Science & Technology REVIEW

January/
February 2002

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

Lawrence Livermore National Laboratory Celebrates 50 Years

Also in this issue:

- **Simulations Advance Magnetic Fusion Energy Development**
- **Collaboration Synthesizes Two New Elements**
- **Portable Detection Systems Combat Bioterrorism**

Lawrence Livermore
National Laboratory

*Making History
Making a Difference*

1952-2002

About the Cover

In September 2002, Lawrence Livermore National Laboratory turns 50. As part of a year-long celebration, *S&TR* will publish a series of short articles on the development and evolution of the Laboratory's research and development activities in support of our core national security mission and other programs that take advantage of Livermore's special capabilities. This series of 50th anniversary highlights kicks off on p. 4 with an account of the Laboratory's origins and early successes in developing nuclear weapon designs that laid the foundation for the present-day stockpile. Pictured on the cover, along with photos of what the Laboratory looked like back in 1952, are the three men most responsible for establishing Lawrence Livermore—(left to right) Ernest O. Lawrence, Edward Teller, and Herbert York, the Laboratory's first director.

Cover design: Amy Henke

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. 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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Lawrence Livermore National Laboratory

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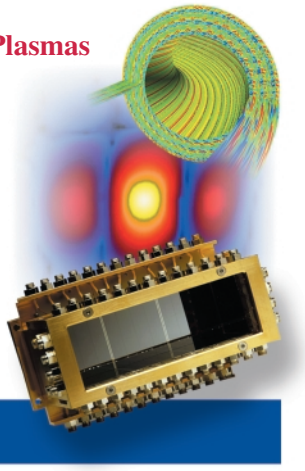

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DNA technique makes cancer diagnosis fast, accurate

A DNA diagnostic technique developed by Laboratory scientists promises to improve the accuracy and speed of cancer diagnosis.

The advance is described in a paper published in the December 2001 issue of *Proceedings of the National Academy of Sciences*. The paper's principal author is Allen Christian, with Melissa Pattee, Christina Attix, Beth Reed, Karen Sorensen, and James Tucker.

With the new technique, researchers can detect mutations in individual cells and make numerous copies of the DNA in the genes that are important for cancer's progression in the cell.

Previously, DNA testing inside cells lacked the resolution needed to detect a localized mutation in the DNA. The best resolution for detecting genetic abnormalities inside a single cell was the identification of a flawed or missing region the length of about 1,000 DNA base pairs out of the 6.6 billion base pairs in each human cell. Furthermore, finding these abnormalities usually took several days.

"Now, with the Lab advance, researchers can locate a single flawed DNA base pair within a cell in a couple of hours," says Tucker. "This technique could greatly speed efforts to measure the effectiveness of treatments in killing tumors and would improve the ability of physicians to individualize cancer treatments," he adds.

For example, when doctors try a particular cancer therapy, they can now evaluate its effectiveness much more rapidly, allowing alternative therapies to be considered earlier if the selected one is not working.

The Livermore technique also has potential applications in genetic screening of plants for agricultural uses, in genetic evaluation of birth defects, in basic cell research, and in determining if a person has been exposed to radiation.

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Solid-state laser weapon successfully tested

In mid-December, program engineers at the Army's High Energy Laser Systems Test Facility (HELSTF) at White Sands Missile Range in New Mexico successfully test-fired a new 10-kilowatt solid-state heat-capacity laser (SSHCL). During the 6-second test, the laser burned a hole through quarter-size samples of steel.

Developed at Lawrence Livermore, the SSHCL has been fired several times since it was transferred to the Army Space and Missile Defense Command (SMDC) for further testing and development at HELSTF.

Under the Army's solid-state laser plan, weapon development begins with a 10-kilowatt laser and moves toward a 100-kilowatt solid-state laser that could be mounted on the back of a high-mobility multipurpose wheeled vehicle (Humvee).

The SSHCL has the potential to be the first high-energy laser that is light and compact enough to be integrated as a direct-fire element of the Army's future combat system, according to Randy Buff, SMDC solid-state laser program manager.

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Lab scientists create virtual star over Hawaii

Livermore scientists, in collaboration with scientists at the W. M. Keck Observatory, have created a virtual guide star over Hawaii. This virtual guide star will be used with the adaptive optics on the Keck II telescope to greatly improve the resolution of images of astronomical objects.

Installed in 1999, Keck's adaptive optics system allows astronomers to minimize the blurring effects of Earth's atmosphere, producing images with unprecedented detail and resolution. The adaptive optics system uses light from a relatively bright nearby star to measure atmospheric distortions and correct for them. However, only about 1 percent of the sky has stars sufficiently bright and close to be of use. The new virtual guide star allows Keck astronomers to study nearly the entire sky with the high resolution of adaptive optics.

The virtual guide star, which achieved "first light" on December 23, 2001, was created using a 20-watt dye laser to illuminate a diffuse layer of sodium atoms present 95 kilometers above Earth's surface. When activated by the laser, the sodium atoms produce a source of light less than a meter in diameter and thus allows the adaptive optics system to measure the distortions of the atmosphere. The virtual star has a magnitude of 9.5, about 25 times fainter than anything the unaided eye can see but bright enough to operate the adaptive optics system.

Using Keck adaptive optics, for which Livermore scientists developed the real-time control system, astronomers are obtaining infrared images with four times better resolution than images from the Hubble Space Telescope, which orbits high above Earth's atmosphere. Many significant discoveries have already been attributed to Keck's adaptive optics, and the Keck virtual guide star will lead to many more.

Additional support was provided to the Keck–Livermore collaboration by the National Aeronautics and Space Administration and the National Science Foundation's Center for Adaptive Optics.

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Fifty Years of Making History, Making a Difference

THE world was a dangerous place in 1952—Stalin was in power, the Cold War raged, U.S. troops were fighting in Korea, and the Soviet Union had exploded an atomic bomb years ahead of most expectations. National leaders recognized the need to accelerate the design and development of nuclear weapons, and to that end, a branch of the University of California Radiation Laboratory opened at the deactivated Naval Air Station in Livermore, California, on September 2, 1952. It was a modest beginning nearly 50 years ago. Now part of the Department of Energy's National Nuclear Security Administration, Lawrence Livermore National Laboratory is a national asset. It provides for the nation's security through activities to maintain the U.S. nuclear weapons stockpile and to prevent the proliferation of nuclear and other weapons of mass destruction.

The world has changed considerably in 50 years, and so has the Laboratory. The research and development capabilities presently at Livermore and necessary for our national security mission were unimaginable in 1952: computers that perform trillions of operations per second, the ability to design and engineer materials at the atomic level, the means of detecting one out of a quadrillion atoms, and a laser under construction that offers the promise of nuclear fusion in a laboratory setting. As a beneficiary, a contributor, and a driver, we have been fully engaged in the post–World War II technological revolution.

Lawrence Livermore's many research and development successes for national security have been significant, as have our contributions to meeting enduring national needs in energy, environment, biology, and biotechnology. Our 50th anniversary provides an opportunity to reflect on those achievements. *Science & Technology Review* will publish a series of articles throughout 2002, each highlighting a specific aspect of the Laboratory's work. They will reflect on our accomplishments—"making history, making a difference"—and our course for the future. Some articles will focus on major programmatic successes, others will feature the scientific or technical advances made at Livermore that have furthered the programmatic achievements. All have a common theme: a Laboratory with an essential and compelling core mission and success in solving important and difficult problems.

The first article in this series deals, appropriately, with the Laboratory's role in nuclear weapons design, which was a primary responsibility for Livermore from the very start (see p. 4). From the outset, Laboratory researchers worked in multidisciplinary teams, took a can-do attitude, and developed unique capabilities to address the complex issues and challenging science involved in designing nuclear weapons. Innovation was central to these efforts and continues to be a hallmark of the Laboratory's efforts.

Future articles will report on Livermore contributions to the nation's Stockpile Stewardship Program and to nonproliferation, arms control, and international security. Other articles will examine the Laboratory's capabilities in computations, engineering, physics, lasers, chemistry, and materials science as well as programs in energy, environment, bioscience, and biotechnology.

One constant has endured over the past 50 years: the need for a national laboratory like Livermore. At the beginning of the 21st century, serious challenges to national security persist. Their resolution requires innovation and the best that science and technology can offer. Livermore's defining combination of attitude, special capabilities, and multidisciplinary team science is the foundation of past successes and current ambitious programmatic goals. It gives rise to our ability to respond to emerging national needs and, in some instances, to anticipate them.

The next 50 years are bound to be as surprising as the last half century. All we can say for certain is that, when the Laboratory prepares to celebrate its centennial, it will be a different world yet again. Following the example set by Livermore's founders and today's exceptional staff, I am sure that the Laboratory will be engaged in the most pressing issues of the time, striving for innovations to keep the nation secure, healthy, and prosperous.

■ C. Bruce Tarter is director of Lawrence Livermore National Laboratory.

Fifty Years of Innovation through Nuclear Weapon Design

WHEN the Livermore branch of the University of California Radiation Laboratory (UCRL) opened its gates on September 2, 1952, the nation was fighting a "hot" war in Korea and a "cold" war with the Soviet Union. The Soviet Union had detonated its first nuclear device three years earlier—much ahead of U.S. expectations. Nuclear weapons were a new and growing part of the U.S. arsenal and seen as essential for deterring Soviet aggression in Europe. Today, the Cold War is history. Relationships with Russia and other countries of the former Soviet Union are more cooperative than confrontational, but new international dangers have emerged. The development of new U.S. nuclear weapons ceased in 1991; presently, the focus is on improving our scientific capabilities to understand weapon performance in the absence of nuclear testing and to refurbish weapon systems as necessary to keep the existing nuclear stockpile reliable, safe, and secure.

> **"Research on nuclear weapons has provided the United States with the ability to deter the use of nuclear weapons throughout the past half century."**
>
> —Edward Teller, *Memoirs: A Twentieth-Century Journey in Science and Politics*

Throughout the half century since its inception, the "Rad Lab at Livermore" (which became Lawrence Livermore National Laboratory in 1979) has helped the nation meet important challenges through innovations in science and technology. The initial challenge, the one that set the stage for all that followed, was the design of nuclear weapons.

The Heart of Innovation

At first, Livermore scientists and engineers were mainly responsible for developing diagnostic instrumentation to support tests of thermonuclear devices "in close collaboration with the Los Alamos Scientific Laboratory." The Joint Committee on Atomic Energy also hoped "that the group at UCRL (Livermore) will eventually suggest broader programs of thermonuclear research to be carried out by UCRL or elsewhere." Under the direction of Herbert York—a 32-year-old physicist designated by UCRL Director Ernest O. Lawrence to "run the place"—the Laboratory's mission rapidly evolved. It was not long before Livermore became the second U.S. nuclear weapons design laboratory.

"Weapons are an integral part of the past and present of the Laboratory," says retired weapons designer Bill Lokke, winner of an E. O. Lawrence Award for innovative weapons design work in the 1960s. "Livermore is one of the two 'go-to' laboratories for nuclear weapons research in the nation, along with Los Alamos. A key attribute of our success is our attitude toward innovation. . . . We want to do things the best possible way, find the best possible solution to a scientific problem. Even if it means inventing something new."

Livermore used this approach to explore the heart of nuclear weapons work—improving the performance of fission and thermonuclear weapons through better designs that contributed to better systems for the U.S. military. The Laboratory did not hesitate to tackle bold designs that appeared to be the best solutions, even though pursuit of these solutions had no guarantees of success. Livermore's weapon designers were willing to take risks and to accept failures as

part of the process. And failures did occur, a number of them right at the start.

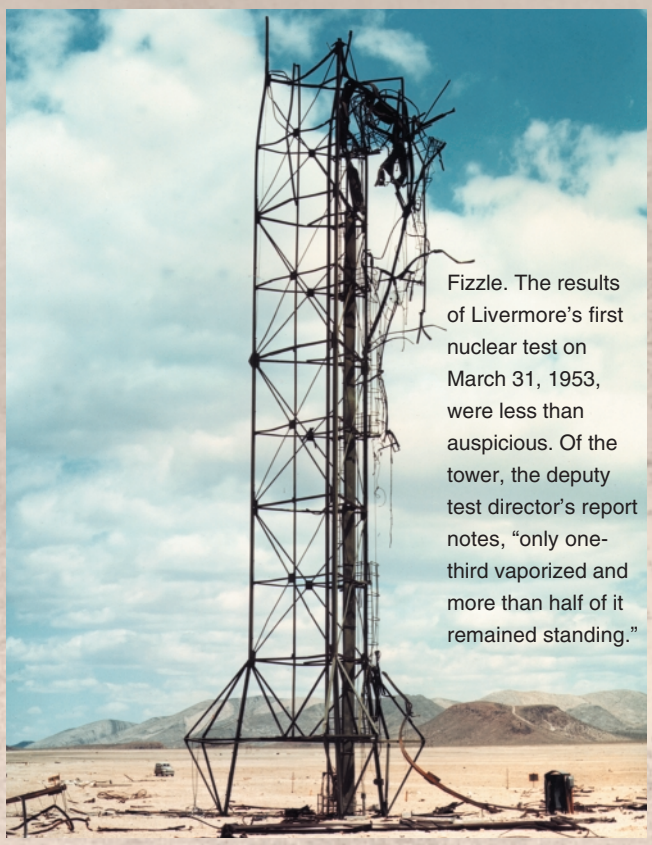
For its first nuclear test, just six months after its founding, Livermore planned to detonate a fission test device of unusual design. The test was to shed light on certain thermonuclear reactions key to two Livermore hydrogen bomb tests planned for 1954. The test device was fastened to a 90-meter-tall tower at the test site in Nevada. When the smoke cleared after the countdown, the tower was still there, albeit in somewhat reduced form. The sad remains of this "fizzle" were immortalized in a photograph that one still finds pinned up in various offices at the Laboratory. The photo, below right, is a vivid reminder of the Laboratory's humble beginnings and, more importantly, its willingness to take chances on innovative approaches.

Pushing the Limits

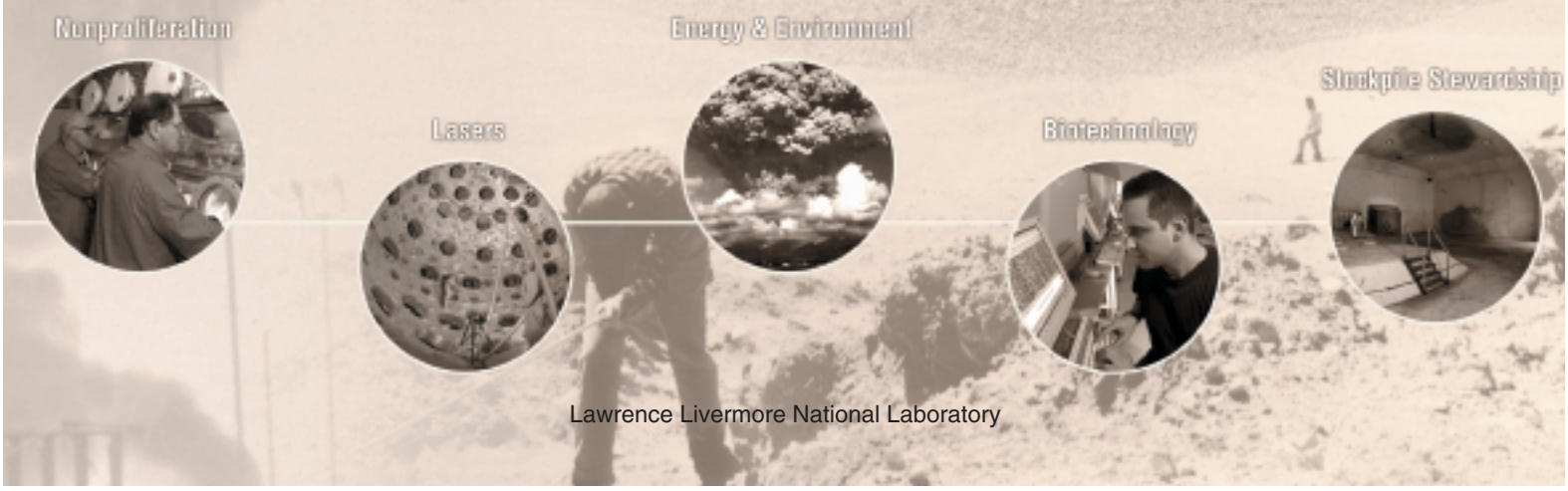
In August 1953, York submitted a formal proposal to the Atomic Energy Commission (the forerunner to the current National Nuclear Security Administration within the Department of Energy) for expanding Livermore's research to small fission weapons. A principal goal of the program, as outlined by York, would be the development of small, lightweight nuclear warheads for air-to-air defense missiles and improved atomic artillery shells. The design objectives were to develop reasonably efficient fission weapons of relatively small size, weight, and yield. The small weapons research being pursued by Livermore was of interest particularly to the Army, which could use the designs in artillery shells. Up to that time, fission weapons were enormous and heavy. For instance, "Fat Man"—the fission bomb dropped on Nagasaki, Japan, to help end World War II—weighed over 4,500 kilograms. Another reason for Livermore's interest in small fission weapons was the important goal of developing small primaries to shrink the size of thermonuclear weapons. (A thermonuclear weapon has two basic nuclear components: the primary, which is a fission device that serves as the nuclear "trigger" to set off the secondary, which produces most of the weapon's yield.)

In the 1950s, Livermore designers, led by physicists Harold Brown and John Foster, were increasingly successful in producing innovative designs. The table on p. 6 lists the systems Livermore developed. In 1955, joint responsibility for the warhead for the Navy Regulus II system was assigned to Livermore and Los Alamos; in 1956, Livermore shouldered the nuclear design of an atomic demolition munition for the Army and the warhead for the Navy Terrier system. With the assignment in 1957 of developing the warhead for the Navy's Polaris missile, the Laboratory really came into its own. "Polaris was a turning point in nuclear weapon design," notes Kent Johnson, chief of staff for Livermore's Defense and Nuclear Technologies Directorate.

Physicist Edward Teller, a driving force behind Livermore's founding and its director from 1958 to 1960,



Fizzle. The results of Livermore's first nuclear test on March 31, 1953, were less than auspicious. Of the tower, the deputy test director's report notes, "only one-third vaporized and more than half of it remained standing."



Livermore's Contributions to the Nation's Nuclear Stockpile

Category	System	Service	Date assigned to Livermore
Strategic nuclear weapons			
Intercontinental ballistic missiles (ICBMs)			
W38	Atlas/Titan	Air Force	February 1959
W56	Minuteman	Air Force	December 1960
W62	Minuteman	Air Force	June 1964
W87	Peacekeeper	Air Force	February 1982
Submarine-launched ballistic missiles (SLBMs)			
W47	Polaris	Navy	August 1957
W58	Polaris	Navy	March 1960
W68	Poseidon	Navy	December 1966
Air-launched missiles			
W27 (cruise)	Regulus	Navy	September 1955*
Ground-launched missiles			
W84	Cruise	Air Force	October 1978
Bombs			
B41	B52	Air Force	February 1957
B83	Modern strategic bomb	Air Force	January 1979
Defensive nuclear warheads			
W71	Spartan	Army	March 1968
Tactical nuclear weapons			
Atomic demolition munitions (ADM)			
W45	ADM	Army	November 1956
Missile warheads			
W45	Little John	Army	November 1956
W70	Lance	Army	April 1969
W70 (Mod. 4)	Lance	Army	April 1976
Artillery-fired atomic projectiles (AFAPs)			
W48	155-mm howitzer	Army/Marines	August 1957
W79	8-in. artillery gun	Army	January 1975
Fleet antisubmarine (surface-to-air missile) warheads			
W45	Terrier	Navy	November 1956
W55	Submarine rocket	Navy	March 1959

*Joint Livermore–Los Alamos assignment.

championed the effort to develop small, efficient thermonuclear weapons that could be carried by submarine. For Polaris, Livermore designers came up with radical new designs for the primary and secondary as well as novel ways to minimize the overall mass. The result—a weapon for a reentry vehicle carried by a solid-fueled missile—fit inside a submarine and met Navy specifications for yield and weight. Polaris was a critically important breakthrough, greatly adding to the stability of the nuclear deterrent.

"This development [of Polaris] made it impossible for the Soviets to attack the United States and prevent retaliation," noted Teller. "Indeed, rocket-delivered explosives are hard to shoot down, and the submarines that carry them are hard to detect." The innovative design for the Polaris warhead was first validated in 1958. In 1960, the first Polaris submarine armed with Livermore-designed warheads took to sea, ahead of the most optimistic schedule.

The design improvements introduced in the Polaris warhead had far-reaching effects. "Small, lightweight designs, whose evolution can be traced to the Polaris W47, were adopted in most subsequent U.S. strategic nuclear weapons," says Johnson. "They set the tone and stage for the modern nuclear stockpile."

The 1960s were an extremely productive time for the Laboratory, which was assigned to develop warheads for the second-generation Polaris system and the Poseidon missile, both for the Navy. Livermore design teams also developed the warheads for the Air Force Minuteman II and III missiles. Throughout the decade, the Laboratory maintained a strong focus on strategic missile systems, particularly on those that carried multiple reentry vehicles (MRVs) and, later, multiple independently targetable reentry vehicles (MIRVs). Livermore's designs made it possible to meet the severe size and weight constraints placed on the warheads and still fulfill yield requirements for these systems.

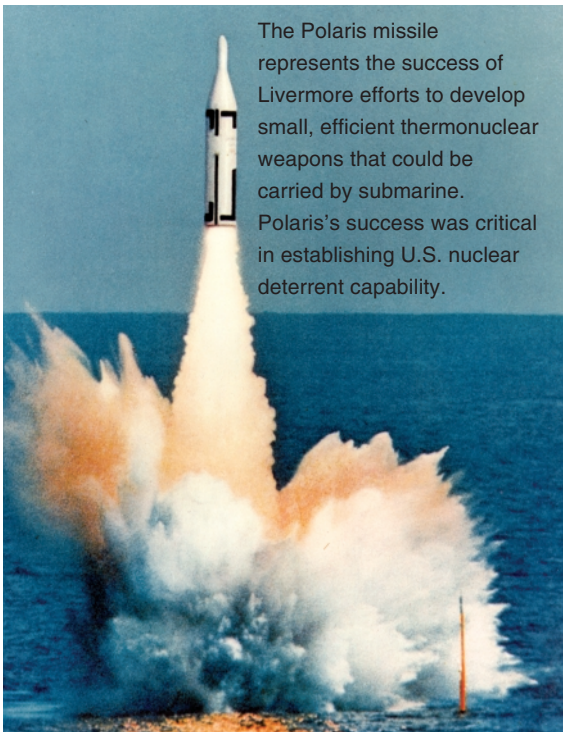
Variations on a Theme

Livermore was also at the forefront of designing new types of nuclear explosives with tailored output. For example, increasing the fraction of energy generated by nuclear fusion rather than fission produced a "low-fission" nuclear weapon, which would produce less fallout. In addition, in 1957, Laboratory scientists began to explore possible peaceful uses of nuclear explosives through Project Plowshare. Reduced amounts of residual radiation—fewer fission products from the explosion and less induced radioactivity of the ground—were necessary to make feasible peaceful applications such as earth moving and power production. The design approaches to reduce residual radiation in these early efforts proved critical to the Laboratory's development of warhead concepts that were

deployed on the Spartan and Sprint antiballistic missile systems in the early 1970s. Development of the high-yield W71 warhead for Spartan, which was designed to intercept a cloud of reentry vehicles and decoys in space, was a major undertaking for Livermore.

Tailoring the output of low-yield tactical nuclear weapons was also a focus of the Laboratory. Enhanced radiation weapons, which had low total yield yet produced large amounts of neutrons, were designed to be effective against military units while limiting the collateral blast damage to noncombatants. Nuclear weapon designs with specifically tailored effects were also the springboard for exploring the feasibility of third-generation, or directed-energy, weapons, such as nuclear-powered x-ray lasers, for use in strategic defense.

The Laboratory also applied innovation to enhancing the safety of nuclear weapons. The most modern safety features in U.S. nuclear weapons are incorporated in the Peacekeeper intercontinental ballistic missile warhead (W87), the ground-launched cruise missile warhead (W84), and a modern strategic bomb (the B83)—all first deployed in the 1980s. They include features such as high explosive that is virtually impossible to detonate inadvertently (developed by Los Alamos and Livermore in the 1970s) as well as creative features that enhance electrical nuclear detonation safety and make the weapons safe in the event of fire.



The Polaris missile represents the success of Livermore efforts to develop small, efficient thermonuclear weapons that could be carried by submarine. Polaris's success was critical in establishing U.S. nuclear deterrent capability.

Testing the Designs

Innovation was also key to Livermore's Test Program, which was given the task of experimentally testing nuclear devices to prove the designs. Project Plowshare was one way that Livermore staff gained valuable experience and expertise in underground testing that helped to prepare the U.S. for the Limited Test Ban Treaty, which ended atmospheric nuclear testing in 1963. For instance, one Plowshare idea was to use nuclear explosives to generate large volumes of heat for electrical production. The Laboratory tested this idea in underground salt domes, which contain the explosion. When the end of atmospheric testing came, Livermore scientists were already knowledgeable about containment and how to measure results underground.

Innovation also gave rise to a host of new technologies and exotic instruments and measurement techniques. For example, as the Laboratory explored designs with tailored nuclear output in the mid-1960s, those research efforts made necessary more detailed characterization of the x-ray output of various test "x-ray bombs." Hal Mallett, who headed the X-Ray Measurements Group from 1977 to 1986, notes, "This need

A comparison of (a) "Fat Man," the bomb dropped on Nagasaki, Japan, in 1945, and (b) a modern reentry vehicle, 10 of which are mounted in the nose of a Peacekeeper intercontinental ballistic missile, shows how Livermore's innovative designs allowed the U.S. to reduce the size and weight of nuclear warheads without compromising the systems' yield requirements.

In an underground test, a nuclear device was placed down a hole, typically 300 meters deep. A separate canister above held the diagnostic instruments. The explosion would vaporize the detectors, apparatus, and cables in a fraction of a second. But by that time, all the data needed had been fully recorded a safe distance away. (Top) The need to test underground led to a burst of engineering innovation. For example, mammoth drilling rigs, available nowhere else in the world, were specifically designed to dig the deep vertical shafts. (Bottom) Data signals from the test explosion moved up and out of the hole through cables, which in turn fanned out on the surface to trailers that housed instruments for reading the signals. As a signal flashed across the face of an instrument—often a specially designed oscilloscope—a camera snapped its picture. In later years, much data moved "up hole" in digital form, eliminating the need for recording analog signals.

provided an impetus for a renaissance in x-ray diagnostics here at the Lab. From that time through the 1980s, basic x-ray physics technology and knowledge grew, as did our experimental development and calibration capabilities."

It Started with Weapons

The Laboratory's willingness to try out new ideas and new approaches to solve problems began with nuclear weapons design and came to embrace all areas of research the Laboratory was asked to pursue. Whether the challenge lies in stockpile stewardship, computations, engineering, bioscience, lasers, national security, chemistry, or energy and the environment—in one way or another, that challenge can probably trace its lineage to the early days of the Laboratory.

—Ann Parker

Key Words: 50th anniversary, nuclear weapon design, nuclear stockpile, Polaris missile, Project Plowshare, Test Program.

For further information about the Laboratory's beginnings, see the following Laboratory Web sites:

On the history of Lawrence Livermore
www.llnl.gov/timeline/
www.llnl.gov/llnl/02about-llnl/history.html

On Ernest O. Lawrence
www.llnl.gov/str/October01/Lawrence.html

On Edward Teller
www.llnl.gov/str/07.98.html

On Herbert York
www.llnl.gov/llnl/history/york.html

Making History, Making a Difference

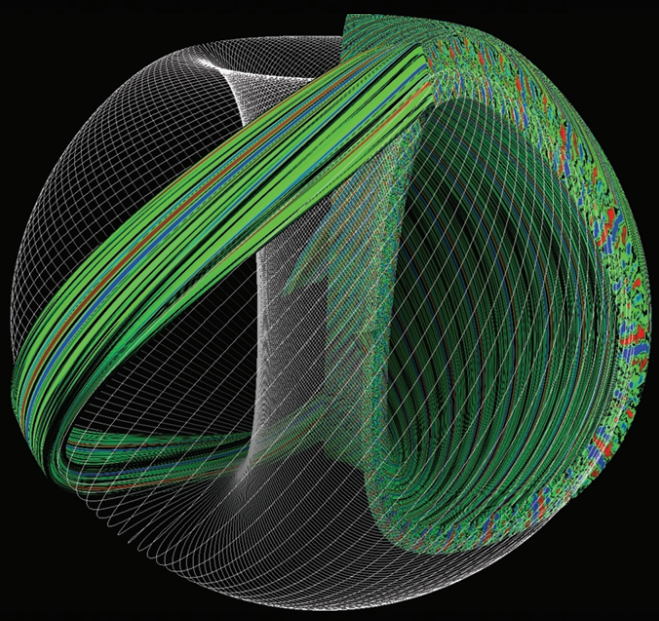
Throughout 2002, Livermore Laboratory will be celebrating its 50th anniversary. We invite our readers to join us on the journey of remembering our past accomplishments, discovering their influence on the present, and pondering their potential for future achievements.

This article on Livermore's origins in innovative nuclear weapons design research is the first in a series of 10 articles that will appear in *S&TR* throughout this anniversary year. For more information about other activities planned for the 50th anniversary celebration, see www.llnl.gov/50th_anniv/.

This list of anniversary-related events and publications will be updated and expanded in each issue of *S&TR*.

Simulating Turbulence in Magnetic Fusion Plasmas

Microturbulence, a long-time nemesis of magnetic fusion energy experiments, is being understood in unprecedented detail thanks to new three-dimensional simulations.



This Livermore simulation shows a magnetic field line (white) wrapping around a torus, or doughnut-shaped configuration of plasma. Magnetic field lines are embedded within the plasma, with individual particles traveling along each field line. The color contours indicate microturbulent fluctuations in the plasma density. Regions with similar density—microturbulent eddies indicated by regions of similar color—stretch along the field lines, while varying rapidly across the field lines. These microturbulent eddies transport heat from the plasma's superhot core to the cold outer edge.

SINCE the 1950s, Lawrence Livermore has been one of the world's leading centers of magnetic fusion energy research. Magnetic fusion uses intense magnetic fields to confine an extremely hot gas of electrons and positively charged ions called a plasma. Under the right conditions, the plasma ions undergo fusion reactions, the energy source of the Sun and other stars.

The long-standing goal of fusion researchers has been to duplicate the cosmos's means of producing energy to provide a virtually inexhaustible source of reliable and environmentally benign energy on Earth. Despite the immense technical challenges involved in making magnetic fusion a source of commercial electrical power, important progress has been made in the past decade as researchers nationwide have collaborated on experiments and computer simulations.

Lawrence Livermore's Fusion Energy Program carries out magnetic fusion energy research in two complementary thrusts. The first thrust is performing advanced fusion experiments. Livermore researchers are collaborators at the national DIII-D tokamak experiment at General Atomics in San Diego, California.

Laboratory scientists are also pursuing novel designs for magnetic fusion reactors, such as the spheromak experiment dedicated in 1998. (See *S&TR*, December 1999, pp. 18–20.)

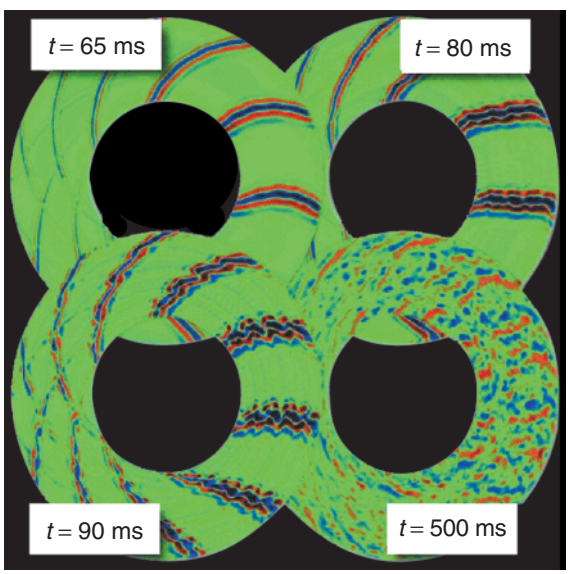
Complementing the experimental work is an effort to accurately simulate the extraordinarily complex physics involved in magnetically confined plasmas. Lawrence Livermore scientists have developed a number of codes for simulating different aspects of magnetic fusion energy experiments. Its PG3EQ program, developed by physicists Andris Dimits, Dan Shumaker, and Timothy Williams, for example, is one of the most advanced programs available for simulating plasma turbulence. Another Livermore code, called CORSICA, goes a step further and links individual programs that model different aspects of magnetic fusion energy physics. (See *S&TR*, May 1999, pp. 20–22.)

Focus on Tokamak

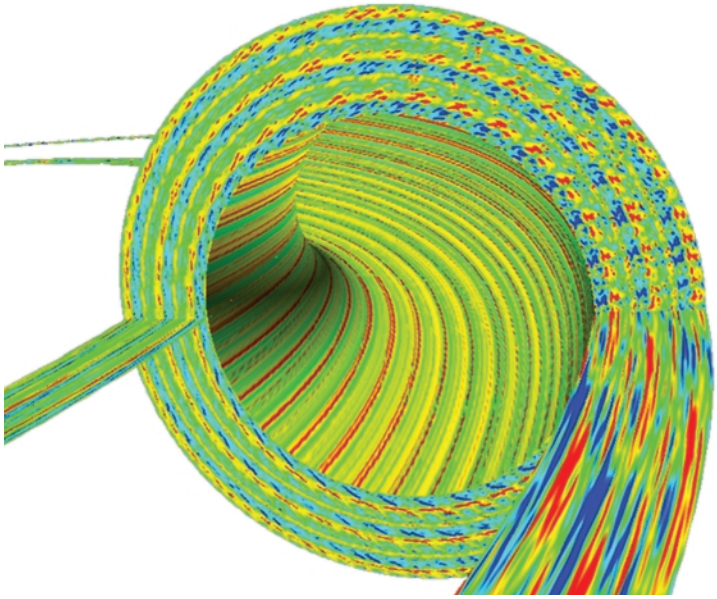
A national team of researchers led by Laboratory physicist Bill Nevins is developing advanced simulation codes running on supercomputers to deepen scientific understanding of the plasma turbulence that occurs inside a tokamak, a magnetic confinement device. Tokamaks use powerful magnets to confine plasmas of fusion fuel on the toroidal, or doughnut-shaped, magnetic "surfaces" defined by individual magnetic field lines as they wind about within a vacuum chamber.

Plasma turbulence causes thermal energy to leak across the magnetic surfaces faster than it can be replaced by fusion reactions. This lost energy must be replaced by external sources to prevent the plasma from cooling below the 100-million-degree temperatures needed to optimize the rate of fusion reactions. However, current tokamak experiments are close to the major goal of breakeven, that is, the point at which the energy produced by the fusion reactions equals the energy applied from an external source to heat the fuel. A better understanding of plasma turbulence may allow researchers to reduce the rate of energy loss so that energy breakeven could be achieved in the current generation of tokamaks.

The national collaboration is called the Computational Center for the Study of Plasma Microturbulence. It is funded by the Department of Energy's Office of Fusion Energy Sciences, a part of DOE's Office of Science. The work is part of the Office of Science's Scientific Discovery through Advanced Computing (SciDAC) program, which was launched in late 2000. SciDAC's goal is to develop the scientific computing hardware and software needed for terascale (trillion-operations-per-second) supercomputing. The effort is similar to the National Nuclear Security Administration's Accelerated Strategic Computing Initiative, which is making



This simulation, done by Livermore collaborator General Atomics of San Diego, California, with the GYRO code, shows a cross section of a tokamak over time (*t*) in microseconds (ms). The color contours indicate microturbulent fluctuations in the plasma density. The center sections have been removed to facilitate comparison.



Part of the cross section of a tokamak plasma. The color contours indicate microturbulent fluctuations in the plasma density. Livermore's PG3EQ code, which was used to produce this simulation, models a "tube" of magnetic flux as it wraps once around the tokamak poloidally, or the short way around. Toroidal symmetry was then used to displace this flux tube and fill the annulus.

available terascale computers for the nation's Stockpile Stewardship Program.

The collaboration involves researchers from Lawrence Livermore, the Princeton Plasma Physics Laboratory, the University of California at Los Angeles, the University of Colorado, the University of Maryland, and General Atomics. These institutions were part of previous DOE magnetic fusion energy simulation efforts, including the Numerical Tokamak Turbulence Project (1993 to 1999), led by Livermore physicist Bruce Cohen, and the Plasma Microturbulence Project (2000 to 2001), led by Nevins.

The simulations are focused on microturbulence, a long-time nemesis of achieving breakeven conditions in magnetic fusion energy experiments. Microturbulence is one of two forms of plasma turbulence observed in magnetic confinement experiments. Macroturbulence, on the scale of centimeters to meters, has been largely tamed in advanced tokamak designs. Microturbulence, on the scale of tenths of millimeters to centimeters, has not.

Fluctuating Plasma Soup

Microturbulence is an irregular fluctuation in the plasma "soup" of electrons and ions. The fluctuations are caused by gradients of density and temperature. The fluctuations, a collective phenomenon, form unstable waves and eddies that transport heat from the superhot core across numerous magnetic field lines out to the much cooler plasma surface and, ultimately, to the tokamak's walls. Energy researchers call this phenomenon energy transport.

Nevins notes that a tokamak's plasma will undergo fusion reactions only if it is hot enough, dense enough, and kept away from the much colder reactor walls. By causing heat to be lost from the plasma core, microturbulence helps to degrade confinement and prevent breakeven conditions. "We want plasma at about 100,000,000°C in the center and below 1,000°C at the walls, so they don't melt," says Nevins. "We obviously need good thermal insulation, and that's provided by the confining magnetic field. If we can minimize microturbulence, we can prevent heat leaking out faster than the fusion reactions can generate heat."

Controlling microturbulence will be immensely important in determining whether an advanced experiment, currently in the early planning stages, will be a success. Nevins says that the largest tokamaks cost several hundred million dollars to build. Constructing an experimental device that would go beyond breakeven for a net production of energy would cost about $2 billion. If a way were found to control microturbulence, construction costs could decrease significantly.

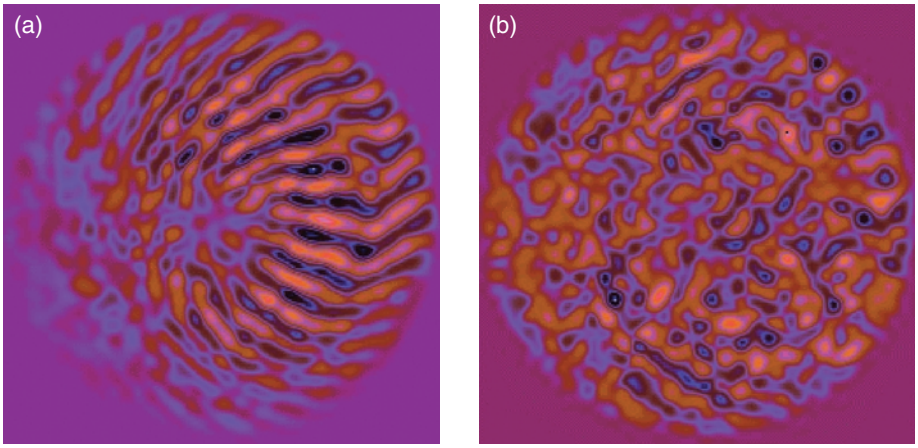
Says Cohen, "If we had better energy confinement, we could build the next generation device at a much lower cost. To do that, we need to understand better the nature of plasma microturbulence."

Simulation Focus

The collaboration's current focus is on advanced codes, algorithms, and data analysis and visualization tools. Nevins says that simulating microturbulence has proved difficult because of the enormous range of time and space scales that occur in magnetic fusion plasmas. Indeed, scientists within the national magnetic fusion energy program have worked to model microturbulence for more than two decades.

Fortunately, massively parallel computers, which use thousands of microprocessors in tandem, are well-suited to this simulation task. These machines are ideal because the collective behavior of trillions of electrons and ions is complex, but the underlying physics—and the equations that describe it—are relatively straightforward.

Most computing is done remotely at the Department of Energy's National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley



The UCAN code, developed by Livermore collaborators at the University of California at Los Angeles, produced these two images of tokamak plasmas. (a) Early in the development of the microturbulence, small-amplitude, radially elongated turbulent eddies form. (b) Fully developed microturbulence exhibits smaller, disordered structures.

Fusion for the Future

Fusion combines the nuclei of light elements to form a heavier element. For example, two nuclei of hydrogen isotopes, deuterium and tritium, will overcome the natural repulsive forces that exist between such nuclei and combine under enormous temperature and pressure. The fusion reaction produces a single nucleus of helium, a neutron, and a significant amount of energy.

A device that creates electricity from fusion must heat the fuel to a sufficiently high temperature and then confine it for a long enough time so that more energy is released than must be supplied to keep the reaction going. To release energy at a level required for electricity production, the fusion fuel must be heated to about 100,000,000°C, more than 6 times hotter than the interior of the Sun. At this temperature, the fuel becomes a plasma, an ionized gas of negatively charged electrons and positively charged ions. Although rare on Earth, plasmas constitute most of the visible universe.

The challenge for scientists is how to confine the plasma under extreme temperatures and pressures. One solution is to use powerful magnetic forces. In the absence of a magnetic field, a plasma's charged particles move in straight lines and random directions. Because nothing restricts their motion, the charged particles can strike the walls of a containing vessel, thereby cooling the plasma and inhibiting fusion reactions. In an appropriately designed magnetic field, the particles are forced to follow spiral paths about the magnetic field lines so they do not strike the vessel walls. The plasma is thus confined to a particular magnetic field line. The magnetic field line itself can be confined within a vacuum chamber if its path is restricted to a toroidal, or doughnut, shape.

A bundle of such magnetic field lines forms a doughnut-shaped magnetic "bottle" called a tokamak, an acronym derived from the Russian words meaning toroidal chamber and magnetic coil. In the tokamak, the stable magnetic bottle is generated both by a series of external coils, which are wrapped around the outside of the doughnut, and by a strong electrical current, up to several million amperes, that is induced in the plasma itself.

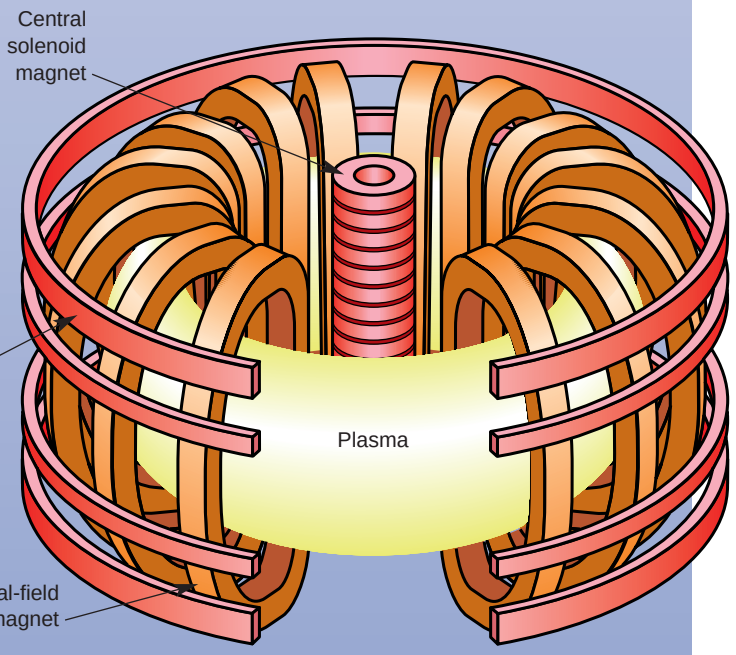
Half Century of Research

Magnetic fusion energy research has been under way for more than a half century and was one of Lawrence Livermore's original programs. The idea was classified because the concept uses the energy released by the same reaction that takes place in a hydrogen or thermonuclear bomb. In the late 1950s, the research program, called Project Sherwood, was partially declassified because it was viewed as a long-term effort without immediate military application and one that would benefit greatly from international cooperation.

Considerable progress has been made in the last 20 years at Livermore and other research centers in meeting the scientific challenges of attaining the combination of temperature, density, and confinement time necessary to promote fusion reactions. At one point, several different types of devices, including Livermore's magnetic "mirror" design, were pursued within the national program. Budget constraints, however, led to the adoption of the tokamak as the principal design for the U.S. program, with other approaches being explored at lower levels of resources.

The long-standing goal of magnetic fusion energy is to produce abundant, environmentally acceptable electric energy from a fusion-powered reactor. In fusion power plants, the heat from deuterium–tritium fusion reactions would be used to produce steam for generating electricity. Deuterium is abundant and easily extracted from ordinary water (about one water molecule out of every 6,000 contains deuterium). Tritium can be made from lithium, a plentiful element in Earth's crust.

One kilogram of deuterium–tritium fusion fuel would produce the same energy as 30 million kilograms of coal. Other major advantages include no chemical combustion products and therefore no contribution to acid rain or global warming, radiological hazards that are thousands of times less than those from fission, and an estimated cost of electricity comparable to that of other long-term energy options.



In a tokamak, magnetic fields from surrounding magnets confine a plasma fuel of hot, ionized gas within a hollow, doughnut-shaped vacuum chamber.

National Laboratory. In fact, the collaboration is the biggest user of NERSC facilities. The current simulations typically require from 10 to 20 hours to complete using NERSC's most powerful machines.

With the latest generation of supercomputers, says Cohen, "We can do bigger pieces of the simulation, with more physics." Nevertheless, no computer yet built can perform simulations requiring six orders of magnitude in spatial size, eight to nine orders of magnitude in time scale, and three dimensions in space. As a result, "We have to be clever about reducing the scales and still obtaining accurate results," says Cohen.

The hardware advances have been accompanied by the equally impressive development of efficient algorithms with which to solve the equations that form the basis of plasma simulation. The algorithms are of two kinds, particle-in-cell (PIC) models and continuum models, depending on how they track simulated electrons and ions in space and time. PIC models track individual electrons and ions; continuum models solve equations that do not involve individual particles.

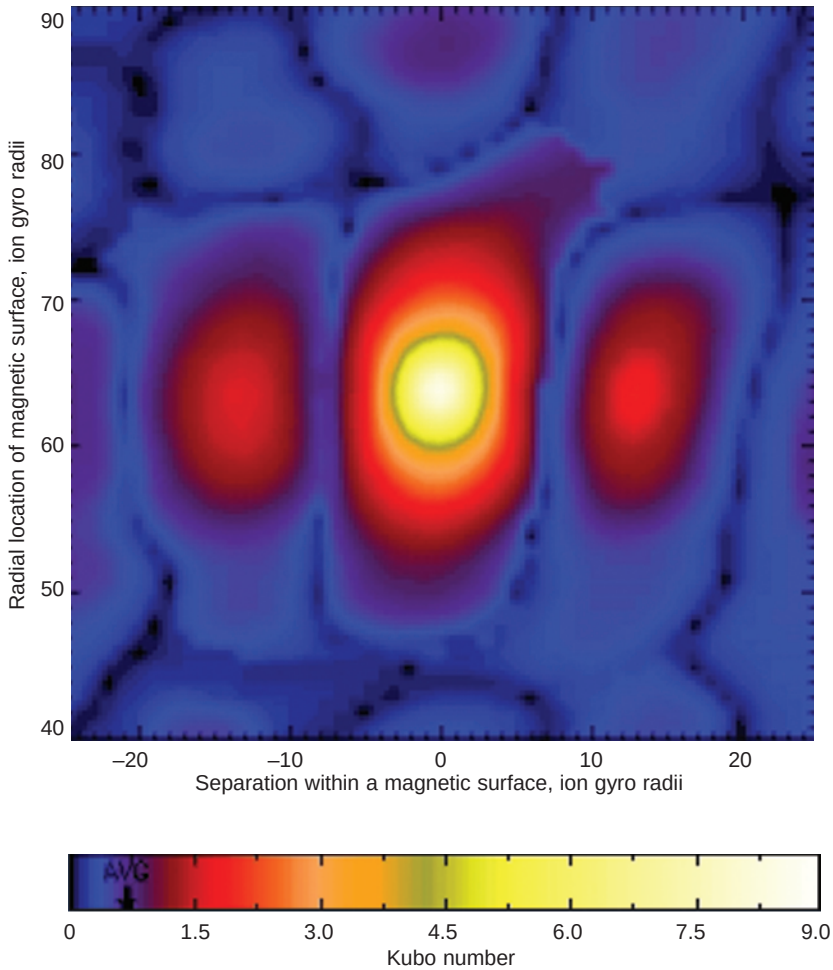
The national effort is developing both kinds of algorithms because they offer a valuable means of verifying new codes. "Together, the two kinds of algorithms provide a balanced scientific approach to understanding microturbulence," says Nevins. Each approach, however, pushes the limits of current supercomputer capability.

PIC and continuum algorithms can be used in two geometric representations: global and flux tube. Global simulations model the entire plasma core of a tokamak, whereas flux tube simulations represent a more limited area. Here again, says Nevins, the two geometric approaches serve as a useful cross-check on the results obtained from each other.

With the increased speed of microprocessors, additional memory, massively parallel supercomputers, and advanced algorithms, important progress has been made in the past few years in modeling microturbulence. Nevins points to significant improvements in the comparisons of simulations to experiment results, in the agreement of results from codes developed by collaborators from different centers of magnetic fusion energy research, and in the increasingly thorough and accurate physics content of the models.

An important aspect of the code work is developing new tools to analyze and visualize the simulation results. Data analysis and visualization provide the bridge between the microturbulence simulation and experimental research. Nevins has developed GKV, a program that allows the user to easily compute, analyze, and display results (in presentation-quality form) easily from microturbulence simulation data. The program is used by researchers nationwide.

A strong numerical model of microturbulence, combined with better



Livermore's GKV program allows users to interactively compute, analyze, and display data from microturbulence simulations. This GKV image displays the Kubo number, or the number of times an ion circulates around a turbulent eddy before that eddy dissipates, versus the separation within a magnetic surface and the radial location of the magnetic surface. Distances are measured in ion gyro radii, that is, the radius of a typical ion's orbit as it gyrates about a magnetic field line.

data analysis and visualization tools, is aiding the interpretation of experimental data and the testing of theoretical ideas about microturbulence and how to control it. The simulations are also helping scientists to plan future experiments. In addition, continued progress in code development may stimulate advances in the understanding of astrophysical plasmas and turbulence in fluids.

Theorists Now Getting Respect

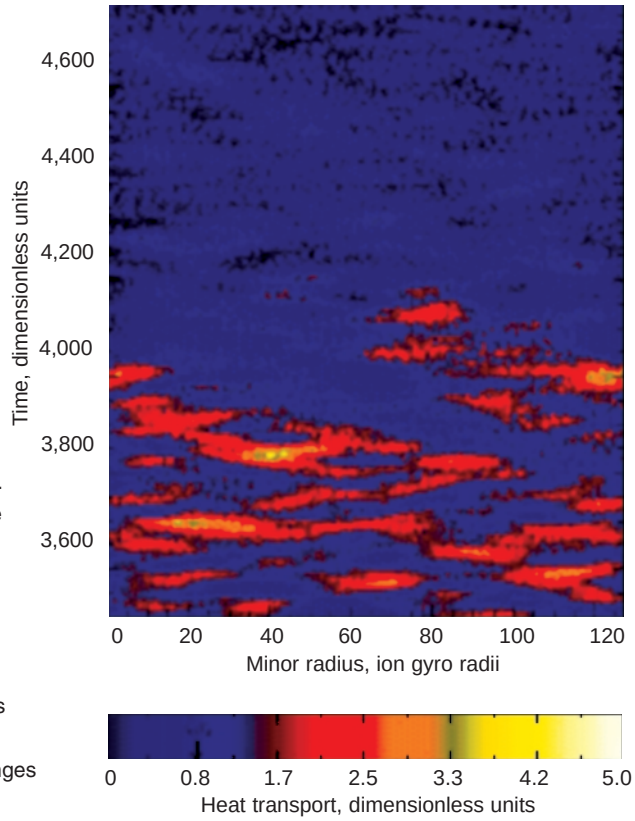
Cohen recalls that five years ago, experimentalists paid much less attention to theorists regarding plasma turbulence. Today, however, simulations do such a good job in predicting experimental results that "experimentalists are really paying attention to the codes." Simulations, he says, have achieved such a level of fidelity to the underlying plasma physics that they can often be used as a tool for experiments regarding plasma microturbulence.

Nevins points out that the cost of doing simulations is nearly negligible compared with the cost of building and running a new fusion ignition experiment (around $1 billion to $2 billion). "Inexpensive but increasingly realistic simulation capability will continue to have immense leverage on relatively expensive experiments," he says.

He also points out that numerical simulation has a distinct advantage over experimental observations of microturbulence: The simulations give users access to virtually any portion of the plasma in time or space. Simulations use "synthetic" diagnostic tools, which mimic the signal that an experiment would be expected to produce on an experimental diagnostic.

Says Nevins, "We can put in better diagnostics on a computer code than we can during an experiment." What's more, the physics underlying observed microturbulence can often be ambiguous. "With a simulation, we can turn different physics on and off to isolate what is driving the microturbulence observed in the experiment."

Not only have recent simulations produced a clearer understanding of microturbulence, but they have also provided a few surprises as well. For example, scientists have long puzzled over large but transient bursts of heat that are transported out of the core plasma by microturbulence eddies. "We would have expected the transfer of heat from the plasma core out to the walls to be homogeneous because of the small eddies caused by microturbulence. Instead, we've seen large, intermittent bursts 10 times the size of the eddies," Nevins says.



Tokamak experiments have detected puzzling bursts of heat produced by microturbulence. Recent simulations show the same phenomenon, where the heat pulses are indicated by bright regions. Researchers have noticed the similarity between these heat pulses and other instances of self-organized criticality, which resemble the sudden occurrence of avalanches as grains of sand are slowly added to the top of a sandpile. The simulation also shows the spontaneous transition in time from a state of high heat transport, with many heat pulses, to a state of low heat transport, in which the heat pulses are largely absent. This transition was caused by microturbulence-induced changes in the plasma's flow shear.

Learning from Sandpiles

Nevins and others have noticed that these intermittent spikes are characteristic of "self-organized criticality," a phenomenon that occurs in a system when certain key parameters reach critical values. Self-organized criticality is responsible, for example, for the occurrence of sudden avalanches as grains of sand are slowly added to the top of a sandpile. The Livermore simulation team is using the insights derived from self-organized criticality to account for these unexpected bursts of heat, which apparently are the combination of many turbulent eddies.

An important recent addition to the simulation codes is a phenomenon called flow shear that works to dampen microturbulence and thereby improve plasma confinement. The plasma rotates (flows) within each of the nested magnetic surfaces defined by individual magnetic field lines. The term flow shear describes spatially

localized changes in the rate of plasma rotation. The flow shear sharply reduces the rate at which heat is transported out to the cold plasma edge by stretching and tearing apart the microturbulence eddies.

Nevins explains that heat must travel to the outer plasma edge across many nested magnetic surfaces. When the magnetic surfaces rotate relative to each other, the eddies transporting the heat tend to dissipate. He offers the analogy of a busy freeway, with each lane of cars (magnetic surface) at a different speed. If a driver must hand a rubber band (microturbulence eddy) to a driver in another lane passing by at a much faster rate, the rubber band will soon break and not be passed to the driver in the faster lane.

Flow shear can appear spontaneously during a magnetic fusion energy experiment. When that happens, says Cohen, "We get it for free." Flow shear can also be created experimentally by applying a twisting force (torque) to the plasma using, for example, intense beams of neutral hydrogen atoms. The force pushes on the center of the plasma core to create barriers to heat transport.

"We want to understand much better how flow shear functions so we can know how much to apply to effectively control microturbulence," says Cohen. Precisely applying flow shear could increase plasma confinement and significantly decrease the cost of new experimental facilities.

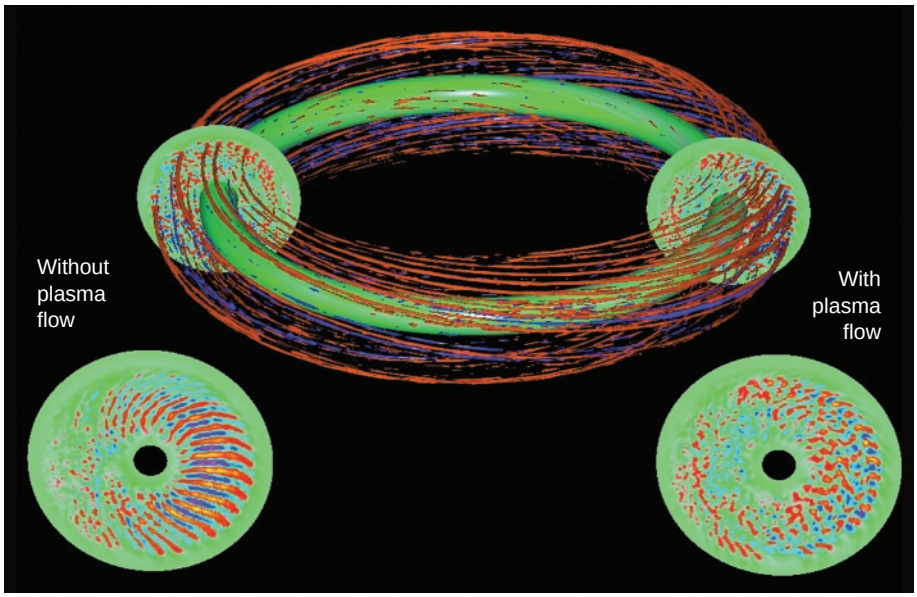
The national collaboration is working to provide a suite of modular, complementary computer programs, each with an identical user interface. Together, the modules will constitute a comprehensive code for microturbulence simulation, data analysis, and visualization. The modular architecture will enable physics simulations on diverse computer architectures with much less effort than current software approaches demand. Says Nevins, "We want to revolutionize the fusion community's ability to interpret experimental data and test theoretical ideas. The result will be a much deeper understanding of microturbulence."

As for the codes themselves, the collaborators are working on consolidating programs developed by individual research groups. Another area of activity is improving the physics simulated by the codes, for example, by refining the simulated diagnostic instruments and more accurately modeling the role of electrons involved in microturbulence.

Nevins is hopeful that by making the simulations easier to run and analyze, even more experimenters will choose to use them. "It was a heroic feat to make the codes work, but now we need to make them available to the experimental community," he says. "We want these tools to be used more widely so that we expand the use of microturbulence simulation well beyond the existing small group of code developers. Our goal is to have experimentalists run the codes and understand the results much faster."

Better simulation tools could bring dependable fusion energy much closer to reality. That would be welcome news for a nation recently reminded about the fragility of steady energy supplies and prices.

—Arnie Heller



Simulation of a tokamak and two plasma cross sections. In the simulation that produced the plasma cross section on the left, the flow shear was suppressed, while the self-generated flow shear was retained in the simulation that produced the cross section on the right. These cross sections illustrate the role of flow shear in suppressing plasma microturbulence and thereby forming barriers to unwanted heat transport. This simulation was created using the GTC code developed at the Princeton Plasma Physics Laboratory.

Key Words: fusion, macroturbulence, magnetic fusion, microturbulence, National Energy Research Scientific Computing Center (NERSC), plasma, Scientific Discovery through Advanced Computing (SciDAC), tokamak, turbulence.

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Present at the Creation

When they synthesized elements 114 and 116, Russian and Livermore scientists confirmed decades-old predictions of the existence of superheavy elements with comparatively long lifetimes.

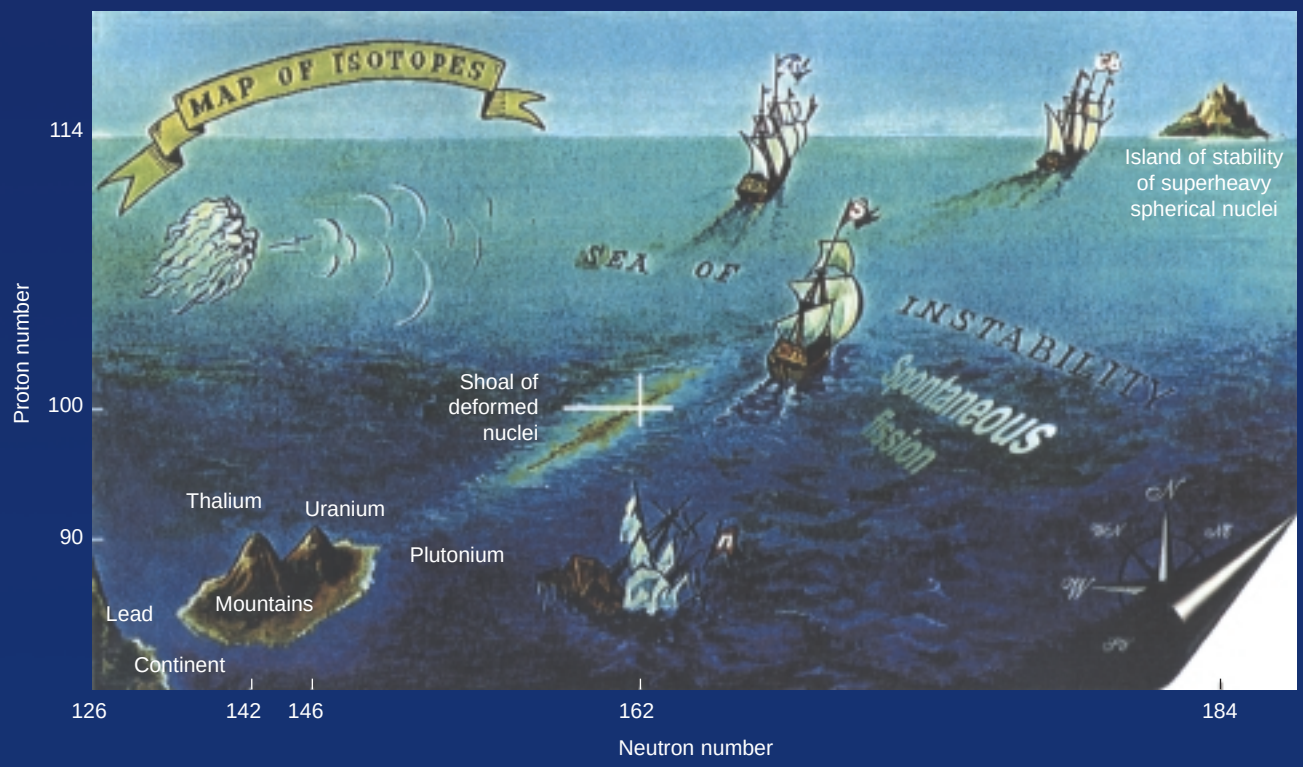
ELEMENTS that do not exist in nature—that have been created in a laboratory—are unstable. After hours or days of one element bombarding another with enough energy for both to fuse, the resulting new element typically is born and begins to decay instantly.

Neptunium and plutonium (elements 93 and 94) were the first elements created in a laboratory, at the University of California at Berkeley in 1940. Scientists have since fabricated many more elements, each one heavier and with a shorter half-life than the one before it.

In the 1960s, a few physicists predicted that some elements around element 114 would survive longer than any of their synthesized predecessors. Early estimates for the half-lives of these more stable elements were as high as billions of years. Later computer modeling reduced the anticipated half-lives to seconds or minutes before the element began to decay.

Half-lives of seconds or minutes may seem brief. But consider that various atoms of element 110 created in the laboratory have had half-lives ranging from 100 microseconds to 1.1 milliseconds. The only atom of element 112 that had been created before 1998 had a lifetime of 480 microseconds. As described further in the box on p. 21, the long-lived nuclei of elements around element 114 would comprise an "island of stability" in a "sea" of highly unstable elements.

When a collaboration of Russian and Livermore scientists at the Joint Institute for Nuclear Research in



Map of the voyage to the island of stability.

Dubna, Russia, created element 114 in 1998, the first atom survived for 30 seconds before it began to decay, a spontaneous process that leads to the creation of another element with a lower number on the periodic table. (See the box on pp. 18–19 for more information on stability and instability.) A total of 34 minutes elapsed before the final decay product fissioned, splitting in two the surviving nucleus. These lifetimes may seem brief, but they are millions of times longer than those of other recently synthesized heavy elements.

Since that groundbreaking effort in 1998, the team has created another atom of element 114. This one has a different number of neutrons and thus a different mass, thereby making it a different isotope of element 114. The team has also created several previously undiscovered isotopes of elements 112, 110, and 108 to which element 114 decayed. More recently, the team added element 116 to the periodic table with the creation of three atoms of the element in a series of experiments.

Nuclear chemist Ken Moody leads the Livermore portion of the international collaboration. “In 1998, we proved that there really was an island of stability,” he said. “We proved that years of nuclear theory actually worked.”

The collaboration began in 1989. with heavy element chemist Ken Hulet representing Livermore and Yuri Oganessian, scientific director of the Flerov Laboratory of Nuclear Reactions at the Joint Institute, leading the Russians. In the early 1990s, the U.S.–Russian team discovered two isotopes of element 106, one isotope of 108, and one of 110 at the Dubna institute.

“In 1990, when Ron Lougheed, who has since retired, and I went to Dubna, we were the first U.S. scientists to perform experiments at that institute,” adds Moody. “Remember what was happening then. The Berlin Wall had just fallen, and Eastern Europe was in turmoil. The early days of the collaboration were definitely interesting.”

Photo of Russian–Livermore team.

Forty Days and Nights

Noah's flood could have come and gone in the time it took the collaboration to create the first atom of element 114. For 40 days of virtually continuous operation, calcium ions bombarded a spinning target of plutonium in Dubna's U400 cyclotron. While the first atom of element 114 was actually created on November 22, 1998, Russian researchers discovered it in data analysis and communicated the news to Livermore on December 25, 1998—quite the Christmas present.

A Primer on Stability and Instability

Why should element 114 be so much more stable and long-lived than so many of its synthesized predecessors? The answer lies in basic chemistry.

The nucleus of an atom is surrounded by one or more orbital shells of electrons. The electron configurations of atoms of the many elements vary periodically with their atomic number, hence "the periodic table of the elements."

Elements with unfilled shells seek out electrons in other elements to fill them. These include carbon, oxygen, and all of the "reactive" elements that want to react with other elements. This is the basis of covalent bonding. The noble gases (on the far right column of the periodic table) have a completely filled outer electron shell and hence are highly stable. They are termed noble because they are "aloof," with no desire to react with other elements.

Protons and neutrons are in analogous shells within the nucleus. The proton shells of helium, oxygen, calcium, nickel, tin, and lead are completely filled and arranged such that the nucleus has achieved extra stability. The atomic numbers of these elements—2, 8, 20, 28, 50, and 82—are known as "magic numbers." These same numbers plus 126 are magic numbers for neutrons. Notice that the magic numbers are all even. No truly stable element heavier than nitrogen has an odd number of both protons and neutrons. Elements with even numbers of protons and neutrons make up about 90 percent of Earth's crust.

A nucleus is "doubly magic" when the shells of both the protons and neutrons are filled. Lead-208 has 82 protons and 126 neutrons, both of which are magic numbers. Lead-208 is thus doubly magic and seems to be virtually eternal.

A long-lived, stable element such as lead does not decay. However, all elements with an atomic number greater than 83 (bismuth) exhibit radioactive decay. Decay may happen in several ways. For heavy elements, an unstable or radioactive isotope usually decays by emitting helium nuclei (alpha particles) or electrons (beta particles), leaving a daughter nucleus of an element with a different number of protons. This process typically continues until a stable nucleus is reached. Plutonium, for example, decays ultimately to lead.

The heavy elements that have been created in the laboratory are so unstable that they decay almost immediately and have extremely

Periodic table

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yitrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	See Lantha-nides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	See Acti-nides	104 Rf Rutherfordium	105 Ha Hahnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110	111	112		114		116		

Lanthanides	57–71 Ln* Lanthanides	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
Actinides	89–103 An* Actinides	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

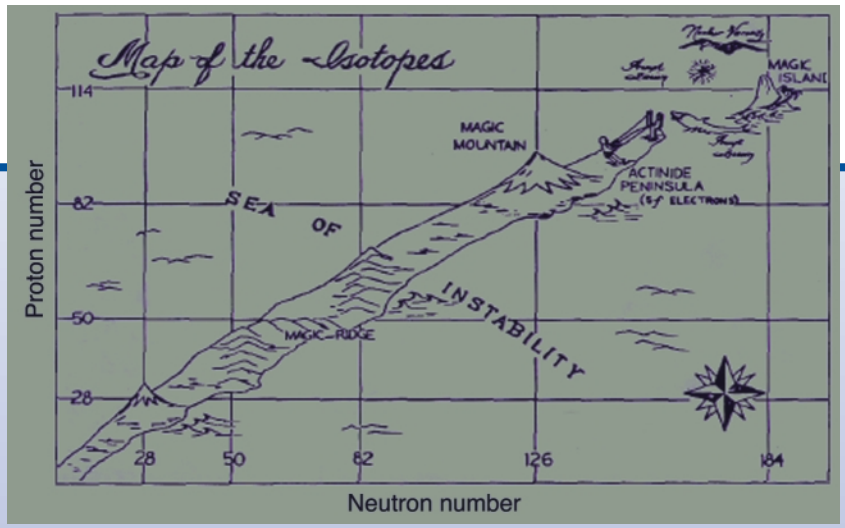
The box on p. 22 shows the "recipe" for the early Dubna experiments that created isotopes of element 114. Plutonium, with an atomic number, or Z, of 94, and calcium, $Z = 20$, add up to the necessary $Z = 114$. By fusing plutonium-244, an isotope of plutonium with 150 neutrons, and calcium-48, a neutron-rich isotope with 28 neutrons, a compound nucleus with 114 protons and 178 neutrons (150 + 28) would in theory be possible. In fact, however, when the plutonium-244 and calcium-48 nuclei collide with enough energy to overcome their mutual electrostatic repulsion, the compound nucleus has excess energy. A few neutrons evaporate to de-excite the nucleus and produce an isotope with 175 neutrons.

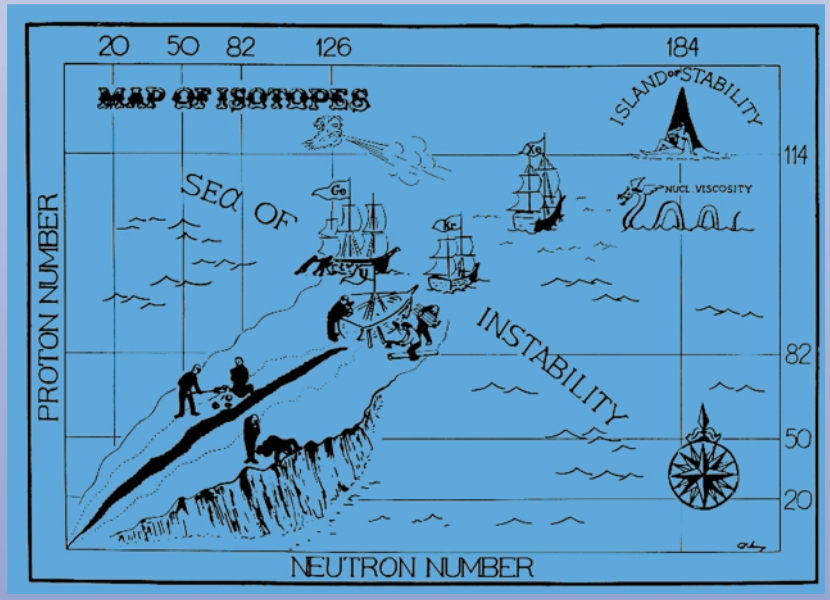
To discover whether new elements were created by the bombardment of plutonium, the team was interested in finding "events" comprising a series of alpha decays ending with spontaneous fission. In alpha decay, an isotope loses an alpha particle, which is two protons and two neutrons (or a helium nucleus). For example, an atom of element 114 with 175 neutrons (described as isotope 114-289) would emit an alpha particle, thereby becoming isotope 112-285, having lost 2 protons and 2 neutrons. The atom of 112-285 would become 110-281, which would become 108-277. At some point, fission would occur, ending the process.

At the same time, however, unwanted nuclei generated by short half-lives and thus lifetimes. How quickly a particular isotope decays is measured by its half-life. Plutonium-239, which decays very slowly, has a half-life of about 24,000 years, while plutonium-238's half-life is just 88 years. Half-lives are a result of a statistical process. If an experiment produces only one atom, then a half-life cannot be determined. Thus, with one or a few atoms, scientists talk instead about lifetimes.

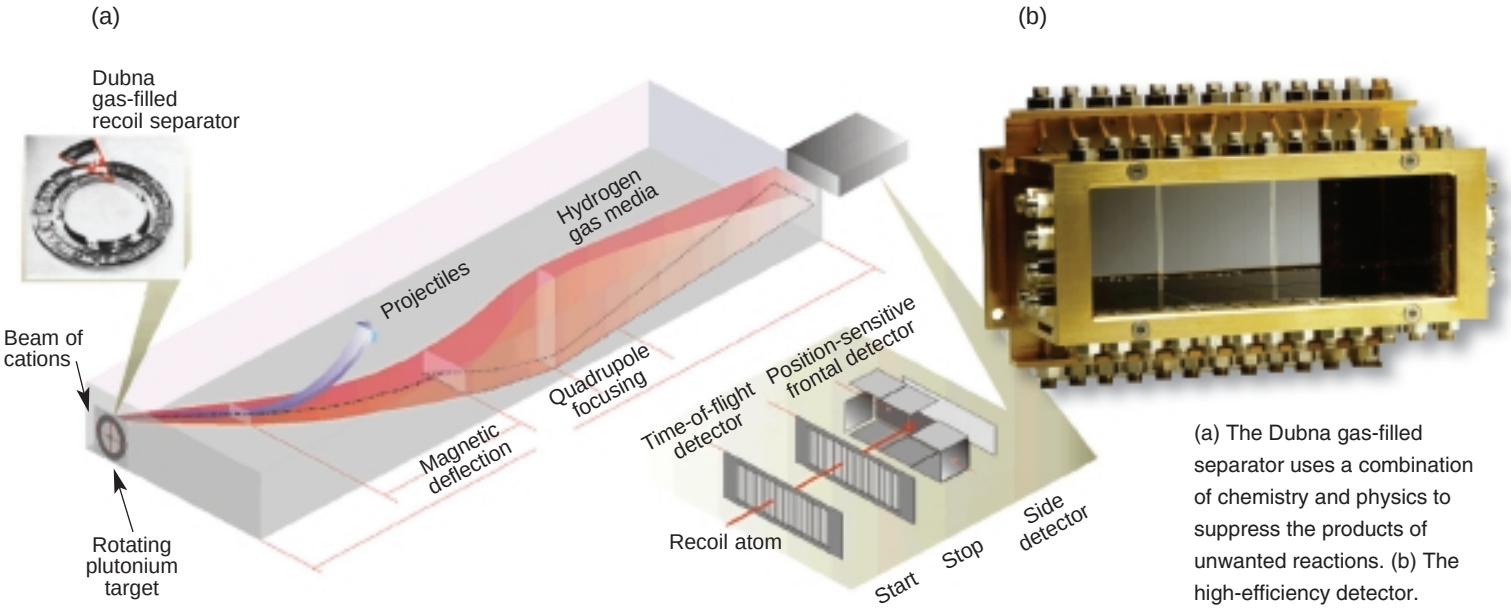
In the mid-1960s, a physicist in the U.S. predicted that the next magic proton number above 82 would be 114, not 126, and that an atom with a doubly magic nucleus of 114 protons and 184 neutrons should be the peak of an island of stability. Russian scientists had come to the same conclusion at about the same time.

In the years since, increasingly sophisticated computer models have indicated that element 114 would exhibit significant nuclear stability even with neutron numbers as low as 175. Note that element 114 is expected to lie in the same column (or group) of the periodic table as lead. The two elements are expected to share many properties.





Nuclear theory (top) in the U.S. and (bottom) in Russia, in about 1969.



(a) The Dubna gas-filled separator uses a combination of chemistry and physics to suppress the products of unwanted reactions. (b) The high-efficiency detector.

the experiment also undergo alpha decay and fission, mimicking the decay sequence of element 114. Trillions of these unwanted nuclei are produced every day, whereas the expected production rate for an element 114 isotope was much less than one atom per day. To deal with the problem of unwanted nuclei in earlier experiments, Dubna scientists had developed a gas-filled mass separator to separate unwanted nuclei from the desired ones. "It worked marvelously," says Moody.

Heavy-element reaction products recoil from the spinning plutonium target wheel and enter the mass separator, a chamber filled with low-pressure hydrogen gas confined between the pole faces of a dipole magnet. The magnetic field is adjusted so that, for the most part, only the nuclei of interest pass through to the detector array.

The desired nuclei are focused with a set of magnetic quadrupoles, pass through a time-of-flight counter, and are captured by a position-sensitive detector. A signal from the time-of-flight counter allows the team to distinguish between the effect of products passing through the separator and the radioactive decay of products that are already implanted in the detector. The flight time through the counter is also used to discriminate between low- and high-*Z* products, because heavier elements travel more slowly. The position-sensitive detector lowers the rate of background interference, allowing scientists to identify and ignore unwanted products.

During 40 days in November and December 1998, with ten-thousand trillion ions per hour of calcium-48 bombarding the plutonium target, the team observed the signals of just three spontaneous fission decays. Three synthesized compound nuclei had been created and passed through the separator before fissioning. Two of them lasted about 1 millisecond each and proved to be products from the decay of the nuclear isomer of americium-244.

Only one of the events involved an implant in the detector followed by three alpha decays in the detector array. This isotope of element 114 (114-289) had a lifetime of 30.4 seconds. It decayed to element 112, which, with a lifetime of 15.4 minutes, decayed to element 110. Element 110, with a lifetime of 1.6 minutes, then decayed to element 108, which decayed by spontaneous fission.

In 2000 and 2001, the collaboration performed three experiments in which a curium-284 target was bombarded with calcium-48 ions to create element 116. The team chose this combination of isotopes because they would produce isotopes of element 116 that should decay to the previously observed isotopes of element 114.

Researchers produced the super-heavy isotope 116-292 once in each of these experiments. They also created some other isotopes repeatedly. Isotopes 114-288, 112-284, and 110-280 have been found five times, lending credibility to several experimental results. However, the first atom of 114-289 with the 30.4-second lifetime has yet to be replicated.

In the Final Analysis

The recipe for element 114 on p. 22 refers to the analysis of 7 gigabytes of data from the first experiments. The team has since accumulated another

A Stormy Voyage to the Island of Stability

As of November 2001, scientists throughout the world had synthesized 20 elements that do not exist in nature. The ones up to meitnerium (109) have been given official names. Elements 110, 111, 112, 114, and 116 will not be named until their existence has been corroborated with several experiments or by several different groups. Recall that one of the fundamental tenets of science is reproducibility.

In 1940, Ed McMillan and his team at Berkeley bombarded uranium with neutrons to create neptunium (element 93). Then Glenn Seaborg and his colleagues created plutonium-238, the first isotope of plutonium (element 94), through the decay of neptunium-238, which they produced by bombarding uranium with deuterium (heavy hydrogen). Elements 99 and 100 were discovered in the debris of the first hydrogen bomb test in 1952 from the simultaneous capture of many neutrons by uranium. The heavy, highly radioactive uranium isotopes decayed quickly by beta emission down to more stable isotopes of elements 99 (einsteinium) and 100 (fermium). Elements 95, 96, 97, 98, and 101 were created by irradiating heavy nuclei with beams of alpha particles to boost the atomic numbers two steps at a time.

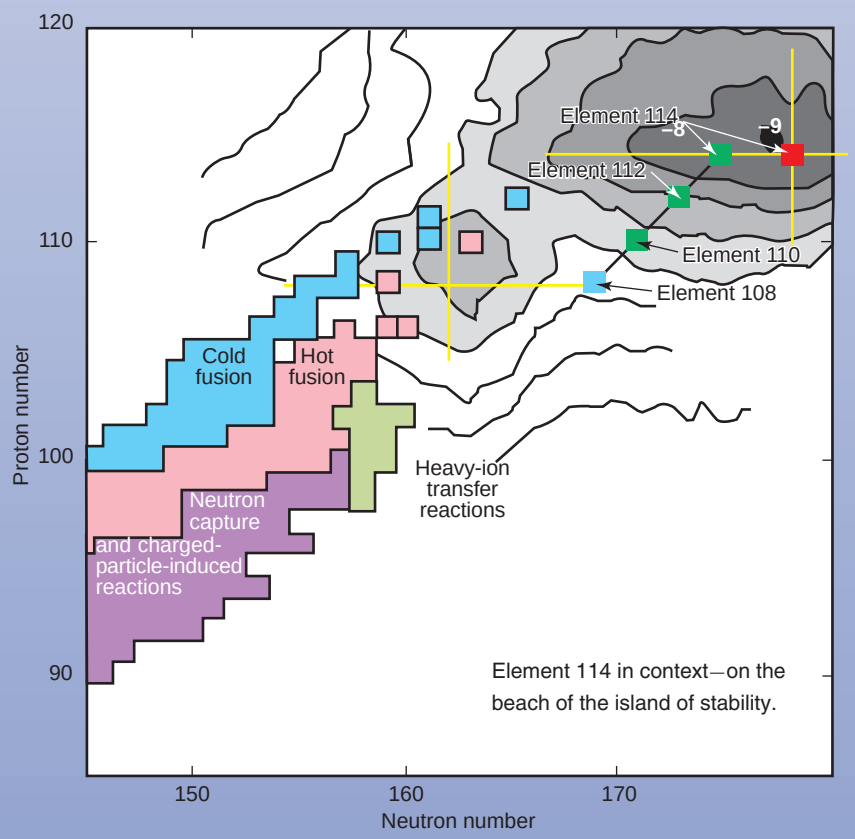
Beginning in the late 1950s, the new particle accelerators were capable of accelerating ions heavier than helium. First, ions of the lightest elements were directed at the heaviest elements. But it took excess energy to cause them to fuse, producing a very hot nucleus that tended to fission almost immediately. Known as "hot fusion," this method yielded elements 102 through 106 by 1974. Many of these experiments included Livermore scientists.

In 1974, Yuri Oganessian at the Joint Institute at Dubna found that if heavier ions are directed at lead and bismuth, less energy was needed to create new elements. These two elements are extra-stable, and thus the resulting compound nucleus has less energy and is more likely to remain intact. This process is known as "cold fusion," not to be confused with the discredited fusion energy process of the same name. Even with cold fusion, so few nuclei of the new element are produced during an experiment that existing detection techniques were not sensitive enough to find them.

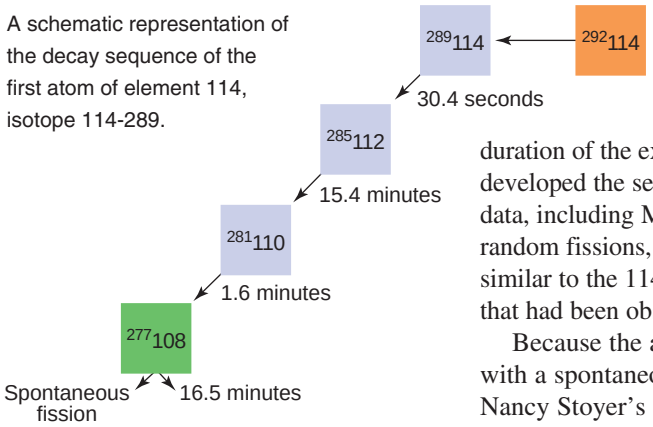
The field of synthesizing ever heavier elements went on hiatus for several years until sophisticated new separation and detection methods were developed in the early 1980s in Germany. German researchers were then able to create and detect elements 107, 108, and 109 in experiments that have since been corroborated such that these synthetic elements now have names. They also created isotopes of 110, 111, and 112, but these results have not yet been fully corroborated.

The German group, the Consortium for Heavy Ion Research at Darmstadt, Germany, has produced an isotope of element 112 that decayed into the same isotope of 110 that the Dubna–Livermore team found in 1994. This isotope had the same energy and lifetime, which is encouraging validation.

The voyage to the island of stability has been a stormy one. It took until 1998 to even reach the beach. As shown in the figure below, the island's peak is still tantalizingly just out of reach.



Element 114 in context—on the beach of the island of stability.



A schematic representation of the decay sequence of the first atom of element 114, isotope 114-289.

23 gigabytes of data, all requiring extensive analysis to verify the times and energies of the alpha decays. Valid decay sequences must fall within the alpha decay time and energy parameters of what is known as the Geiger–Nuttall relationship.

Scientists at Livermore and Dubna analyzed the data in parallel. Livermore gave the Dubna institute a computer workstation for the Russian scientists to use on that mountain of information. Nuclear chemists John Wild and Nancy Stoyer analyzed the data at Livermore. "These duel analyses were independent but were calibrated. In the end, our results agreed," says Wild.

The team must also confirm that the sequences they saw were not composed of random events. "The problem of randomness is real, especially for long-lived elements," adds Wild. "The longer the lifetime of a member of a decay sequence, the greater the probability that the decay could be random."

A novel Monte Carlo method to estimate the probability of whether a decay chain was random or the real thing was the brainchild of nuclear chemist Mark Stoyer. It is a pseudo-random number generator that places random fission events into the real data throughout the duration of the experiment. Nancy Stoyer developed the search code that sifted the data, including Monte Carlo–generated random fissions, for decay sequences similar to the 114-289 decay sequence that had been observed experimentally.

Because the actual decay chains end with a spontaneous-fission event, Nancy Stoyer's search algorithm looks backward from the planted fission event for candidate alpha-decay chains that match actual decay chains and end with a fission event. The number of returned "accidental" decay chains defines the probability that a decay sequence is random. For the first atom of element 114, the random probability was 0.6 percent. "If we eliminate decay chains in which all alpha events do not meet the Geiger–Nuttall relationship," says Moody, "the random probability falls to 0.06 percent. That's fantastic."

Recipe for a New Element

A Livermore chemist with a sense of humor developed this recipe to describe the creation of element 114.

Ingredients:

- 2 grams calcium-48, a rare neutron-rich isotope of calcium. Out of every 100,000 atoms of calcium, only 187 atoms are calcium-48.
- 30 milligrams plutonium-244, the most neutron-rich, long-lived isotope of plutonium. The world's supply of this isotope is only 3 grams.
- The U400 cyclotron at Dubna, Russia, to accelerate calcium ions to 10 percent the speed of light (236 megaelectronvolts).
- A gas-filled recoil separator for removing unwanted reaction products.
- A position-sensitive detector for capturing decays of reaction products.
- 2 computers, one for data acquisition and another for data analysis.
- Numerous Russian technicians and accelerator operators.
- 19 Russian scientists.
- 5 American scientists.

Directions: Combine the first seven ingredients, using 0.3 milligrams per hour of calcium-48. Add lots of patience, a dash of luck, and a dollop of inspiration. Simmer for about 6 months, 24 hours per day, 7 days a week. Use the last two ingredients to analyze 7 gigabytes of data for signature decay sequences of element 114. Garnish with several papers describing the results.

Serves: Very few. In two experiments, makes one atom of 114-289, the lifetime of which is 30 seconds, and two atoms of 114-288, each with a lifetime of 2 seconds.

New Elements Still to Come

The Livermore researchers are continuing its work to explore the southwest shores of the island of stability. With funding from the Laboratory Directed Research and Development program, they have begun efforts to add elements 115 and 113 to the periodic table. They are in the process of sending 22 milligrams of pure americium-243 to Dubna for the work on element 115.

Current exploration of the island of stability, or its beaches, is limited to stable targets and projectile beams. There exists no suitable combination of projectile and target to produce 114-298, the long-predicted highly stable isotope. The isotopes 114-289 and 114-288 require the most neutron-rich isotopes of plutonium and calcium. In the future, when radioactive beam accelerators are capable of producing intense beams of even more neutron-rich isotopes, researchers may venture farther toward the center of the island. For example, calcium-50 has a half-life of 14 seconds, far too short to gather material together to put into a conventional ion source. However, plans are for a radioactive beam facility to produce calcium-50 and accelerate it to energies required for the experiments well before it can decay. Thus, an isotope of element 114 with a mass of 290 or 291, two neutrons closer to the center of the island, may well be possible.

As scientists continue to explore for new elements, they expect that more spherical and longer-lived isotopes will be produced, which will most certainly require more sensitive detection schemes. Challenges abound.

Livermore researchers also want to study the chemical properties of elements 112 and 114. The combination of chemical and nuclear properties defines the usefulness of any nuclide. Most heavy elements exist in such small amounts, or for such short times, that no one has pursued practical applications for them. However, several heavy elements do have uses—americium is used in smoke detectors, curium and californium are used for neutron radiography and neutron interrogation, and plutonium is elemental in nuclear weapons. Although elements 114 and 116 have no immediate use, they do exist, and more of them can be manufactured when uses for them are found. Adds Moody, "Showing that the isotopes of element 114 produced by the collaboration have unique chemical properties will also provide proof that they are indeed a new element."

—Katie Walter

Key Words: element 114, element 116, heavy elements, island of stability, Joint Institute for Nuclear Research in Dubna, Russia.

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Rapid Field Detection of Biological Agents

FOR years, experts in terrorism have been warning that a terrorist attack with biological agents is not a question of "if" but "when." As recent events have proved, when is now.

For almost a decade, researchers at Lawrence Livermore, working on the when-is-now premise, have been developing systems that can rapidly detect and identify biological agents, including pathogens such as anthrax and plague. (For more background on Livermore's research against bioterrorism, see *S&TR*, June 1998, pp. 4–9, and May 2000, pp. 4–12.) Among such systems are the Handheld Advanced Nucleic Acid Analyzer (HANAA) and the Autonomous Pathogen Detection System (APDS).

The Handheld Advanced Nucleic Acid Analyzer can detect biological pathogens in the field.

Although HANAA and APDS are of different sizes and made for different situations, they have a common purpose: to get results, fast. Lawrence Livermore biological scientist Richard Langlois explains, "There are any number of laboratory tests available right now to analyze pathogens. They all require getting a sample and then transporting it to a laboratory for processing. Our systems use new instrumentation and methods that provide faster and more timely results, on the spot. Faster results mean the responders can act quickly and begin treatment earlier."

HANAA in Hand

About the size of a brick, the HANAA biodetection system can be held in one hand and weighs less than a kilogram. The system was designed for emergency response groups, such as firefighters and police, who are often first on the scene at sites where bioterrorism may have occurred. Each handheld system can test four samples at once—either the same test on four different samples or four different tests on the same sample. HANAA can provide results in less than 30 minutes, compared with the hours to days that regular laboratory tests typically take.

The process of detecting and identifying what's in a sample works like this. The operator prepares the samples by putting them in a liquid buffer and adding chemicals. A tiny disposable plastic tube holding about 0.02 milliliter of the prepared liquid is then inserted into the system. Many copies of a sample's DNA are needed to analyze it and identify its makeup. HANAA uses a technique called the polymerase chain reaction (PCR), which amplifies agent-specific DNA fragments to a detectable level. In PCR, an aqueous sample is heated close to the boiling point and then cooled many times (40 times in HANAA). Every time the DNA is heated, the two intertwined strands of DNA unwind and come apart. As the sample cools down, the DNA makes a copy of itself. Thus, at the end of each cycle, the amount of DNA is doubled.

To detect the DNA in a sample, a synthesized DNA probe tagged with a fluorescent dye is introduced into the sample before it is inserted into the heater chamber. Each probe is designed to attach to a specific organism, such as anthrax or plague. Thus, the operator must have an idea of what substances might be involved. "The system doesn't test for all unknowns," says Langlois. "A responder has to decide what kinds of pathogens to test for ahead of time and set up the system accordingly." If that organism is present in the sample, the probe attaches to its DNA, which is then amplified during the PCR process, releasing the fluorescent tag. HANAA

measures the sample's fluorescence and the presence (or absence) of the targeted organism.

One of the big breakthroughs for the handheld system involved the design of a small silicon heater chamber for the heating and cooling cycle, a concept developed at Livermore by Allen Northrup, a former Laboratory scientist. "The commercial thermocyclers used for standard laboratory tests are pretty big, ranging from the size of a microwave oven to a large desk," notes Langlois. "A typical large thermocycler takes about 3 minutes to cycle through one heating and cooling cycle, so a complete analysis requires 2 to 3 hours." In the HANAA system, the thermal cycling process occurs in tiny silicon heater chambers, micromachined by Livermore's Center for Microtechnology. Each chamber has integrated heaters, cooling surfaces, and windows through which detection takes place. Because of the low thermal mass and integrated nature of the chambers, they require little power and can be heated and cooled more quickly than conventional units. The mini-chambers typically cycle from about 55°C to 95°C and back to 55°C in about 30 seconds.

Using this technique, the HANAA system could, in principle, detect as few as 10 individual bacteria in one-hundredth of a milliliter in less than 30 minutes. The system has the potential of saving many lives by saving time—anthrax, for example, is highly treatable if detected early.

The Laboratory has a cooperative research and development agreement for HANAA with Environmental Technologies Group (ETG), a chemical and biological detector company and subsidiary of Smith's Industries, based in Baltimore, Maryland. ETG expects to have a commercial version of HANAA available early this year. Ron Koopman, special projects manager for the Chemical and Biological National Security Program at Livermore, notes that HANAA is essentially ready to go at this critical juncture because of the forward-thinking efforts begun in the previous decade. "A number of people recognized the vulnerability of the country to bioterrorism a long time ago," he says. "In 1996, although bioterrorism seemed far away and was something we hoped would never happen, the Laboratory and members of the defense community decided to invest in the research, just in case. Thanks to that investment, we now have something to put in the hands of people to protect us all, something that can help during the current crisis and in the long run."

A Bio "Smoke Detector"

Whereas HANAA can be hand-carried to sites at which an attack is suspected to have happened, the APDS is stationed in one place for continuous monitoring and is designed to work much like a smoke detector, but for pathogens. When fully developed, the APDS could be placed in a large area such as an airport, a stadium, or a conference hall. The system will sample the air around the clock and sound an alarm if pathogens are detected.

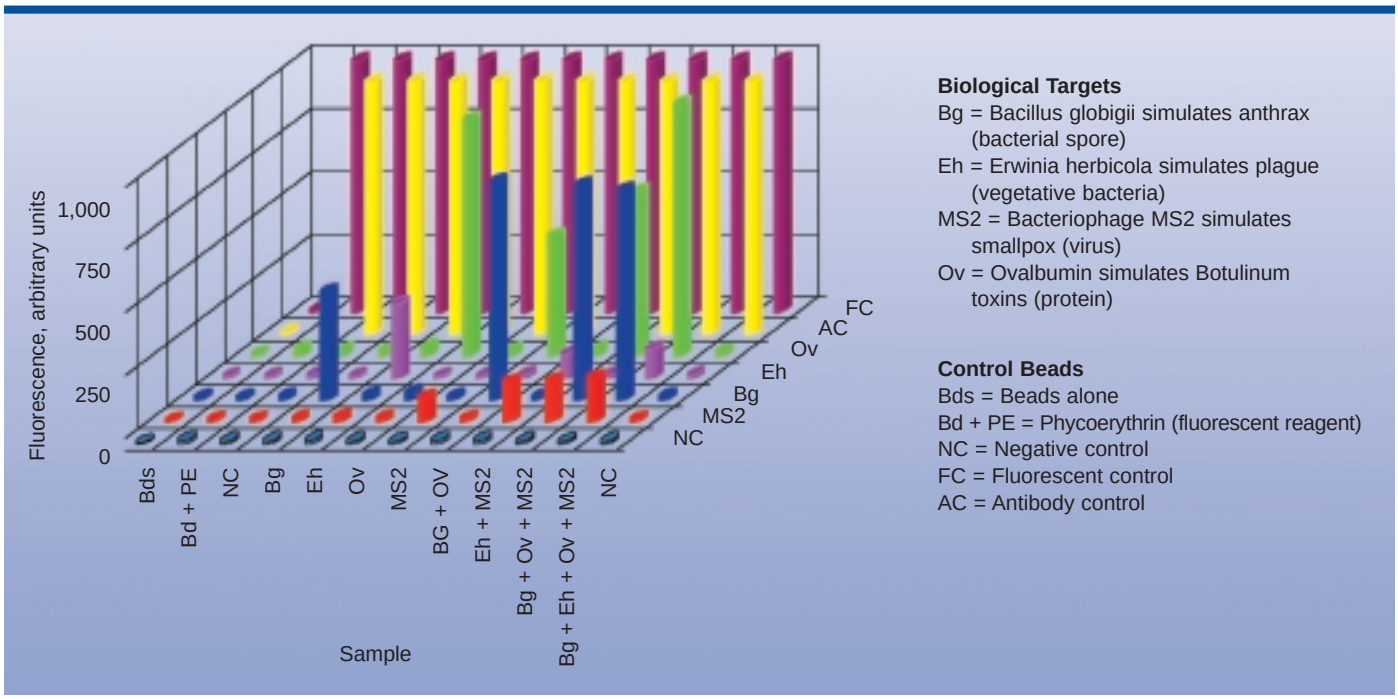
"The important point here is that the system would be fully automated," stresses Langlois. "The system will collect and prepare the samples, do the analysis, and interpret the results, all without human assistance."

Livermore is testing the second APDS prototype, which is about the size and shape of a lectern or mailbox. The APDS-II consists of an aerosol collector, a sample preparation subsystem, and two subsystems for detecting and analyzing the samples: one based on PCR and the other based on flow cytometry, which uses antibodies to identify pathogens. "The final system will double-test each sample to decrease the likelihood of false positives and increase the reliability of identification," explains Langlois.

The aerosol collector, which was designed by Vern Bergman and Don Masquelier at Livermore, gathers an air sample every 30 minutes—the length of time it takes to complete a sample analysis. A built-in fan pulls in the air, which passes through a glass tube containing water. The water traps any particles in the air, and the resulting fluid is pumped to the next stage for sample preparation and testing.

The flow-through PCR subsystem for the APDS includes a Livermore-designed thermocycler—much like the thermocycler in HANAA—along with a sequential injection analysis system. This analysis system performs all the necessary PCR sample preparation functions, such as mixing the sample with PCR

The Autonomous Pathogen Detection System is capable of continuous, automated, 24-hour monitoring for pathogens, with results reported every 30 minutes.



Results from the flow-cytometry subsystem of the Autonomous Pathogen Detection System (APDS) using seven color-coded "capture" beads coated with antibodies specific to the target pathogens. The pathogens attach to their respective antibodies and then to more antibodies added to the sample mixture that are labeled with fluorescent dyes. When the beads pass one by one through the flow cytometer's laser beam, any bead with labeled antibodies will fluoresce, and the APDS identifies the pathogens present, depending on the color of the capture bead.

reagents, delivers the resulting liquid sample to the thermocycler, and decontaminates the thermocycler chamber and fluid delivery tubes to prepare for the next run.

For the flow-cytometry subsystem, small "capture" beads that are 5 micrometers in diameter are coated with antibodies specific to the target pathogens. The beads are color coded according to which antibodies they hold. Once the pathogens attach to their respective antibodies, more antibodies—those labeled with a fluorescent dye—are added to the mix. A labeled antibody will stick to its respective pathogen, creating a sort of bead sandwich–antibody, pathogen, and labeled antibody. The beads flow one by one through a flow cytometer, which illuminates each bead in turn with a laser beam. Any bead with labeled antibodies will fluoresce. The system can then identify which agents are present, depending on the color of the capture bead. "Right now, we use seven bead types to detect four agents simultaneously with controls," says Langlois. The next step is to increase the number of detectable pathogens to 20 or 30. Ultimately, the researchers expect to be able to test for a hundred pathogens simultaneously in a single assay.

Langlois and the APDS team hope that, within the next year or two, the system will be ready to put in place wherever needed. Ultimately, notes Langlois, numerous detector systems could be linked together in a network connected to an emergency response center to protect a complex of buildings or a city.

The Faster the Better

From handheld, immediate testing to autonomous and continuous testing, HANAA and APDS are two of many systems Livermore is developing to help the nation fight bioterrorism. With HANAA, emergency responders can get answers on the scene in less than half an hour. With APDS, no human direction will be necessary, and the system will perform on its own, completely self-contained, monitoring 24 hours a day, 7 days a week. "What ties these approaches together is the ability to analyze a sample quickly—within 30 minutes or less—and do it on site," concludes Langlois. "Getting the answer quickly is important. In the case of a biological attack, the sooner we know what bioagent we're dealing with, the sooner treatment can start for those affected. Systems such as these have the potential for saving many lives."

—Ann Parker

Key Words: anthrax, Autonomous Pathogen Detection System (APDS), biodetectors, biological warfare agents, bioterrorism, DNA analysis, flow cytometry, Handheld Advanced Nucleic Acid Analyzer (HANAA), pathogens, polymerase chain reaction (PCR).

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

Patents

Hand-Held Multiple System Gas Chromatograph

Conrad M. Yu
U.S. Patent 6,306,200 B1
October 23, 2001

A multiple parallel handheld gas chromatograph (GC) system that includes several independent GCs. Each independent GC has its own injector, separation column, detector, and oven, and the GCs are mounted in a lightweight handheld assembly. Each GC operates independently and simultaneously. Because of different coatings in different separation columns, different retention times for the same gas will be measured. Thus, a multiple parallel GC system can measure, in a short period, different retention times, provide a cross-reference to determine what's been measured, and become a two-dimensional system for direct field use.

Method and Apparatus for Capacitive Deionization and Electrochemical Purification and Regeneration of Electrodes

Tri D. Tran, Joseph C. Farmer, Laura Murguia
U.S. Patent 6,309,532 B1
October 30, 2001

An electrically regeneratable electrochemical cell for capacitive deionization and electrochemical purification and regeneration of electrodes. The cell includes two end plates, one at each end of the cell. A new regeneration method is applied to the cell that includes slowing and stopping the purification cycle, electrically desorbing contaminants, and removing the desorbed contaminants. The cell further includes a plurality of generally identical double-sided intermediate electrodes that are equidistally separated from each other, between the two end electrodes. As the electrolyte enters the cell, it flows through a continuous open serpentine channel defined by the electrodes, substantially parallel to the surfaces of the electrodes. When the cell is polarized, ions are removed from the electrolyte and held in the electric double layers formed at the carbon aerogel surfaces of the electrodes. The cell is regenerated electrically to desorb such previously removed ions.

Process for Fabricating High Reflectance–Low Stress Mo–Si Multilayer Reflective Coatings

Claude Montcalm, Paul B. Mirkarimi
U.S. Patent 6,309,705 B1
October 30, 2001

A high-reflectance, low-stress molybdenum–silicon multilayer reflective coating particularly useful for the extreme ultraviolet (EUV) wavelength region. While the multilayer reflective coating has particular application for EUV lithography, it has numerous other applications in which high-reflectance and low-stress multilayer coatings are used. Multilayer coatings with high near-normal incidence reflectance (greater than or equal to 65 percent) and low residual stress (less than or equal to 100 megapascals) have been produced using thermal and nonthermal approaches. The thermal approach involves heating the multilayer coating to a given temperature for a given time after deposition in order to induce structural changes in the multilayer coating that will have an overall relaxation effect without reducing the reflectance significantly.

Modified Electrokinetic Sample Injection Method in Chromatography and Electrophoresis Analysis

J. Courtney Davidson, Joseph W. Balch
U.S. Patent 6,319,379 B1
November 20, 2001

A simple injection method for horizontal configured multiple chromatography or electrophoresis units, each containing a number of separation/analysis channels. The method enables efficient introduction of analyte samples. When used in conjunction with horizontal microchannels, this loading method allows much reduced sample volumes and a means of sample stacking to greatly reduce the concentration of the sample. This reduction in the amount of sample can lead to great cost savings in sample preparation, particularly in massively parallel applications such as DNA sequencing. By this method, sample volumes of 100 nanoliters to 2 microliters have been used successfully, compared to the typical 5 microliters of sample required by the prior separation/analysis method.

Microfabricated Instrument for Tissue Biopsy and Analysis

Peter A. Krulevitch, Abraham P. Lee, M. Allen Northrup, William J. Benett
U.S. Patent 6,319,474 B1
November 20, 2001

A microfabricated biopsy/histology instrument that has several advantages over conventional procedures, including minimal specimen handling, smooth cutting edges with atomic sharpness capable of slicing thin specimens approximately 2 micrometers or greater, use of microliter volumes of chemicals for treating the specimens, low cost, disposability, a fabrication process that renders sterile parts, and easy use. The cutter resembles a cheese grater made from a block or substrate of silicon with extremely sharp and precise cutting edges formed by anisotropic etching of the silicon. As a specimen is cut, it passes through the silicon cutter and lies flat on a piece of glass bonded to the cutter. Microchannels are etched into the class or silicon substrates for delivering small volumes of chemicals for treating the specimen. After treatment, the specimens can be examined through the glass substrate.

Mitigation of Substrate Defects in Reticles Using Multilayer Buffer Layers

Paul B. Mirkarimi, Sasa Bajt, Daniel G. Stearns
U.S. Patent 6,319,635 B1
November 20, 2001

A multilayer film is used as a buffer layer to minimize the size of defects on a reticle substrate prior to deposition of a reflective coating on the substrate. The multilayer buffer layer deposited between the reticle substrate and the reflective coating produces a smoothing of small particles and other defects on the reticle substrate. The reduction in defect size is controlled by surface relaxation during the buffer layer growth process and by the degree of intermixing and volume contraction of the materials at the multilayer interfaces. The buffer layers are deposited at near-normal incidence by a low-particulate ion-beam-sputtering process. The growth surface of the buffer layer may also be heated by a secondary ion source to increase the degree of intermixing and improve the mitigation of defects.

Awards

Four Laboratory physicists have been named **fellows** of the **American Physical Society** (APS): **Peter Beiersdorfer** and **Karl van Bibber** of the Physics and Advanced Technologies (PAT) Directorate, **David Munro** of the Defense and Nuclear Technologies (DNT) Directorate, and **Seigfried Glenser** of the National Ignition Facility (NIF) Programs Directorate.

Beiersdorfer, leader of PAT's Atomic Spectroscopy Group, was cited for his "many contributions to precision X-ray spectroscopy of highly charged systems and application of this spectroscopy to plasma and astrophysical problems." He joined the Laboratory in 1988, earned his B.S. and M.S. in physics from Auburn University and an M.S. and Ph.D. in plasma physics from Princeton University.

Van Bibber, chief scientist in PAT, was elected for his "leadership role in an ultra-sensitive search for dark-matter axions, and the conception of other elegant experiments for detection of the axion." Van Bibber, who received his bachelor's and doctorate at the Massachusetts Institute of Technology, came to Livermore in 1985 from Stanford University, where he had been an assistant professor of physics. He started the Laboratory's High-Energy Physics and Accelerator Technology Group in 1991 and was Livermore's project leader for the construction of the B Factory at the Stanford Linear Accelerator Center (SLAC), a collaboration of SLAC and Lawrence Berkeley and Lawrence Livermore national laboratories.

Munro, a Laboratory employee for 21 years, is a physicist involved in laser fusion target design. He was singled out for "seminal contributions to the design of laser-driven Rayleigh–Taylor experiments, and to the analysis and design of shock-timing experiments for cryogenic inertial confinement fusion targets." He earned his Ph.D. at the Massachusetts Institute of Technology in 1980 and has focused on laser fusion throughout his career. Until a few years ago, he was mostly involved in designing experiments on the Nova laser. Currently, he is designing targets for NIF.

Glenser, an experimental physicist, was cited for "the development of Thomson Scattering for the diagnostics of high-temperature inertial confinement fusion plasmas and for important contributions to understanding of plasma waves, atomic physics, and hydrodynamics of hot dense plasmas." Currently a group leader for Plasma Physics in NIF's Inertial Confinement Fusion program, he earned his undergraduate degree and Ph.D. at Ruhr-Universität Bochum in Germany. He has been in the U.S. since 1994, when he first joined Livermore as a postdoctoral fellow.

In late 2001, Livermore's **Clinton M. Logan** was made a **fellow** of the **American Society of Mechanical Engineers** in recognition of his outstanding engineering achievements. A graduate of the University of California at Davis (M.S., 1972), Logan performed the structural design for the first vacuum line-of-sight employed in underground tests of nuclear explosives. Later, he designed and patented a rotating vacuum seal that became an enabling technology for an international radiation effects program at the rotating Target Neutron Source II. As the leader of the Material Characterization Group for Livermore's X-Ray Laser program, Logan stretched film radiography to unprecedented accuracy. Recently, he has been an innovator in developing digital (filmless) mammography and in applying flat-panel electronic x-ray imagery to nondestructive evaluation.

Recently, **Tim Andrews**, **Mark Mintz**, and **Bill Blevins**, employees of Livermore's Tritium Facility, received **Pollution Prevention Awards** from the Department of Energy–National Nuclear Security Administration Oakland Operations Office. The awards honor their efforts in tritium recycling in support of the U.S. Army Industrial Operations Command project to recover and reuse tritium from military field devices. The project involves disassembling the equipment and segregating tritium-containing ampules from nonradioactive components. The Livermore tritium specialists release the tritium from the ampules, capture it, and accumulate the captured tritium in specialized shipping containers. These containers are sent to the Tritium Facility at DOE's Savannah River Site, where the tritium is reused. During fiscal year 2001, this waste minimization project recovered an estimated 27,000 curies of tritium, avoiding approximately 16,000 kilograms of radioactive waste.

Abstracts

Simulating Turbulence in Magnetic Fusion Plasmas

A team of Lawrence Livermore scientists is leading a national effort to simulate the extraordinarily complex physics involved in magnetically confined plasmas. The team's focus is on deepening the understanding of the plasma microturbulence that occurs inside a tokamak, a doughnut-shaped magnetic confinement device. Microturbulence is an irregular, and unwanted, fluctuation in the plasma "soup" of electrons and ions. The fluctuations generate unstable waves and eddies that transport heat from the superhot core across numerous magnetic field lines out to the tokamak's walls. The collaboration's current focus is on advanced codes, algorithms, and data analysis and visualization tools. The simulations run on massively parallel supercomputers, which use thousands of microprocessors in tandem. The team has made important progress in the past few years, as seen in the comparisons of simulations to experiment results, in the agreement of results from codes developed by collaborators from different research centers, and in the codes' increasingly thorough and accurate physics content.

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Present at the Creation

A collaboration of Russian and Livermore scientists has added two new elements, 114 and 116, to the periodic table. It took 40 days of almost continuous effort in 1998 to produce the first atom of element 114, which was a fusion of plutonium-244 and calcium-48. Its lifetime was 30.4 seconds before decay began. Daughter particles survived for a total of 34 minutes before the final decay product fissioned. A subsequent experiment produced a single atom of a different isotope of element 114. In 2000 and 2001, experiments using calcium-48 and curium-248 resulted in a single atom of element 116. Previously, Livermore's collaboration with the Joint Institute for Nuclear Research in Dubna, Russia, which began in 1989, produced new isotopes of elements 106, 108, and 110. Upcoming experiments hope to result in the new elements 113 and 115.

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How Does Virulence Work in Bioterrorism Agents?

Livermore scientists are studying the plague bacterium to understand what genes turn virulence on. Their goal is to thwart agents of biological terrorism.

Also in March

- ***Livermore-developed L-Gel can decontaminate surfaces poisoned by chemical and biological warfare agents.***
- ***A new high-speed technology finds defects in laser glass.***
- ***50th Anniversary Highlight—Throughout its history, Livermore has used and promoted the development of the most advanced computational tools to aid in the design and stewardship of nuclear weapons.***

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