimensional spectral format that is focused onto a two-dimensional infrared detector array. The spectrometer incorporates a common collimating and condensing lens assembly in a near-aberration-free, axially symmetric design.
Alan D. Conder	**Vacuum Compatible Miniature CCD Camera Head** U.S. Patent 6,078,359 June 20, 2000	A charge-coupled device (CCD) camera head that can replace film for digital imaging of visible light, ultraviolet radiation, and soft-to-visible x rays, such as within a target chamber where laser-produced plasmas are studied. The camera head is small, versatile, and capable of operating both in and out of a vacuum. It uses personal computer boards with an internal heat sink connected to the chassis for heat dissipation, allowing for close stacking of the boards. Integration of the CCD camera head into existing instrumentation provides a substantial enhancement of diagnostic capabilities for studying high-energy-density plasmas and for a variety of military–industrial and medical imaging applications.
Jesse D. Wolfe Norman L. Thomas	**Durable Silver Coating for Mirrors** U.S. Patent 6,078,425 June 20, 2000	A durable multilayer mirror includes reflective layers of aluminum and silver and has high reflectance over a broad spectral range from ultraviolet to visible to infrared. An adhesion layer of a nickel or chromium alloy or nitride is deposited on an aluminum surface, and a thin layer of silver is then deposited on the adhesion layer. The silver layer is protected by a passivation layer of a nickel and/or chromium alloy or nitride and by one or more durability layers made of metal oxides and, typically, a first layer of metal nitride. The durability layer may include a composite silicon aluminum nitride and an oxynitride transition layer to improve bonding between nitride and oxide layers.

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Harold D. Ackler Stefan P. Swierkowski Lisa A. Tarte Randall K. Hicks	**Fusion Bonding and Alignment** U.S. Patent 6,082,140 July 4, 2000	An improved vacuum fusion bonding structure and process for aligned bonding of large-area glass plates, patterned with microchanels and access holes and slots. The plates are for use at elevated glass-fusion temperatures. Vacuum pumpout of all the components is through the bottom platform, yielding an untouched, defect-free top surface that greatly improves optical access through this smooth surface. Also, a completely nonadherent interlayer, such as graphite, with alignment and location features is located between the main steel platform and the glass plate pair. This interlayer makes large improvements in quality, yield, and ease of use of the process and enables aligned bonding of very large glass structures.
Kenneth L. Blaedel Pete J. Davis Charles S. Landram	**Hydrodynamic Blade Guide** U.S. Patent 6,082,239 July 4, 2000	A saw having a self-pumped hydrodynamic blade guide or bearing for retaining the saw blade in a centered position in the saw kerf (the width of the cut made by the saw). The hydrodynamic blade guide or bearing uses pockets or grooves incorporated into the sides of the blade. The saw kerf in the workpiece provides the guide or bearing stator surface. Both sides of the blade entrain cutting fluid as the blade enters the kerf in the workpiece, and the trapped fluid provides pressure between the blade and the workpiece as an inverse function of the gap between the blade surface and the workpiece surface. If the blade wanders from the center of the kerf, one gap will increase and one gap will decrease. The consequent pressure difference between the two sides of the blade will cause the blade to recenter itself in the kerf. Saws using the hydrodynamic blade guide or bearing have application in slicing slabs from boules of single-crystal materials, for example, as well as for cutting other difficult-to-saw materials such as ceramics, glass, and brittle composite materials.

Awards

The Laboratory's **Engineering Manufacturing and Services Group** has been registered officially as in compliance with the **International Standards Organization ISO 9002**—a worldwide benchmark for assuring high quality and customer satisfaction in production, installation, and service. The official certificate was awarded by Bureau Veritas Quality International.

According to group leader Ken Luu, the Livermore group is believed to be the first Department of Energy national laboratory to receive this quality certificate.

The Engineering Manufacturing and Services Group is a collection of small service teams that provide manufacturing and technical expertise throughout the Laboratory, including electronics design, manufacturing and installation expertise, engineering support, and infrastructure support for radio, television, and paging.

The ISO 9002 certification is the result of seven years of continuous improvement in the quality, consistency, and cost-effectiveness of the services provided by the group. It shows that the group's standards and performance, which are independently audited for continued compliance every six months, have attained an internationally recognized level of excellence.

Livermore physicist **John Lindl** recently received a **Fusion Power Associates Year 2000 Award** at the association's annual meeting and symposium at the University of California at San Diego. These awards are given annually for leadership and excellence in fusion engineering.

Lindl, a leading inertial confinement fusion researcher, is a member of the Department of Energy's Fusion Energy Science Advisory Committee and currently chairs the Steering Committee of the U.S. Fusion Integrated Program Planning Activity. His award recognizes the guidance and leadership he has provided over the years to the inertial confinement fusion program in general and especially the perspective he has provided the fusion community as a whole on the energy applications of inertial fusion.

Cutting-Edge Environmental Modeling

Terascale computing has come to simulations of the natural environment, bringing with it multidimensional, time-seqenced models that take a fraction of the time that similar but less complex simulations once took. The computing know-how that arrived at Livermore with the Department of Energy's Accelerated Strategic Computing Initiative—an important component of the Laboratory's mission to assure the safety and reliability of the U.S. nuclear deterrent—has spread throughout the Laboratory. Now it is being applied to advanced models of groundwater, earthquakes, the atmosphere, and global climate change. With these models, scientists can better understand, predict, and safeguard our ever-changing environment.

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Protons Reveal the Inside Story

In the absence of nuclear testing, advanced radiography is the most important experimental tool available to help maintain the nation's aging nuclear stockpile. A team of Lawrence Livermore scientists has been investigating whether beams of high-energy protons focused with magnetic lenses can be used as an advanced radiography probe. Over the past five years, the scientists have conducted a series of tests at Los Alamos and Brookhaven national laboratories. The tests have centered on basic proton science as well as proton radiography's ability to image and distinguish materials in both static and explosive situations. The researchers have gained confidence that proton radiography offers significant advantages over current x-ray technology. Because of its strong attributes, proton radiography is a leading candidate for the proposed Advanced Hydrotest Facility (AHF). The AHF would be able to image the detonation of a mock nuclear device at multiple vantage points and at various times to form a three-dimensional movie.

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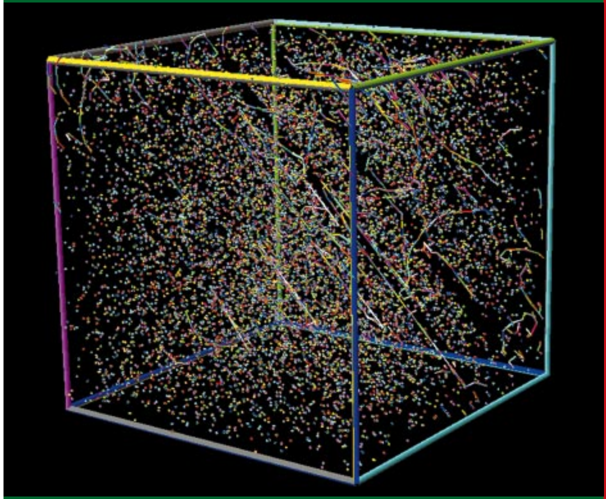
U.S. Government Printing Office: 2000/683-051-80042

Coming Next Month

Modeling Materials from the Atom Up



Leaps in supercomputing capability have led to corresponding advances in materials science codes and models. Now, scientists are performing simulations, once considered intractable, to predict the performance of materials in a variety of environments for a range of time and length scales.

Also in December

- *Systems science, a tool for optimizing performance on complex projects.*
- *Sequestering excess carbon dioxide in the ocean may be one way to stave off global warming.*
- *Site-specific seismic analyses help prepare University of California campuses for large-magnitude earthquakes.*

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