70

1952 - 2022

MAKING
THE
IMPOSSIBLE
POSSIBLE

U.S. DEPARTMENT OF **ENERGY**

NNSA
National Nuclear Security Administration

LAWRENCE LIVERMORE NATIONAL SECURITY LLC

Lawrence Livermore National Laboratory

1952 – 2022

MAKING
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IMPOSSIBLE
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About the Cover
From the pioneering use of a Univac "supercomputer" and the development of a warhead for the Polaris submarine-launched ballistic missile to achievement of a burning fusion plasma at the National Ignition Facility, generations of exceptional staff dedicated to national service have strived to make the impossible possible in support of the Laboratory's important national security missions.

About the Laboratory
Lawrence Livermore National Laboratory (LLNL) was founded in 1952 to enhance the security of the United States by advancing nuclear weapons science and technology and ensuring a safe, secure, and effective nuclear deterrent. With a talented and dedicated workforce and world-class research capabilities, the Laboratory strengthens national security with a tradition of science and technology innovation—anticipating, developing, and delivering solutions for the nation's most challenging problems.

The Laboratory is managed by Lawrence Livermore National Security, LLC (LLNS), for the National Nuclear Security Administration (NNSA), a semi-autonomous agency within the U.S. Department of Energy (DOE). LLNS is a limited liability company managed by Bechtel National, Inc.; the University of California; BWXT Government Group, Inc.; and Amentum. Battelle Memorial Institute also participates in LLNS as a teaming subcontractor. Cutting-edge science is enhanced through the expertise of the University of California and its 10 campuses and LLNS' affiliation with the Texas A&M University system.

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PREFACE

For 70 years, Lawrence Livermore National Laboratory has been making history and making a difference. The outstanding efforts by a dedicated work force have led to many remarkable accomplishments. Creative individuals and interdisciplinary teams at the Laboratory have sought breakthrough advances to strengthen national security and to help meet other enduring national needs.

The Laboratory's rich history includes many interwoven stories—from the first nuclear test failure to accomplishments meeting today's challenges. Many stories are tied to Livermore's national security mission, which has evolved to include ensuring the safety, security, and reliability of the nation's nuclear weapons without conducting nuclear tests and preventing the proliferation and use of weapons of mass destruction. Throughout its history and in its wide range of research activities, Livermore has achieved breakthroughs in applied and basic science, remarkable feats of engineering, and extraordinary advances in experimental and computational capabilities.

From the many stories to tell, one has been selected for each year of the Laboratory's history. Together, these stories give a sense of the Laboratory—its lasting focus on important missions, dedication to scientific and technical excellence, and drive to make the world more secure and a better place to live.

The twentieth-century stories are now thrice told. A first edition of this collection was issued in 2002, at the time of the Laboratory's fiftieth anniversary. A generation has passed since then, and more recent remarkable stories have been added.

The Fifties

New Leadership

Herbert F. York
(1952 • 1958)

Edward Teller
(1958 • 1960)

The Cold War was raging, and on August 29, 1949, the Soviet Union detonated its first atomic bomb—much sooner than expected by Western experts. Less than a year later, Communist North Korean forces crossed the 38th parallel to invade the Republic of Korea. National security was at stake. The urgent need to accelerate the nation's H-bomb program led Ernest O. Lawrence and Edward Teller to argue for the creation of a second laboratory to augment the efforts of Los Alamos. On September 2, 1952, a

A "new ideas" laboratory

branch of the University of California's Radiation Laboratory opened in Livermore, California.

Livermore's first director, Herbert F. York, and a remarkable group of young scientists set out to be a "new ideas" laboratory. They were committed to pursuing innovative solutions to the nation's pressing needs to advance nuclear weapons science and technology. The Laboratory's first nuclear experiments were failures. But later in the decade, Livermore scientists made a major breakthrough—the design of a megaton-class warhead for ballistic missiles that could be launched from submarines.

Team Science in the National Interest

The Livermore branch of the University of California Radiation Laboratory (UCRL) at Berkeley opened for operation on September 2, 1952, at a deactivated Naval Air Station. The infirmary at the old air station had been used by a group of UCRL physicists to help Los Alamos with diagnostics for the George thermonuclear test fielded at Enewetak Atoll (Central Pacific) in May 1951. The site also was being used by California Research and Development, a subsidiary of Standard Oil, to build the Materials Testing Accelerator (MTA), a pilot for a larger accelerator to produce tritium and plutonium for weapons. Conceived by Ernest O. Lawrence, founder of UCRL, the MTA project was abandoned in 1954 after the discovery of large domestic deposits of uranium ore, and the "Rad Lab" took sole possession of the square-mile site.

Working conditions at the Rad Lab were primitive. The staff were housed in old wooden buildings with poor heating and no air conditioning. Initially, they had fewer telephones than promised, no post office box for mail delivery, and, according to the minutes of an early administrative meeting, "The desk lamp situation is very bad." The infirmary building was in the best shape, so Herbert F. York, the first director, and an opening-day staff of 75 located there. York's office was in the x-ray room—it was lead shielded, and he could carry on classified

When the Laboratory opened in 1952, the old Navy infirmary served as the administration building, and it housed Livermore's first computer.
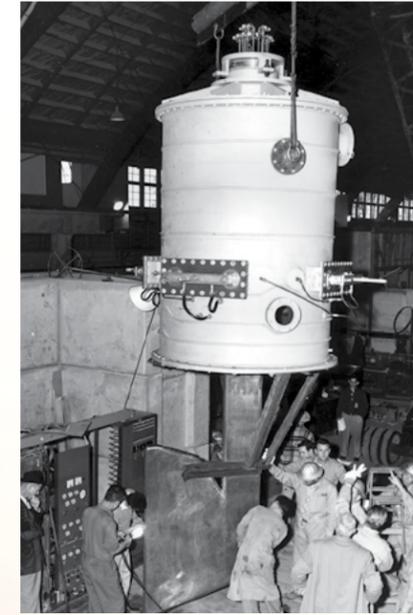
Two of the Laboratory's first major facilities for nuclear research were the 90-inch cyclotron (far left), which operated from 1954 to 1971, and the Livermore Pool-Type Reactor (left), which was used for experiments from 1957 to 1980.

discussions without being overheard.

Establishment of the Laboratory was triggered by the detonation of the first Russian atom bomb in 1949, which alarmed some American scientists who feared a quick Soviet advance to the next step, the hydrogen bomb. Edward Teller and Lawrence, both very concerned, met on October 7, 1949, at Los Alamos to discuss the crisis. The ensuing actions taken by key figures in Washington led to the creation of the Laboratory at Livermore to more rapidly advance nuclear weapons science and technology. Activities began with a sketchy mission statement and a commitment by York and his team to be a "new ideas" laboratory.

York, then 32 years old, was singled out by Lawrence to head the new laboratory. He had co-led the team that worked on diagnostics for the George event. York faced two principal challenges: planning the Laboratory's research program and recruiting the first employees. His plan had four main elements: development of diagnostics for weapons experiments (for both Los Alamos and Livermore), the design of thermonuclear weapons, Project Sherwood (a magnetic fusion energy program), and a basic physics program. Staff recruitment relied

Livermore's first director, Herbert F. York (right), confers with founders Ernest O. Lawrence (left) and Edward Teller (center).

heavily on connections with Berkeley. By the end of 1952, the staff had grown to 300, by the end of the first year of operation to 1,000, and within just five years to 3,100.

Following the lead of his mentor, York established a matrix organization for the Laboratory, a distinguishing feature of Livermore still in use today.

In this approach, experts in various relevant disciplines assemble as a team and work together to understand and solve complex problems. This way of structuring and organizing research and development enables the Laboratory to better reach its mission-directed technological goals. And the rest is history.

1953 Ruth

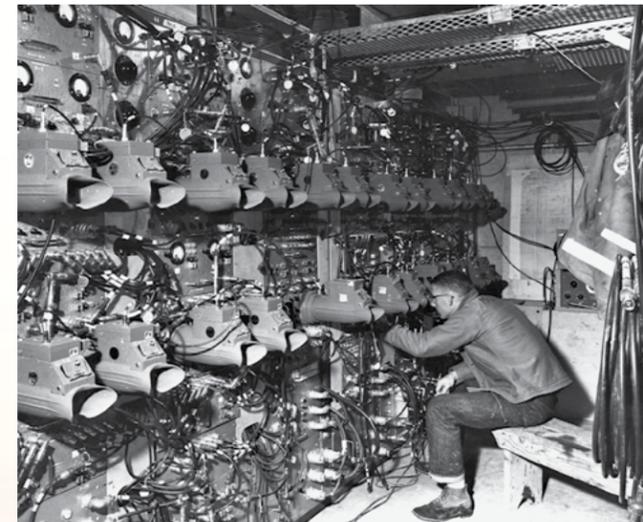# Pushing the Frontiers of Nuclear Design

Ruth, the Laboratory's first nuclear test, explored a new design approach and provided information about certain thermonuclear reactions. The experiment, and the test that followed (named Ray), exemplified Livermore's commitment to be a "new ideas" laboratory and, in the words of Edward Teller, to "plan and explore all kinds of new developments in the field of bomb physics."

The device was mounted on a 300-foot steel tower, and Ruth was fired on March 31, 1953—just six months after Livermore opened. The test was a fizzle. More than half of the tower remained standing afterward. Fired on April 11, 1953, Ray produced about the same yield as Ruth. Legend has it that Ray was mounted on a shorter 100-foot tower to ensure its complete destruction.

In addition to their interest in thermonuclear weapons, Livermore scientists focused attention on novel small fission weapons designs. This work would come to fruition in the 1950s, in part because of Los Alamos's attention to meeting the Air Force's needs for large H-bombs. The Army was interested in atomic projectiles between 8 and 11 inches in diameter, and the Air Force envisioned the need for nuclear-tipped antiaircraft missiles. Livermore's main thrust in this area was a new design concept that combined disparate elements from previous fission weapons designs. Ideas matured for fission weapons with a smaller diameter, requiring less nuclear materials and/or an increased yield to weight.

The remains of the Ruth test tower after the first device fielded by the Laboratory was detonated in 1953. The test failed.

This research led to some of the Laboratory's early weapons-development assignments, including the W45 for the Little John and Terrier tactical missile systems and the W48 155-millimeter howitzer atomic projectile. (Livermore's first assignment was the W27 warhead, which was deployed on the U.S. Navy's shipborne Regulus supersonic cruise missiles.) A strong continuing interest in improved designs for tactical systems culminated in the Laboratory's work on the W79 enhanced-radiation artillery shell in the 1970s (see Year 1975).

The role of Livermore as the "new ideas" laboratory also guided the decision to focus thermonuclear work on the design of small H-bombs. As early as the Castle test series in 1954, Livermore investigated H-bomb designs smaller in size and yield than those designed by Los Alamos. The first thermonuclear test, Koon, also was a fizzle, yielding only 100 kilotons of an expected 1 megaton. Continuing efforts and future successes led to Livermore's development of much smaller diameter H-bomb missile warheads later in the 1950s, which made the Polaris submarine program possible (see Year 1956).

Banks of oscilloscopes are used to capture data at the Nevada Test Site during Operation Teapot in 1955.

Shown in position inside a barge, one of the Laboratory's largest designs, the Tewa device, yielded 5 megatons when it was detonated near Bikini Atoll in 1956.

An Eyewitness Account of Ruth

Wally Decker, who later headed the Mechanical Engineering Department and finished his long career on the Director's Office staff, was a young engineer when he witnessed Ruth. According to Decker, "We got everything ready. We stood back with our dark glasses on, waiting for the device to go off. When it was fired, all we could see was a small speck of light on the horizon—no mushroom cloud, no nothing.

"But we didn't give up. We prepared for another event with a slightly different design. And when we fired the device, it was dismal, too.

"After those failures, our fortunes were at low ebb. We always said that we got a lot of good information from those failures—and we did—but you don't always get to stay around to play your best game. Fortunately, we did, and things got better for the Lab."

1954 The IBM 701

Speed is the Game

The IBM 701 computer was delivered to the Laboratory in 1954—it was five to six times faster than its predecessor, the Univac-1.

Delivery of the IBM 701 in 1954 dramatically improved the Laboratory's capability to perform scientific calculations. With 72 cathode-ray tubes, 2,048 words of memory, and accompanying gadgetry, the machine was the first commercially successful "scientific" supercomputer because of its speed. It was five to six times faster than its predecessor, the Univac-1, which the Laboratory acquired during its first year of operation. The Univac-1 correctly predicted the Eisenhower landslide victory in the 1952 presidential election with only 7 percent of the vote tallied, but Livermore's needs quickly outgrew the machine's capabilities.

Even before the Laboratory was a reality, founders Ernest O. Lawrence, Edward Teller, and Herbert York

understood the need for mammoth amounts of computing power. Almost from the opening of the doors in 1952, a sizable team of Livermore people was learning to use the Univac-1 and troubleshoot its problems. At election time, the machine earmarked for Livermore was loaned to a TV network to predict the results. Acquisition of the Univac-1, and soon after the IBM 701, marked the beginning of the Laboratory's not-so-coincidental links to commercial supercomputing—their nearly identical birth dates, efforts to develop the fastest and most powerful machines, and use of machines to solve large, complex problems.

The IBM 701 and all of Livermore's subsequent computers have been developed in part at the Laboratory's encouragement. The IBM 701 was

Delivered in May 1960, the building-size LARC (Livermore Advanced Research Computer) was built by Remington Rand to specifications provided by the Laboratory.

the last vacuum-tube model before magnetic core and transistor memory. With the change in technology to transistors, computer speed and storage capacity have rapidly advanced in accordance with a phenomenon dubbed "Moore's Law," formulated in 1965 by Gordon Moore, founder of Intel Corporation. The law has accurately described the trend that every 18 months technology advances have doubled the number of transistors that could be put on a computer chip. Whether the law will continue to hold is uncertain; one possibility is the use of extreme ultraviolet lithography (see Year 1999).

Through the 1980s, Moore's Law drove processor speed but not fast enough to meet the supercomputing needs for science-based stockpile stewardship. DOE launched the Advanced Simulation and Computing Initiative (ASCI) in 1995. ASCI and its successor, the Advanced Simulation and Computing Program, pushed the development of supercomputers that use thousands and now millions of processors working in parallel in increasingly complex machine architectures. The IBM Sierra machine, which is being delivered to Livermore in 2017–2018, will provide more than 120 petaflops (1015 floating-point operations per second) peak performance—300 trillion times faster than the Univac-1 (see Year 2017).

Livermore's petascale—and planned for exascale (1018)—computing capabilities keep the Laboratory at the forefront of scientific computing in the early 21st century. They promise to help experts maintain the nation's nuclear deterrent and open many new avenues of scientific discovery.

The Origin of FORTRAN

The Univac-1 was a simple computer to program in machine language; however, the IBM 701 was more difficult to use—one reason was its reliance on punch cards for input and output. Programmers in companies and laboratories that owned 701s talked among themselves informally, resulting in various "home-brewed" systems. IBM soon began to develop a higher level language, FORTRAN (formula translation), and the Laboratory sent Robert Hughes to IBM for an extended visit to contribute to the effort. The original FORTRAN manual lists four contributors; one of them was Robert Hughes.

Flying and Terrestrial Nuclear Reactors

Construction was required to expand the "tank farm" that supplied high-pressure air to the ramjet reactor, which was tested inside a special facility (in the lower left corner). In one experiment, Tory II-C (far right photo) required hundreds of tons of heated air to operate for nearly 5 minutes.

In 1955, the Laboratory and Los Alamos began work on Rover, a project intended to supply nuclear propulsion for space travel. The nuclear rocket program continued for many years at Los Alamos with many technical successes, while Livermore's attention shifted in 1957 to a new flying reactor effort, Project Pluto, for the Atomic Energy Commission and the U.S. Air Force. An awesome undertaking, Project Pluto entailed the design and testing of a nuclear ramjet engine for low-flying, supersonic cruise missiles that could stay aloft for many hours.

For Project Pluto, Livermore designed and built two Tory II-A test reactors to demonstrate feasibility, and Tory II-C was designed as a flight-engine prototype. Laboratory experts in chemistry and materials science were challenged to devise ceramic fuel elements that had the required neutronics properties for the reactor yet were structurally strong and resistant to moisture and oxidation at high temperatures. The reactors needed hundreds of thousands of the elements, which

had to be mass producible. Testing the reactors required novel remote-handling technologies, as well as systems capable of ramming about a ton of heated air through the reactor each second.

For 45 seconds on May 14, 1961, Livermore tested the Tory II-A at the Nevada Test Site. After additional successful experiments in 1961, Tory II-C was designed and built. Generating 500 megawatts of power (about half the power capacity of Hoover Dam), it was successfully tested in the spring of 1964. All six tests of the two Tory reactors were conducted without failure. However, that summer, the project was halted for lack of a firm military commitment.

Laboratory expertise in reactors and the nuclear fuel cycle continued to find many applications. The year Project Pluto ended, Super Kukla began operation in a shielded bunker at the Nevada Test Site. Super Kukla was a prompt-burst neutron-pulse reactor designed to serve as a neutron source for irradiating a variety of test specimens, including fissile material used in weapon components.

Experiments using the reactor helped to assure that U.S. nuclear warheads would function in wartime environments. In addition, from 1957 to 1980, the Livermore Pool-Type Reactor (a megawatt-class reactor) was operated onsite for neutron radiography, fundamental research on radiation damage to materials, and the detection of trace quantities of materials through neutron activation.

Later efforts applied Livermore's fission-energy science and engineering capabilities to protect public health and safety and develop advanced technologies to close the nuclear fuel cycle. Examples include work on the Yucca Mountain Project (see Year 1980), safety studies in the 1990s for the Nuclear Regulatory Commission, development of methods to immobilize plutonium, and recovery of highly enriched uranium to enhance security. Today, Laboratory expertise in fission energy focuses on understanding, detecting and monitoring, and closing paths to nuclear proliferation.

1956 Polaris

A Strategic Breakthrough
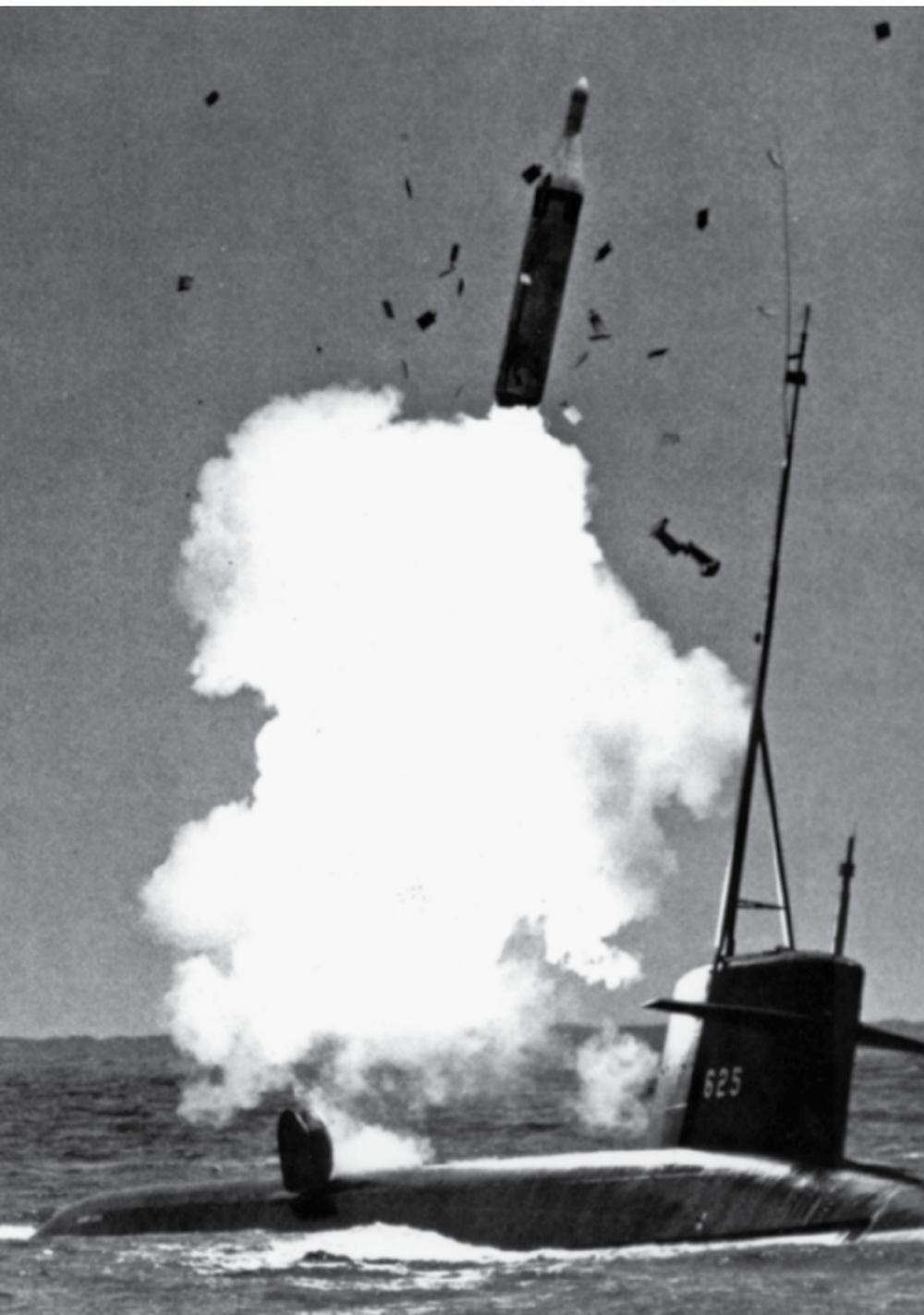
In the summer of 1956, a U.S. Navy-sponsored study on antisubmarine warfare was held at Nobska Point in Woods Hole, Massachusetts. Edward Teller attended the Project Nobska study. His bold input would profoundly affect the course of the Navy's Fleet Ballistic Missile Program and the future of the Laboratory. At the time, the approved program plans called for the deployment in 1965 of submarines that would carry horizontally four 80-ton Jupiter S ballistic missiles, which were large enough to carry existing thermonuclear warheads.

During Project Nobska, Frank E. Bothwell from the Naval Ordnance Test Station raised the possibility of designing ballistic missiles 5 to 10 times lighter than the Jupiter S missiles, with a range of 1,000 to 1,500 miles; however, they would be able to carry only a relatively low-yield nuclear weapon. Teller discussed the feasibility of a 1-megaton warhead compact enough to fit onto a torpedo—a radical concept. When asked whether his ideas could be applied to the Navy's ballistic missile program, Teller replied with a question, "Why use a 1958 warhead in a 1965 weapon system?" He opened the door to development of Polaris: a highly efficient deterrent system in which 16 compact missiles would be placed vertically aboard a submarine for launch on demand.
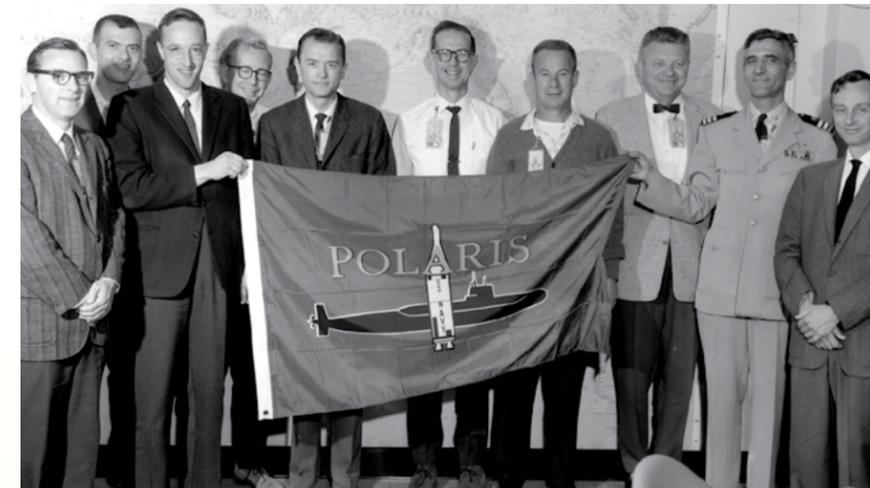
So began a crash, three-year effort. In early 1957, the Navy issued a requirement for an underwater-launched solid-fuel missile system by 1965. By the end of the year, following successful tests of Livermore's warhead design at the Nevada Test Site, the Secretary of Defense authorized a step-up to deploy the system by 1960, which was accomplished.

The summer of 1958 brought genuine breakthroughs based on ingenious proposals by Carl Haussmann, Kenneth Bandtel, Jack Rosengren, Peter Moulthrop, and David Hall in A Division and by B Division's John Foster (Laboratory Director, 1961–1965), Chuck Godfrey, and Wally Birnbaum. The significance of the innovations was confirmed during tests in the Pacific only a few months before the 1958–1961 nuclear testing moratorium began. Work continued at the Livermore and Sandia laboratories, and through the efforts of weapons designers and engineers, computer specialists, and other experts, the W47 Polaris warhead was created.

The program's remarkable achievements were demonstrated in spectacular fashion on May 6, 1962. The USS Ethan Allen, the sixth-launched Polaris submarine, conducted a complete operational test of the Polaris A-1 missile system, culminating with the successful detonation of the Livermore-designed megaton-class warhead (see Year 1962).

Conceived as a highly survivable system able to counterattack in the event of a Soviet first strike, Polaris has a unique place in American nuclear weapons history.

The Laboratory's innovative design and development of the W47 as part of a crash program established Livermore's reputation as a major nuclear weapons design facility. The work spurred additional innovations and provided a model for future strategic weapon development.

The Polaris flag was presented by the Navy to Livermore scientists and engineers for the Laboratory's outstanding work in the development of the Polaris warhead.

The Laboratory's design for the W47 Polaris warhead made it practical for U.S. nuclear deterrent forces to be deployed in highly survivable submarines.

Teller Recalling Project Nobska

"The Navy asked if we could make a nuclear explosive of such and such dimensions and such and such a yield. What they wanted was a small, light, nuclear warhead in the 1-megaton range. Everyone at the meeting, including representatives from Los Alamos, said it could not be done—at least in the near future. But I stood up and said, 'We at Livermore can deliver it in five years and it will yield 1 megaton.' On the one hand, the Navy went away happy, and the program got approved. On the other hand, when I came back to Livermore and told them of the work that was in store for them, people's hair stood on end. They said, 'What have you done? We can't get a megaton out of such a small device, not in five years!'"
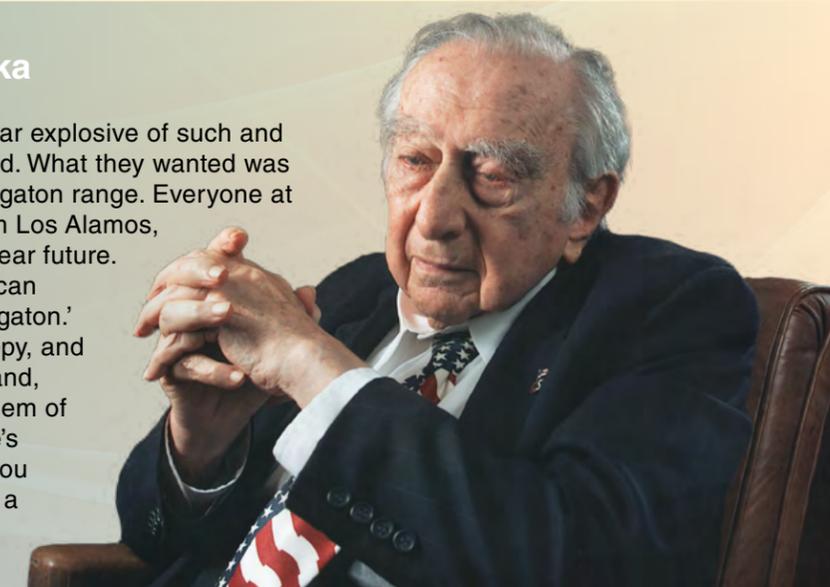
The First Underground Nuclear Test

On September 19, 1957, the Laboratory detonated the first contained underground nuclear explosion. Rainier was fired beneath a high mesa at the northwest corner of the Nevada Test Site, which later became known as Rainier Mesa.

Carrying out such an explosion had been proposed early in 1956 by Edward Teller and Dave Griggs, a geophysicist who greatly contributed to Teller's effort to establish a second nuclear laboratory while serving as Chief Scientist of the U.S. Air Force in the early 1950s. Their interest

was in the coupling of the explosion energy to the surrounding geology and in the resulting seismic effects. They also noted the environmental advantages of such a test at a time when there was growing concern about atmospheric nuclear testing. Rainier would prove to be a pivotal event by giving a boost to the nascent Plowshare Program and affecting the future of nuclear arms control and the conduct of nuclear tests.

The idea of using nuclear explosions for nonmilitary purposes— beating swords into plowshares—

Radiation detection equipment in the foreground monitors the environment for a worker in a tunnel at the Nevada Test Site that was dug for the Rainier event in 1957.
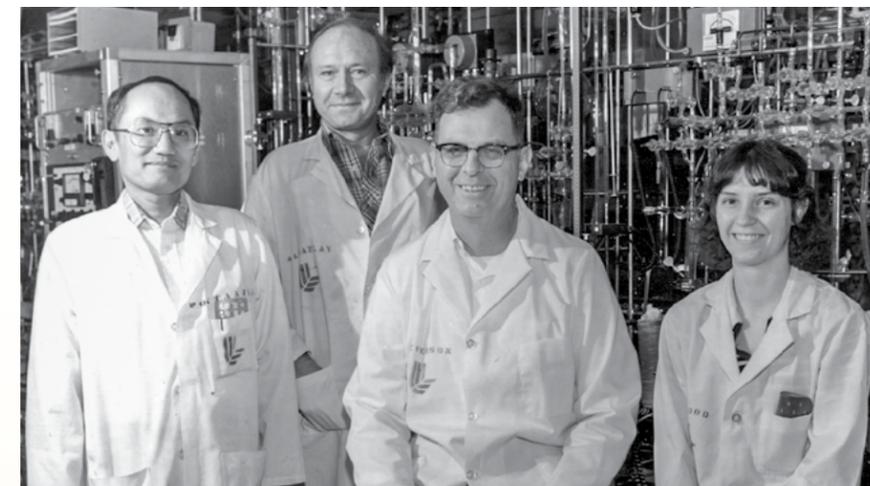
Radiochemical analysis of the isotopes created by a nuclear explosion was an important diagnostic tool for determining the yield and studying the performance of tested devices. Major advances in radiochemistry were made by Peter Stevenson (second from the right), who was killed in a plane crash returning from the Nevada Test Site in 1979.

preceded the Rainier event. In the summer of 1956, Harold Brown (Laboratory Director 1960–1961) proposed a symposium on the subject to the Atomic Energy Commission (AEC), and it was eventually held at Livermore in February 1957. Some 24 papers were presented covering a broad array of ideas. Although the discussions were hampered by the lack of data on the effects of underground explosions, interest was high. In June, the AEC established the Plowshare Program to explore peaceful nuclear uses, such as the building of canals and dams, and the stimulation

of natural gas reservoirs. Subsequently, the Rainier test and its data gave a tremendous boost in confidence that a variety of applications were possible and could be implemented safely.

The Rainier event was announced in advance so that seismic stations throughout the U.S. and Canada could attempt to record a signal. In addition, samples were collected for radiochemistry analysis by drilling a series of holes through the mesa above and in the original tunnel. More data were collected by mining a tunnel into the bottom of the explosion cavity about 15

months later, when radioactivity had decayed to manageable levels. From these post-shot investigations, scientists developed the understanding of underground explosion phenomenology that persists essentially unaltered today. That information provided a basis for subsequent decisions in 1963 to agree to the Limited Test Ban Treaty, which banned atmospheric nuclear weapons tests and led to systems being established for monitoring nuclear test activities worldwide, including an international array of seismic detectors.

The Legacies of Plowshare
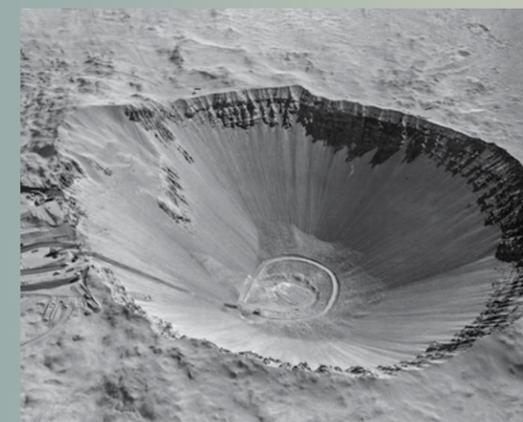
The first Plowshare test, Gnome, created a nearly 70-foot-high, 165-foot-diameter underground cavity in a dry salt bed near Carlsbad, New Mexico. Many potential applications were explored until the program ended in 1977, and they drove nuclear design to the two extremes—minimum fission or minimum fusion depending on the application. The most dramatic relic of Plowshare is a 350-foot-deep, 1,200-foot-diameter crater (left) at the Nevada Test Site created by the Sedan event in 1962. Important legacies of the effort include Livermore's biomedical research program to study the effects of fallout and other radioactive hazards on biological systems (see Year 1963) and the Laboratory's Atmospheric Release and Advisory Capability (ARAC) program, which grew out of the need to predict the potential for atmospheric release from cratering shots (see Year 1979).

1958 Test Moratorium

Providing Technical Support for Arms Control Negotiations

Soviet Premier Nikita Khrushchev delivers a speech during the reception in the Kremlin's Georgian Hall following the formal signing of the Limited Test Ban Treaty on August 5, 1963. Hoping he would not be caught taking this picture, University of California Professor Glenn T. Seaborg, who was then Chairman of the Atomic Energy Commission, captured the image.

In July and August 1958, Ernest O. Lawrence and Harold Brown (Laboratory Director, 1960–1961) attended the Conference of Experts held in Geneva, Switzerland, to examine how a comprehensive ban on nuclear testing could be verified. Their participation signaled the beginning of the Laboratory's long history of providing technical support for arms control negotiations and implementation. Lawrence served as one of the three U.S. representatives at the conference, and Brown was a member of the delegation's technical advisory group. At the conference, Lawrence performed his final service to the nation before suffering an acute attack of colitis that led to his death. Many Livermore scientists would follow in Lawrence's and Brown's footsteps by contributing their expertise to the negotiations of nuclear arms reduction and nuclear test ban treaties.

At the conclusion of the Conference of Experts, President Dwight D. Eisenhower announced U.S. willingness to suspend nuclear weapons testing and begin negotiations on a comprehensive test ban. Concurrent with these negotiations, a feasible verification regime was to be developed. Research on monitoring nuclear explosions ensued at the Laboratory as part of the Vela program. The seismic detection of underground explosions (the Vela Uniform effort) proved to be more of a challenge than anticipated by the report of the experts.

A worldwide network of seismic stations was built as a part of Vela Uniform, and for more than 50 years, this network has been the primary source of data for the seismic community. In 1961, the moratorium was broken when the Soviet Union resumed atmospheric testing. With the confidence gained through Vela in detecting and monitoring nuclear explosions, President John F. Kennedy signed the Limited Test Ban Treaty in August 1963, which banned nuclear weapons testing in the atmosphere,

Michael May comments at one in a series of workshops held in 2001 on the future of deterrence. The meetings were sponsored by Livermore's Center for Global Security Research, which focuses on the nexus between technology and national security policy.

under water, and in space.

Nuclear explosion monitoring remains an important research activity at the Laboratory. Current efforts focus on enhancing monitoring capabilities with particular emphasis on detection of low-yield nuclear explosions (see Year 2008). More broadly, technical support of arms control negotiations continues to be an integral part of

Livermore's overall mission. For example, experts at the Laboratory provided technical assistance to the U.S. government in the negotiations of the Joint Comprehensive Plan of Actions with Iran. Livermore also provides technical input to decision makers supporting deliberations about the nation's nuclear weapons posture and force structure.

The Evolution of Nuclear Force Postures

Michael May's distinguished career included many contributions to the evolution of U.S. strategic forces. May, Laboratory Director from 1965 to 1971, served as Technical Adviser to the Threshold Test Ban Treaty negotiations (1974) and as U.S. Delegate to the Strategic Arms Limitation Talks (SALT) with the Soviet Union (1974–1976). Although never ratified, the SALT II Treaty effectively capped the growth of strategic nuclear arsenals during the Cold War. In 1981, May participated in a panel chaired by University of California at Berkeley Professor Charles Townes that recommended to President Ronald Reagan how to base MX (Peacekeeper) missiles, and in 1988, he was lead author of "Strategic Arms Reductions" in International Security, a seminal paper that provided an intellectual basis for the subsequent Strategic Arms Reduction Treaty. Serving as a member of the National Academy of Sciences Committee on International Security and Arms Control, May also directed a study that resulted in the 1991 report The Future of the U.S.–Soviet Nuclear Relationship, which paved the way for later decisions about post-Cold War nuclear policy and strategic force reductions.

1959 — E. O. Lawrence Awards Created

Exceptional Contributions to U.S. Department of Energy Missions

Established in November 1959, the Ernest Orlando Lawrence Memorial Award was at first presented to scientists and engineers for their exceptional contributions to the development, use, or control of nuclear energy. The criteria have since been expanded to include exceptional scientific, technical, and/or engineering achievements related to the broad missions of the U.S. Department of Energy and its programs. Researchers at Livermore have won 31 of the more than 200 awards presented to date. Today, the award consists of the medal and a $20,000 honorarium.

Lawrence was the father of "big science" and founder of the nuclear science laboratories (or "Rad Labs") at Berkeley and Livermore that were named for him. His invention of the cyclotron in the 1930s started nuclear science on a path that has led to inventions ranging from advanced accelerators for elementary particle physics and the atom bomb to cancer therapies.

After Lawrence's death in August 1958, John A. McCone, Chairman of the Atomic Energy Commission, wrote to President Dwight D. Eisenhower suggesting the establishment of a Memorial Award in Lawrence's name. President Eisenhower agreed, saying, "Such an award would seem to me to be most fitting, both as a recognition of what he has given to our country and to mankind and as a means of helping to carry forward his work through inspiring others to dedicate their lives and talents to scientific effort."

John S. Foster, Jr. 1960

Herbert F. York 1962

John H. Nuckolls 1969

Michael M. May 1970

Thomas E. Wainwright 1973

Seymour Sack 1973

Charles A. McDonald 1974

William Lokke 1975

John L. Emmett 1977

B. Grant Logan 1980

Lowell L. Wood 1981
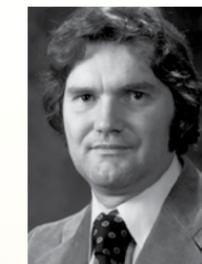
George F. Chapline 1982
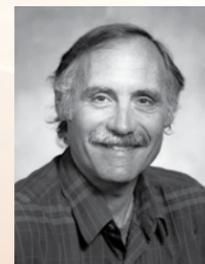
George B. Zimmerman 1983

Robert B. Laughlin 1984

Peter L. Hagelstein 1984

Thomas A. Weaver 1985

Joe W. Gray 1986

Wayne J. Shotts 1990

Richard Fortner 1991

John D. Lindl 1994

E. Michael Campbell 1994
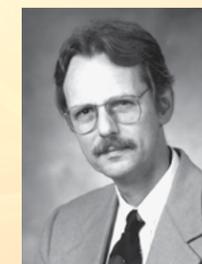
Charles R. Alcock 1996

Benjamin D. Santer 2002

Bruce T. Goodwin 2002

Clair E. Max 2004

Omar Hurricane 2009

Thomas P. Guilderson 2011

Siegfried H. Glenzer 2013

Stephen C. Myers 2013

Jennifer Pett-Ridge 2022

Sofia Quaglioni 2022

The Sixties

New Leadership

Harold Brown
(1960 • 1961)

John S. Foster, Jr.
(1961 • 1965)

Michael M. May
(1965 • 1971)

Since its establishment, the Laboratory has followed Ernest O. Lawrence's approach of how large-scale science should be pursued: through multidisciplinary teams dedicated to solving challenging problems and responding to national needs. A rapid response was called for when the Soviet Union broke the international nuclear testing moratorium in August 1961. The following year, the United States mounted its most ambitious—and last—series of nuclear tests in the Central Pacific, Operation Dominic. The Laboratory proof-tested nuclear designs fielded during the moratorium and laid the groundwork for future Livermore designs of

Multidisciplinary team science

compact, high-yield ballistic missile warheads.

Multidisciplinary expertise gained by the Laboratory, along with the need to understand the consequences of atmospheric nuclear testing, spawned bioscience and environmental programs at Livermore. Subsequent biotechnology developments contributed to the Department of Energy's bold decision to launch its Human Genome Initiative. Environmental programs have led to novel groundwater remediation technologies and atmospheric modeling capabilities that range from local to global scales. A multidisciplinary approach is also the hallmark of Livermore's international assessments program, which has supported the U.S. Intelligence Community since 1965.

Improved Nonnuclear Testing Capabilities

Site 300, the Laboratory's remote experimental test site, was a busy place in 1960. In the midst of a nuclear testing moratorium, Livermore was enhancing its nonnuclear testing capabilities. Two test complexes, a chemistry facility, a high-explosives preparation facility, a remote disassembly complex, and three other buildings were completed that year. In addition, a new linear accelerator (linac) was delivered to Site 300. That machine, which was installed in Bunker 351 (now 851), has undergone
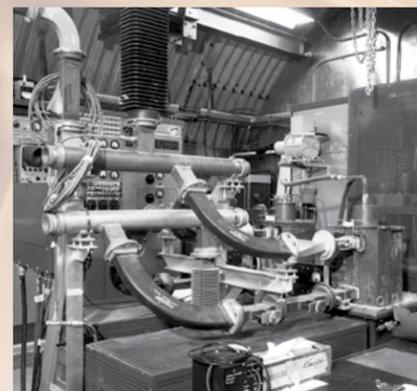
The XR2 machine (above and left) was located in Sugar Bunker (far left) at the Nevada Test Site (NTS) until it was moved to Site 300 near Livermore. There, it provided the Laboratory's first primitive radiographic capability. A new linear accelerator was delivered to NTS in 1960.

Accelerator Technology Development

The Laboratory has a long history of advancing the technology of electron linear accelerators for scientific and national security applications. After ASTRON, the Electron Test Accelerator (ETA) was built to study electron beam propagation in air as a possible directed-energy weapon. Completed in 1983, the 10-times more energetic Advanced Test Accelerator at Site 300 (right) furthered the study of beam propagation, and the beam was used as a pump for a free electron laser (FEL). In the 1990s, Livermore collaborated with the Stanford Linear Accelerator Center (now SLAC National Accelerator Laboratory) and Lawrence Berkeley National Laboratory to design and build the B-Factory at SLAC. More recently, Livermore scientists and collaborators have demonstrated capabilities to accelerate electrons to extremely high energies over very short distances using a tabletop-sized ultrashort-pulse laser.

numerous upgrades and is still used for hydrodynamics experiments. The accelerator generates the powerful x-ray flashes needed for taking images of mock nuclear-weapon primaries as they implode.

The linac for Bunker 351 superseded the capabilities of Bunker 312's XR2 machine, which had been moved from Sugar Bunker at the Nevada Test Site to Site 300 in the late 1950s. Charles McDonald, who later rose to senior management positions at the Laboratory, was one of the graduate students who helped build the XR2 in 1951 at the Radiation Laboratory in Berkeley. Starting at the Laboratory in fusion science research, McDonald became a weapon primary designer and then used the machine at Sugar Bunker.

Meanwhile, in another part of the Laboratory, Nicholas Christofilos, one of his generation's most original thinkers in physics, was pursuing a magnetic fusion concept, ASTRON. Born in Boston, Massachusetts, Christofilos grew up in Greece, where he received a degree in engineering, privately studied physics, and first invented and patented the concept of alternate gradient (strong) focusing for particle accelerators. ASTRON required the invention of a new kind of electron accelerator, the induction linear accelerator (or induction linac), to produce an intense circulating electron beam to magnetically confine and heat a plasma to, it was hoped, thermonuclear ignition temperatures. The world's first induction linac was built for the ASTRON project in 1963.

Induction linacs are now the heart of the nation's two most modern hydrodynamic testing facilities—the Contained Firing Facility at Site 300 (with the Flash X-Ray (FXR) machine) and the Dual Axis Radiographic Hydrodynamic Test Facility (DARHT) at Los Alamos. Built in 1982 and subsequently upgraded, FXR was used in the 1990s to perform the first experiments in which scientists recorded a detailed digital image of a highly compressed gas cavity inside a weapon (see Year 1985). Other successor induction linacs include three accelerators built (and since retired) at Livermore for beam research: the Electron Test Accelerator (ETA), ETA-II, and the Advanced Test Accelerator at Site 300.

Magnetic Fusion and International Cooperation

In 1961, the International Atomic Energy Agency held its first conference on controlled nuclear fusion in Salzburg, Austria. It was the second international gathering of fusion researchers, following the 1958 Atoms for Peace Conference in Geneva, Switzerland. The Geneva conference had attracted 5,000 scientists, government officials, and observers, who witnessed the unveiling of fusion research by American, British, and Russian scientists. The weekend before the conference, the United States and Great Britain announced the end of secrecy in their controlled fusion research efforts. The Russians then announced that they had built the world's largest fusion research device, a doughnut-shaped machine called a tokamak, and declassified their research as well.

Livermore's Controlled Thermonuclear Reactions (CTR) Program, which was part of the Atomic Energy Commission's Project Sherwood, began when the Laboratory opened in 1952. Herbert York's original written prospectus for the Livermore site included the establishment of a small CTR group of about seven physicists and engineers. Richard Post, who wrote many of the CTR group's first monthly reports, was recruited by York to help launch the program. Early exploration of various concepts led the team to focus its efforts on the magnetic mirror concept, in which a hot fusion plasma (charged particles) would be confined in a cylindrical region by a uniform magnetic field with intensified fields at the ends. Researchers explored two

experimental lines using two series of machines: one led by Post (Table Top, Felix, ALICE, and Baseball I and II) and the other led by Fred Coensgen (Toy Top, Toy Top II, 2X, 2XII, and 2XIIB).

At the 1958 Geneva conference, the Laboratory's significant achievements in magnetic fusion were reported: the creation of a hot, mirror-confined plasma in Toy Top; the confinement of a hot-electron plasma between mirrors for a millisecond using Table Top; successful measurement of plasma density; and the development of ultrahigh vacuum techniques for use in Felix. Laboratory researchers also formulated the idea of hydromagnetic instability of plasma confined in a simple mirror machine, developed the theory of adiabatic (i.e., slow) confinement of charged particles in mirror systems, and recognized the need to overcome impurity radiation losses from plasmas to achieve fusion temperatures.

After Geneva, fusion energy research hit roadblocks—plasma instabilities in Livermore's mirror machines allowed the hot plasma to escape. At the 1961 Salzburg conference, the Soviet Union's chief fusion experimentalist, L. A. Artsimovich, was sternly critical of Livermore's fusion research; however,

the meeting did pave the way for future cooperation with Russian scientists while the Cold War raged. Artsimovich's colleagues shared how they suppressed plasma instabilities by reshaping the mirror field. Within months, Livermore researchers duplicated this result and went on to pioneer new and improved mirror field configurations (see Year 1977). However, overcoming other high-frequency plasma instabilities would prove to be a major obstacle.

The Table Top machine was used by researchers to confine a hot electron plasma between magnetic mirrors for about a millisecond.

Physicist Fred Coensgen (shown) led the development of the Toy Top fusion research devices, which created a hot, mirror-confined plasma by plasma injection and magnetic compression. Toy Top experiments produced fusion neutrons, a significant early achievement in the controlled fusion program.
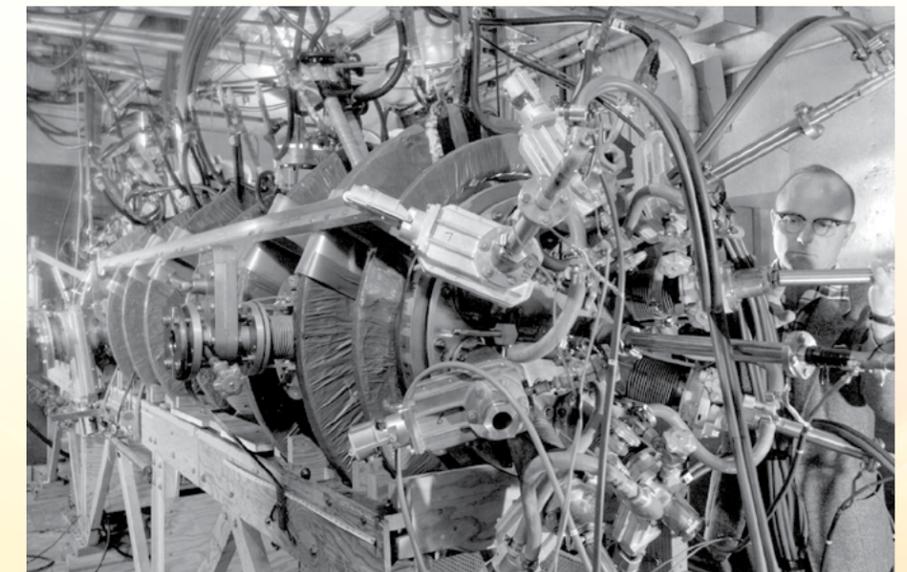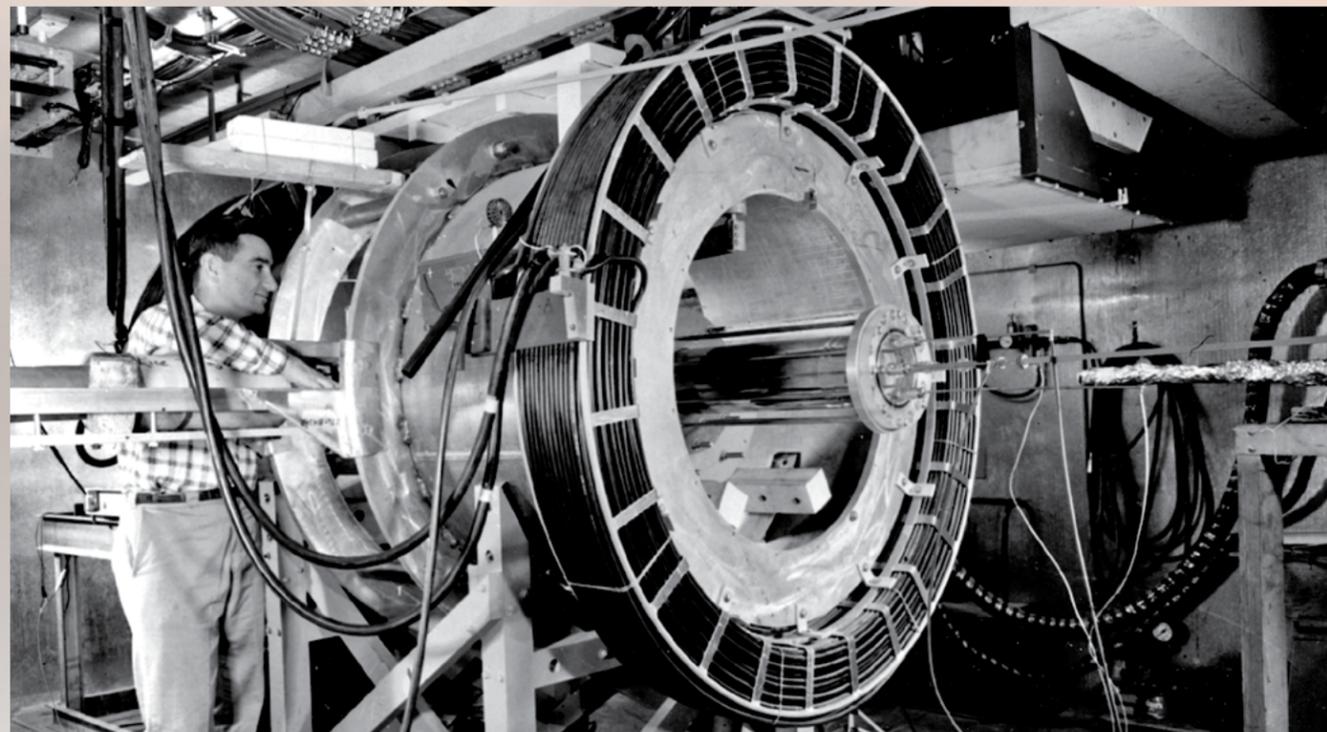
Richard Post—A Lifetime of Service

The December 1952 Laboratory phone book listed 250 employees, including a newly transferred physicist named Richard (Dick) Post, who still came to work four days each week 63 years later. During his remarkable career, which earned him a host of awards and honors, Post was a leader in magnetic fusion research and an innovator of solutions to energy-related needs, such as better flywheels for energy storage and fail-safe magnetic levitation for transportation. He received 34 patents—with 9 issued after he turned 90—and some 85 records of invention.
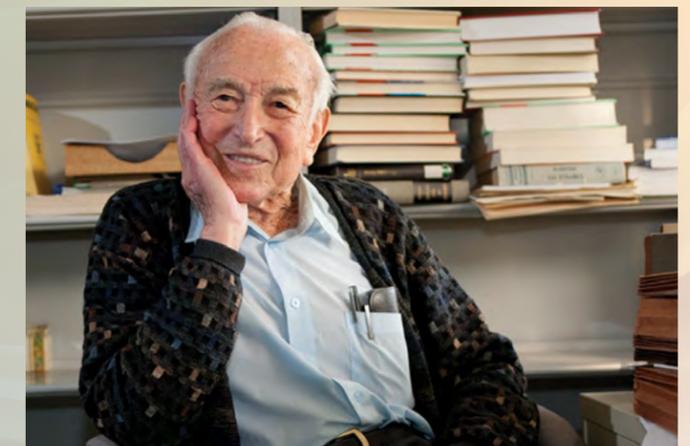
The Largest U.S. Nuclear Testing Operation

On August 30, 1961, Premier Nikita Khrushchev announced that the Soviet Union would break the three-year moratorium and resume nuclear testing. Two days later, the Soviets started an unprecedented series of atmospheric tests, including the detonation of a 50-megaton device. Subsequently, President John F. Kennedy decided that the nation must resume atmospheric nuclear testing, and he approved Operation Dominic—the largest U.S. nuclear testing operation ever conducted.

Thirty-six atmospheric tests were conducted at the Pacific Proving Grounds under Operation Dominic between April and November 1962. Approximately 28,000 military and civilian personnel participated in the test series, and more than 200,000 tons of supplies, construction materials, and diagnostics equipment were shipped or airlifted to the test areas. About 500 of the Laboratory's 4,700 employees participated in Operation Dominic. The Laboratory's Task Unit 8.1.2 was directed by Robert Goeckermann of Chemistry and Chuck Gilbert of Test Division.

Operation Dominic experiments proof-tested weapons introduced into the stockpile during the moratorium. The most dramatic experiment was Frigate Bird, in which the USS *Ethan Allen* launched a Polaris missile, and the Livermore-designed warhead successfully detonated over the open ocean. Most of the other tests were airbursts with the devices dropped by B-52 bombers. The data collected from these tests laid the groundwork for future Livermore designs of the Minuteman and Poseidon warheads, which were compact enough that numerous warheads could be carried by a single missile (see Year 1970).

Experiments were also carried out in 1962 to gather weapons effects data for the Department of Defense (DOD). For Operation Fishbowl (part of Operation Dominic), five Los Alamos–designed devices were lofted by Sandia-designed rockets and detonated at high altitude. Starfish Prime, for example, was a 1.4-megaton explosion at 400-kilometers altitude. Information was collected about the electromagnetic pulse phenomenon as well as other data related to ballistic missile defense systems (see Year 1966). Later in the year, additional tests for DOD were performed at the Nevada Test Site. In Johnnie Boy and Danny Boy, Livermore-designed devices were used to study cratering effects. The collected data also helped to validate later fallout models developed at the Laboratory.

Operation Dominic was the last series of atmospheric nuclear weapons tests conducted by the United States. Signed in Moscow on August 5, 1963, the Limited Test Ban Treaty banned weapons tests in the atmosphere, under water, and in outer space (see Year 1958).

The mushroom cloud from the Frigate Bird operational test of the Polaris missile and warhead was observed through the periscope of the USS *Carbonero*, which was stationed some 30 miles from ground zero.

For Livermore's Muskegon test in Operation Dominic, the nuclear device was air-dropped from a B-52 bomber near Christmas Island. The yield of the weapons-related experiment was in the range of 50 kilotons.
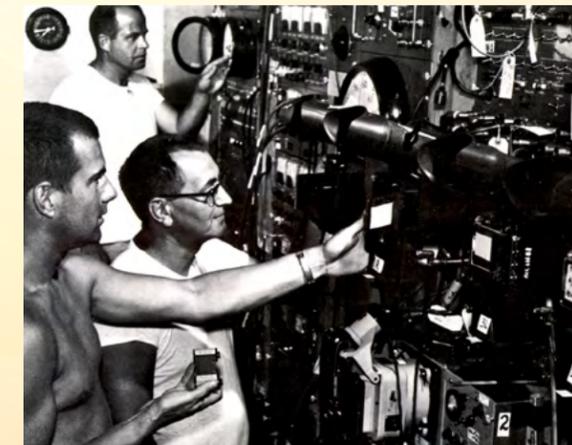
During Operation Dominic, diagnostic measurements were gathered aboard ships, and aircraft were used to collect debris samples.

To Understand the Effects of Radiation

The first biomedical and environmental research program began at Livermore in 1963. The Atomic Energy Commission recognized a growing need for a bioenvironmental presence at the Nevada and Pacific test sites, and the decision was made for this work to take place at Livermore. John Gofman, a distinguished professor at the University of California at Berkeley, was recruited to set up the program, which would study the effects of radiation on humans.

In the early 1970s, the biomedical focus of the program shifted toward biological measurements that indicated the dose to subjects who had been exposed to radiation. That work led to an examination of the effects of radiation and other toxins on the building blocks of the human genetic apparatus. Increasingly, the focus was on DNA—how it is damaged, what damages it, how it repairs itself, and how these processes may vary with the genetic makeup of the individual. Technology development at Livermore and Los Alamos provided the basis for DOE's decision to launch its Human Genome Initiative in 1987 (see Year 1987). That initiative evolved into the international Human Genome Project, which took on the task of sequencing all 3 billion base pairs of human DNA. Livermore was a major player among the dozen or so laboratories in the world participating in the largest biological research project ever undertaken.

Biomedical scientists worked with engineers, physicists, laser experts, chemists, and materials scientists to develop Livermore's preeminence in flow cytometry, a technique for measuring and separating cells. Other Livermore innovations included analyzing and purifying biological samples, imaging chromosomes and DNA, early sequencing procedures, and associated database processes. The Laboratory's strength in computation also led to unique capabilities in computer simulation of biological processes, such as predicting the three-dimensional structure of proteins directly from DNA sequence data.

This same cooperative approach led Livermore's Center for Accelerator Mass Spectrometry (CAMS) to concentrate on biological measurements (see Year 1990). The extraordinary sensitivity of AMS means that it can detect the interaction of mutagens with DNA in the first step in carcinogenesis. Now, LLNL is a major participant in DOE's support for the National Cancer Institute's Cancer Moonshot.

In the 1990s, research efforts began to focus on emerging concerns about bioterrorism as a threat to international security. Laboratory scientists took the initiative to develop advanced microtechnologies needed to improve detection systems for biological and chemical agents (see Year 2001). The Winter Olympics of 2002 was the staging ground for Livermore methods to continuously monitor crowd venues for the presence of such agents.

Given the growing concerns about bioterrorism, the Olympics were the first of many applications of our bioscience research to homeland and international security.

Dr. John Gofman (second from left) discusses with colleagues an abnormal chromosome pattern in malignant cells. Gofman came to the Laboratory in 1963 to set up a new biomedical and environmental research program.
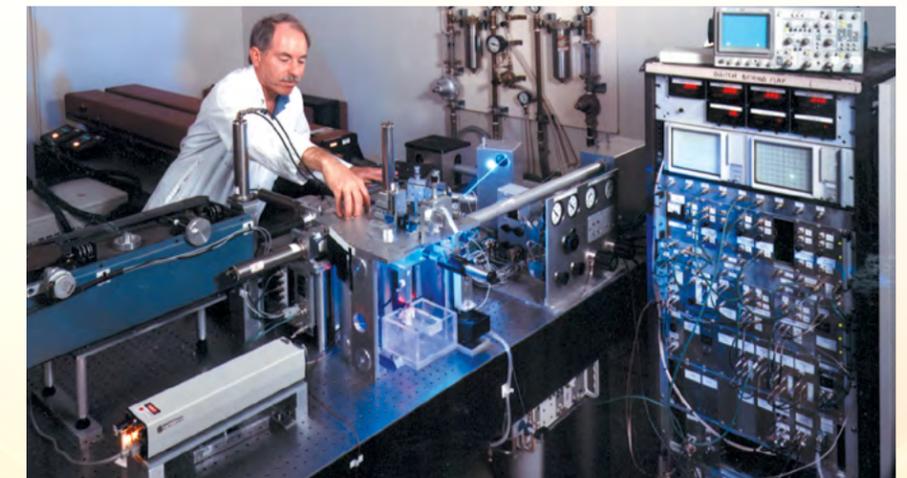
Early groundbreaking work in flow cytometry, a technique for separating specific cells from other cells, led to numerous medical research applications in genomics research and national security applications, such as biosensors that detect specific agents used in biological weapons.

Contributing to the Cancer Moonshot

Livermore's high-performance computing will play a major role in the National Cancer Institute's Cancer Moonshot, launched in 2017 as a $1.8-billion, seven-year undertaking to accelerate cancer research. LLNL is strongly contributing to the DOE's three pilot projects. Much of this effort builds on partnerships that the Laboratory leads. The research draws on Livermore's exceptional capabilities in large-scale simulation of biological systems and deep analysis of complex and diverse data.

Bringing Academia to the Laboratory

In the early 1960s, Edward Teller championed the need for a graduate program in applied science. He wanted to see a university-level educational facility established at Livermore. Teller held numerous meetings with University of California (UC) administrators at Berkeley and Davis before finally negotiating an agreement to create the UC Davis Department of Applied Science. That department, which was part of UC Davis's newly formed College of Engineering, has often been referred to as "Teller Tech."

With a trailer for administrative offices and two rooms in an old barracks building for classrooms, the UC Davis Department of Applied Science was officially dedicated on January 16, 1964. In 1977, a permanent building for the department was dedicated just outside the Laboratory's gates, with no less than former Vice President Nelson Rockefeller on hand for the ceremonies.

Teller served as the department's first administrator, and his staff included one full-time employee as well as a half-time vice chairman. The Department of Applied Science opened with 81 students—12 full-time students and 69 Laboratory employees working to finish their advanced degrees. Altogether, the department awarded more than 400 Ph.D.s with about 50 percent of its graduates taking their first job at the Laboratory. In 2011, facing a $100 million budget shortfall, UC Davis closed the Department of Applied Science. Yet, over the same span of years, many ties with UC campuses grew stronger and outreach extended to more university partners.

For example, in 1982, a branch of the UC multicampus Institute of Geophysics and Planetary Physics (IGPP) opened. Other academic outreach centers and institutes followed, such as the Center for Accelerator Mass Spectrometry (see Year 1990), the Institute for Scientific Computing Research, the Center for Bioengineering, the Glenn T. Seaborg Institute, the Jupiter Laser Facility, and the Center for High Energy Density Science.

Currently, LLNL researchers are engaged in more than 500 collaborations with faculty world-wide. More than 250 postdoctoral fellows work at the Laboratory—many of whom stay on to become full-time employees. More than 1,000 graduate and undergraduate students per year participate in LLNL's Visiting Scholar and Summer Employment programs. In addition, Laboratory employees engage in a wide range of science, technology, engineering, and mathematics (STEM) outreach activities directed at K–12 students.

Ties remain very strong with UC. In addition to the many LLNL researcher–UC professor relationships, UC administers a collaborative research projects program funded by contract management fees received as a Lawrence Livermore National Security, LLC, partner. Other strategic partnerships include those with Texas A&M University, Georgetown University, the Historically Black Colleges and Universities/Minority Serving Institutions, the California State University system, and local community colleges.

Former Vice President Nelson Rockefeller (shown between Edward Teller and a student) visited the Laboratory in 1977 to dedicate the new building (right) for the University of California at Davis Department of Applied Science. Plans are being developed for the facility's use for academic outreach as part of the Livermore Valley Open Campus.

In June 2017, the tenth annual Institutional Postdoctoral Poster Symposium showcased a total of 183 posters presented by Laboratory postdoctoral researchers and Livermore graduate scholars.

Assessing the Weapons Capabilities of Others

Since the early days of Livermore, intelligence agencies have sought Laboratory expertise in nuclear weapons design to analyze atmospheric nuclear tests conducted by the Soviets and to develop an understanding of the Soviet nuclear program and weapon designs. The Soviet Union's first test of an atomic weapon in the late 1940s took the West by surprise, and monitoring the Soviet effort to rapidly develop nuclear weapons became a paramount concern of U.S. intelligence agencies.

In 1965, Laboratory scientists and engineers helping intelligence agencies understand the significance of Soviet nuclear weapons tests were consolidated into Z Division, today known as the Intelligence Program or Z Program. Under Laboratory Director John Foster, a formal relationship with the U.S. Intelligence Community (IC) was established in a memorandum of understanding signed between the Central Intelligence Agency (CIA) and the Atomic Energy Commission, a predecessor to the Department of Energy. LLNL celebrated the 50th anniversary of this successful relationship in 2015.

Scientists and engineers in Z Division analyzed radiological samples from Soviet, and later Chinese, nuclear tests. They also developed new technologies for monitoring tests and collecting data that allowed analysts to determine what type of weapon was being tested—atomic or thermonuclear. Anticipating that nuclear proliferation could become a major problem, Z Division started a proliferation monitoring program in the mid-1970s. That effort has continued to grow together with the IC's need for all-source analyses of the nuclear programs in an expanding list of countries of concern. Involving both regional specialists and technical experts, these multidisciplinary analyses draw on general technical knowledge about nuclear testing, specifics about each country's nuclear capabilities, and evaluations of nontechnical issues that motivate nuclear programs.

Z Division was a primary building block of Livermore's Nonproliferation, Arms Control, and International Security Directorate (NAI), established by Director John Nuckolls to respond to an emerging threat—weapons-of-mass-destruction (WMD) proliferation and terrorism. NAI has since transformed into the Global Security Principal Directorate, with Z-Division activities relocated after 9/11 into a new facility to accommodate growth (see Year 2002).

The Laboratory's Intelligence Program applies the complete set of LLNL's science and technology capabilities to support the IC in overcoming its most difficult challenges. Z Program's strategic intelligence mission involves developing deep contextual understanding to support national decision making with a particular focus on analyzing foreign nuclear weapons programs, identifying and evaluating WMD proliferation, and identifying foreign threats to U.S. national security posed by new technologies. Its anticipatory intelligence mission involves working to understand and identify emerging threats and delivering solutions in time to counter those threats. LLNL's top anticipatory initiatives focus on data analytics, additive manufacturing, biosecurity, and data collection systems. Z Program also supports current operations by providing timely, actionable solutions to achieve national security goals. Three primary topical missions include cyber intelligence, counterterrorism, and counterproliferation.

To help develop an understanding of the Soviet nuclear weapons program and nuclear forces, analysts studied photographs taken by satellites, such as this 1966 image of a Soviet military airfield with bombers visible.

Transports

Bombers
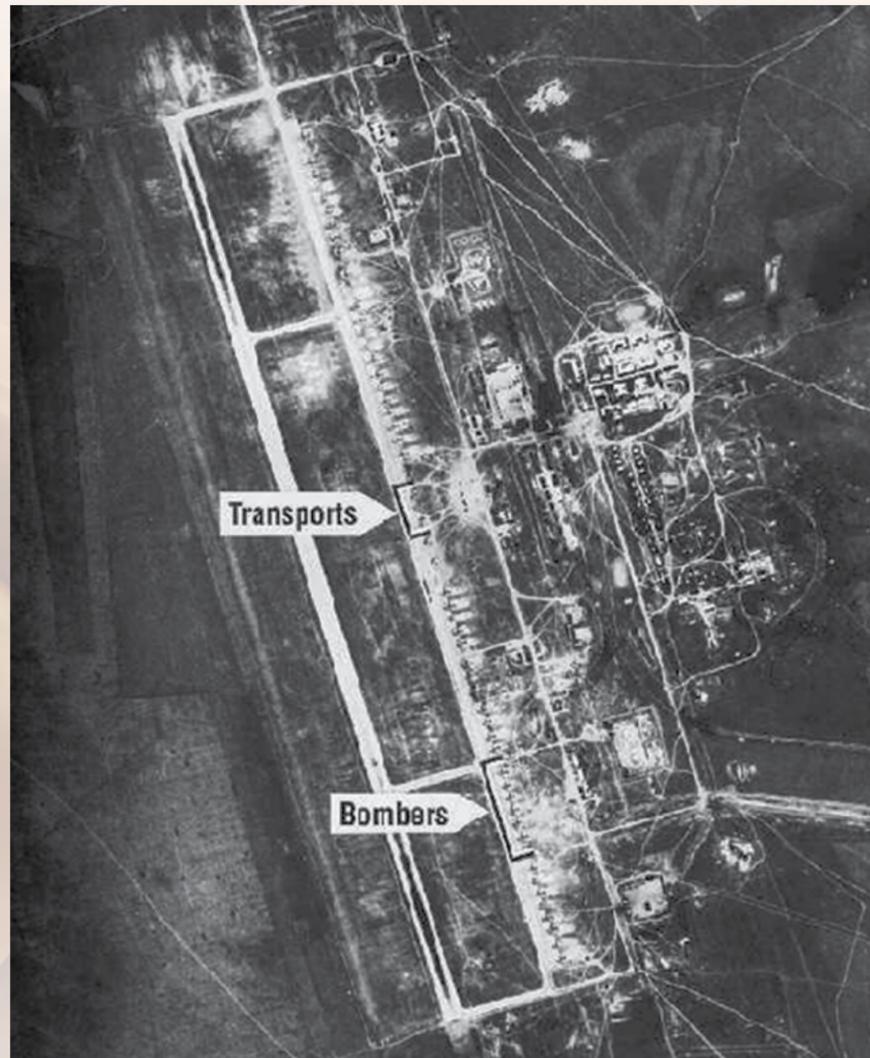
Developing Cyber Security Tools

Cyber security specialists at the Laboratory are developing tools to enhance the security of complex networks. Network Mapping Systems (NeMS) is a computer network mapping tool that is fast and unobtrusive to the network being mapped. It can routinely identify network connections that were unexpected by the network operator. NeMS scans and probes a computer network to characterize its operating environment in detail, building a visual representation of its current structure and activity profile. The nation depends on many critical complex networks. Operators need to understand an entire network as it evolves to prevent intrusions and accomplish critical tasks when system failures do occur.

Dealing with Transient Electromagnetic Pulses

A scale model of a Grumman A-6 aircraft is tested in the EMPEROR facility, an anechoic chamber still in use at the Laboratory. The cone-shaped copper structure in the chamber produced extremely high-bandwidth electromagnetic fields for EMP and high-power microwave vulnerability studies.

A consequence of the Starfish Prime high-altitude nuclear test in 1962 was the failure of 30 strings of streetlights in Oahu, Hawaii, 1,300 kilometers away. Although only about 1 percent of Oahu's streetlights were affected, their failure raised concerns that the electromagnetic pulse (EMP) generated by a nuclear weapon burst could cause widespread damage to the nation's civilian and military infrastructures. The phenomenon needed to be understood.

Modeling and experimentation to study transient electromagnetic pulses has been a research topic at the Laboratory ever since the Starfish Prime test (see Year 1962). Researchers have provided support to the Defense Nuclear Agency—now the Defense Threat Reduction Agency—which is the Department of Defense agency responsible for assessing the hardness of military equipment to EMP. In addition, for the weapons program, the effects of fast electromagnetic pulses had to be understood to develop nuclear test diagnostics and to ensure the hardness of U.S. nuclear warheads to electromagnetic effects.

In 1966, the Institute of Electrical and Electronic Engineers published a paper by a Livermore researcher, K. S. Yee, that greatly advanced the art of modeling electromagnetic phenomena. "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media" introduced the Finite Difference Time Domain algorithm—a stable, efficient computational means for solving Maxwell's equations that has been widely used ever since.

Follow-on leading-edge electromagnetic simulation models were developed at the Laboratory. An example is Livermore's Numerical Electromagnetic Code (NEC), an imported model that was greatly improved by Laboratory researchers in the 1970s. NEC is still the world's most widely used code for analyzing the performance of wire-frame antennas; over 3,000 copies have been distributed. Expertise in applied electromagnetics continues to be critical to the Laboratory's national security missions. Today's premier simulation capability, EMSolve, models in detail the electric and magnetic fields of complex systems ranging in size from integrated circuits to entire buildings and over timescales from billionths to tens of seconds.

LLNL computer scientists and engineers developed EMSolve to run on parallel computer architectures. With advances in supercomputing, they have increased simulation accuracy and speed, added capabilities, and coupled EMSolve for use with thermal, structural, and hydrodynamic codes. The code has been used to address pulsed-power issues that
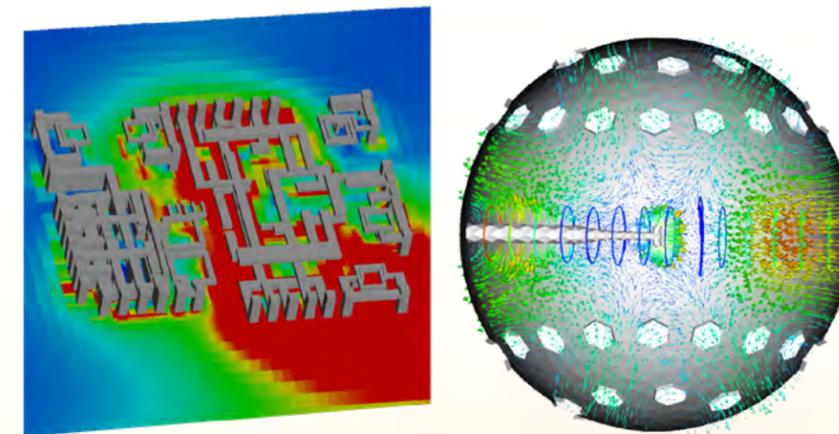
The LLNL-developed EMSolve code finds wide-ranging applications: to study electromagnetic noise in integrated circuits (left) and to ensure that electromagnetic pulses resulting from extremely short but high-energy laser bursts in the National Ignition Facility's target chamber (right) do not lead to data loss or damage to diagnostic equipment.
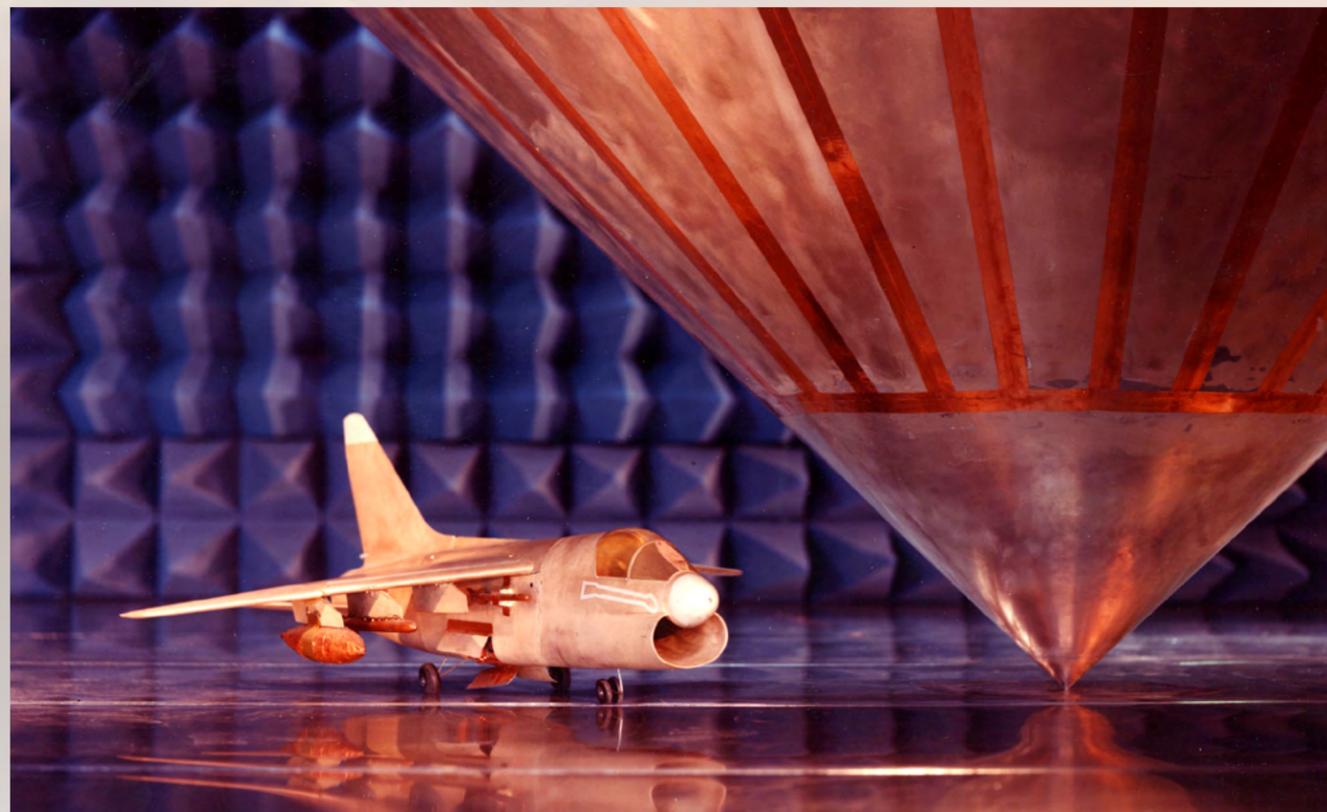
Hardening U.S. Nuclear Warheads

A transient electromagnetic pulse is only one of a variety of nuclear effects that a U.S. intercontinental ballistic missile or submarine-launched ballistic missile warhead might encounter—and have to survive—on the way to its target. Hardening warheads to nuclear effects has been an important issue since the Soviets began deploying antiballistic missile (ABM) defenses in the 1960s. Missile warheads have been designed with special hardening features to improve survivability when penetrating an ABM system (see Year 1970). These features were developed with the aid of experimental facilities, such as the Super Kukla burst reactor, and an extensive series of "exposure" nuclear tests conducted in conjunction with the Defense Nuclear Agency.

arise related to nuclear weapons, design and test wall-penetrating and ground-penetrating radars, analyze the effectiveness of radar systems to detect space debris, and characterize the electromagnetic signatures from conventional explosions.
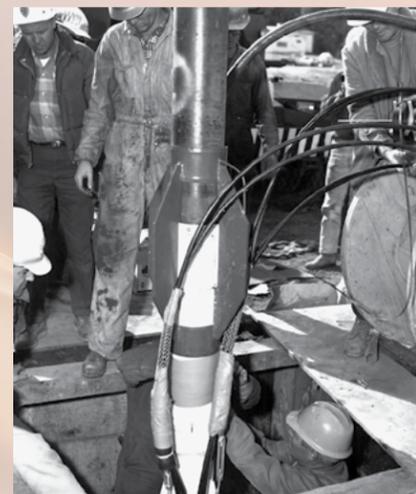
Expertise in applied electromagnetics includes experimentation. LLNL operates facilities for development of pulsed-power systems and components (including explosive systems), an anechoic chamber and laboratory space for high-power radio-frequency experiments, and particle accelerators for radiography and accelerator component development.

The Quest for Energy Resources

On December 10, 1967, under the technical direction of Livermore scientists, a 29-kiloton nuclear device exploded in a sandstone formation at a 4,000-foot depth in the San Juan basin of New Mexico. The experiment, Gasbuggy, was a joint venture of the Atomic Energy Commission, El Paso Natural Gas Company, and the Bureau of Mines of the U.S. Department of the Interior. It was the first of three Project Plowshare experiments, each partially funded by U.S. industry, to test the feasibility of using nuclear explosives to stimulate natural gas production in rock too impermeable for economical production by conventional means. Tight sandstone formations, like those in the San Juan basin, were projected to hold at least 300 trillion cubic feet of natural gas in the western United States.

The detonation produced an underground chimney 335 feet high with a diameter of almost 165 feet. Gas was extracted from the chimney in six subsequent major production tests (the last in 1973). Results were encouraging in that gas production was increased six to eight times over previous rates. However, the "clean" Plowshare device used in Gasbuggy, which was designed to minimize the post-detonation residual radiation, still resulted in undesirably high concentrations of tritium in the gas. Livermore's device design was acceptably clean for the subsequent Rio Blanco experiment; however, it was not economically viable to use nuclear explosives to stimulate gas production.

Gasbuggy and two subsequent gas-stimulation nuclear tests brought Project Plowshare field experiments to a close, but they marked the beginning of Livermore's work with U.S. industry to enhance subsurface energy production. After the 1973 energy crisis, Laboratory researchers engaged in a variety of energy projects that culminated in large-scale demonstrations of technical feasibility and commercial viability. For example, processes for in situ coal gasification—converting coal beds to gas without mining—were developed. Activities ran from 1974 through 1988, with the first large-scale tests conducted at the Hoe Creek Site in Wyoming in 1977. In addition, researchers pursued activities that led to a technical demonstration of retorting oil shale to recover oil from large U.S. reserves. A 6-ton-capacity pilot oil-shale retort facility operated at the Laboratory in the early 1980s.

Currently, the Laboratory is partnered with the oil and gas industry, including both large and small companies, in efforts to optimize the production of unconventional oil and gas. Livermore researchers combined expertise in subsurface fracture mechanics and high-performance computing to develop GEOS, a 3D multiphysics supercomputer simulation code for predicting subsurface behavior when shale formations are subjected to hydraulic fracturing. Horizontal drilling strategies are being designed to maximize oil and gas production with the least environmental impact, and field experiments are being conducted at multiple sites, including the Permian Basin in Texas.

In the Gasbuggy experiment, a part of Project Plowshare, a nuclear explosive was lowered down a 4,000-foot hole and detonated in a sandstone formation in New Mexico to increase natural gas production.

GEOS, a high-performance computing model of detailed geomechanics, is used to explore fracture patterns in a 300-meter-long section of a production field. The goal is to enhance resource recovery while reducing environmental impacts.

1968 Royston Plan
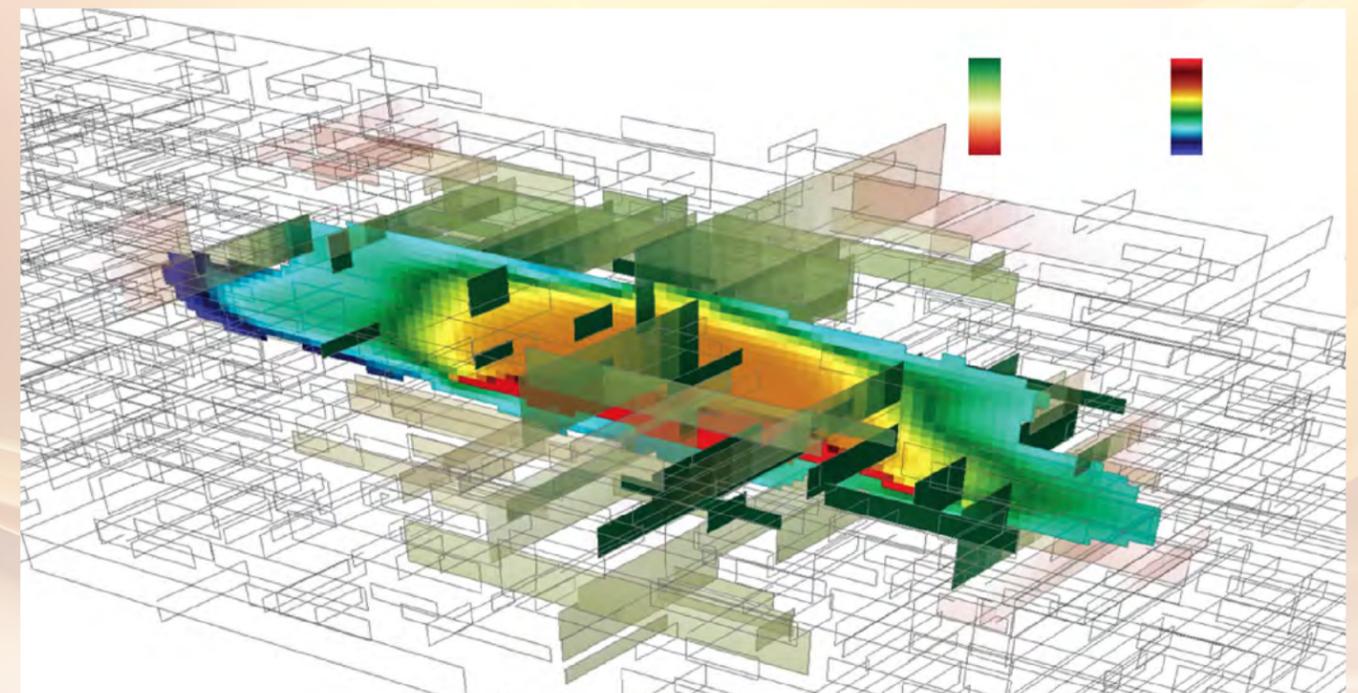
An Attractive Place to Work

In 1968, the Laboratory went for a new look, away from the military aspect it inherited and toward more of a campus environment. At the initiative of Carl Haussmann, then Associate Director for Plans and in charge of Livermore's nascent Laser Program, the Laboratory hired landscape architectural firm Royston, Hanamoto, Beck & Abey to prepare a long-range development master plan for the site. The Royston Plan sought to bring order out of the chaos created by the haphazard, random construction of buildings and roadways that characterized the first 18 years of the Laboratory's existence.

At the time, employees worked in barracks and facilities crowded into a grid pattern in the southwest corner of the site. New facilities were built adjacent to existing buildings in what seemed the most expedient way to grow, but which, in fact, led to congestion and loss of the flexibility conducive for research. By contrast, the northeastern half of the Laboratory was underused.

Royston proposed a flexible development plan based on a curvilinear pattern of loop roads and utilities that would create a wider variety of land parcel shapes and large developable areas. The Laboratory adopted it as the framework for its first master development plan, which established basic planning principles to guide future growth. The Plan, as it has come to be called, was termed exemplary by the Atomic Energy Commission (the Department of Energy's predecessor) and sparked the initiation of comprehensive site plans at other facilities in the complex.

The Royston Plan introduced two loop-road systems—including northern California's first traffic circle—in the undeveloped area of the site, curving around a central hub that was zoned for general support functions such as the business offices, technical information facilities and libraries, and plant engineering. The loop system not only made for more efficient travel and utilities distribution around the site but also reduced traffic and saved money. Another major element of The Plan was making the site more attractive to employees by incorporating liberal landscaping and inviting bicycle and walking paths. An aesthetically pleasing work environment, it was judged, would help attract and retain valuable staff.

The Laser Program's facilities were the first developed in accordance with The Plan. Laser buildings 381 and 391 had offices and main entrances on Inner Loop Road, which was to be the "front door" to future facilities. Outer Loop Road was intended to act as the "service entrance" to the large laboratories behind the office buildings, with smaller laboratories forming a transition between the two areas.

Today, the Laboratory has little undeveloped acreage remaining, but The Plan continues to guide Laboratory growth as the Livermore Valley Open Campus is developed. The Plan was so visionary that it still retains its integrity and flexibility after nearly 50 years.

The Royston Plan guided the Laboratory's transformation from a former military facility to a campuslike setting that is an attractive place to work and a vital part of the community.

FUTURE
LAWRENCE LIVERMORE LABORATORY
University of California / ERDA
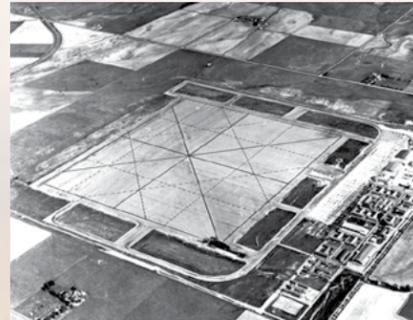
Carl Haussmann

In 45 years of service at the Laboratory, Carl Haussmann made major contributions in many technical areas, including weapons, high-end computing, and lasers. He also had a visionary interest in the strategic development of the site and was the driving force behind commissioning and implementing the Royston Plan. Known as the "Father of the Trees" because of his passion for landscaping, Haussmann arranged for the California Conservation Corps to plant some 300 trees throughout the site.

A plaque affixed near the entrance to Building 111 reads: "In gratitude for the beauty and function of the Livermore site, landscape, architecture, and trees, which Carl planned and patronized over 30 years."
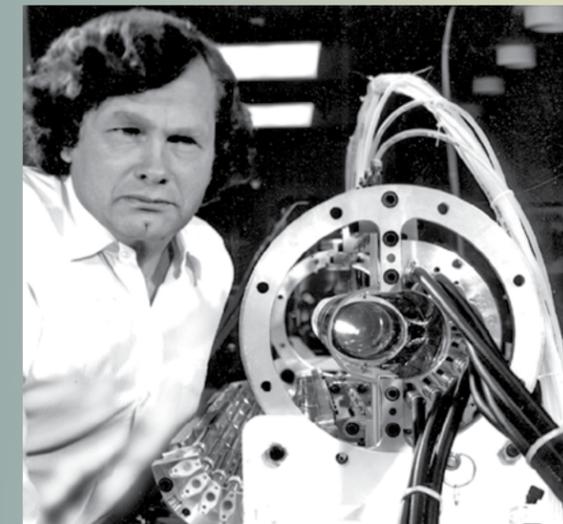
Carl Haussmann with a disk laser, one of the technologies for the Cyclops laser.

Time Sharing and Two-Dimensional Modeling

Always eager for better computer simulations, Laboratory weapons designers enthusiastically greeted the arrival of their first CDC 7600 supercomputer in 1969. Nineteen of the first 20 scientific computers purchased by the Laboratory had been from IBM. That string was broken in 1962 when the Lab bought a CDC 1604 mainframe from then-upstart Control Data Corporation (CDC) of Minnesota.

A young CDC engineer named Seymour Cray was already at work on an innovative design for a machine 50 times faster than the CDC 1604,

The arrival of the first CDC 7600 continued a long period of Livermore leadership in computing and custom software development for nuclear design and plasma simulations.

The innovative Livermore Television Monitor Display System, or TMDS (left), was a familiar sight in the 1970s, providing visual information to users. Data management and storage were improved with the first "chip" storage of the IBM Photostore system (below). It was designed to store online an astonishing (at the time) 1 trillion bits of data.

and Livermore happily acquired one of his CDC 6600 computers for $8 million in August 1964. Cray's design team then further refined this approach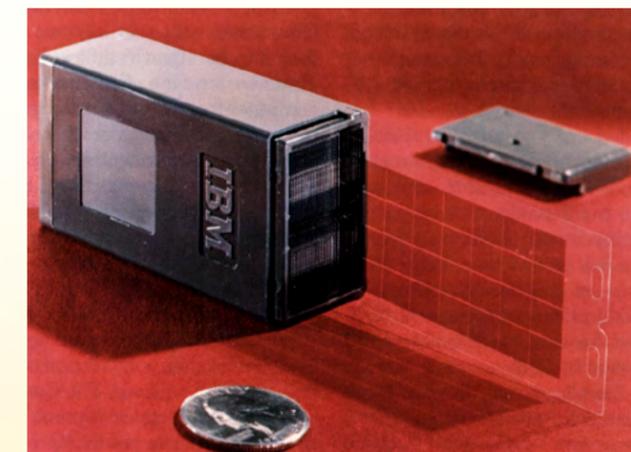, yielding the even larger and faster CDC 7600 in 1969. In the hands of Laboratory users, these machines defined scientific supercomputing for a decade. Their small instruction sets, fast clock speeds, extremely dense custom-soldered circuit boards, and clever use of the machine frame for cooling were ideal for nuclear design and plasma simulations.

Laboratory computer scientists responded to the availability of the CDC 6600 and CDC 7600 with a long, fertile period of custom software development. The Livermore Time Sharing System (LTSS) enabled hundreds of users to run application codes simultaneously and tune them interactively. Large libraries of Fortran subroutines evolved, optimized for the Laboratory's mathematical and graphical needs. The local job-control language, online documentation system, and file-storage service set the standards in their fields, as did the whimsically named Octopus network that efficiently connected hundreds of remote terminals and printers to the central, shared computers.

This combination of leading-edge hardware and innovative support software yielded many benefits for the two-dimensional modeling projects then under way at Livermore. Higher resolution simulations clarified important aspects of ongoing field tests. New experiments could be optimized at the desktop. And scientists gained increased understanding of the physics underlying many Laboratory projects.

The Laboratory's collaboration with Seymour Cray continued for another 15 years. In 1972, he started his own company (Cray Research) and developed his first integrated-circuit (chip-based) scientific computer, the CRAY-1. As they became available, Livermore acquired early serial-number versions of Cray Research machines, refining the Cray Time Sharing System (formerly LTSS) to make the most of each new generation of hardware.

In 1985, when the Laboratory received the world's first CRAY-2 supercomputer, it finally retired its last CDC 7600. In many ways, the hardware–software combination pioneered here was the model on which the National Science Foundation supercomputer centers were later created.

The Seventies

New Leadership

Roger Batzel
(1971 • 1988)

In the early 1970s, the Laboratory completed development of new warheads for the nation's strategic missile forces and for the Spartan antiballistic missile interceptor. Livermore pushed the frontiers of what was possible in nuclear weapons design and engineering. Designers then turned their attention to modernizing NATO's nuclear forces with novel weapon designs and to exploring the use of insensitive high explosives for improved nuclear weapons safety.

Capitalizing on an emerging technology, Livermore also began a laser program and has been at the

On the frontiers of science and technology

forefront of laser science and technology ever since. In 1974, Janus was built, the first in a sequence of ever-larger lasers to explore inertial confinement fusion (ICF) for national security and civilian applications. Design, engineering development, and use of the Laboratory's ICF lasers have contributed to thermonuclear weapons science, enabled new scientific discoveries, and stimulated the development of new products and processes in U.S. industry. The 1970s' energy crisis helped to invigorate long-term research efforts in both ICF and magnetic fusion as well as other energy research programs at the Laboratory.

Multiple Warheads Increase Missile Effectiveness

In the 1970s, Minuteman III missiles with Livermore-designed W62 warheads were deployed in 550 silos at U.S. Air Force bases in three states.

In 1970, the United States introduced a new capability that dramatically increased the effectiveness of its land- and sea-based strategic missile forces. Both the Minuteman III intercontinental ballistic missile and the Poseidon C-3 submarine-launched ballistic missile were deployed with multiple independently targeted reentry vehicles (MIRVs), a technology that allowed each missile to attack multiple targets within a large "footprint." This provided considerable flexibility in targeting. MIRVs also were more cost-effective because they leveraged the large costs of missile silos and submarines. The warheads for each of these missile systems were designed by Livermore. The W62 warhead for Minuteman III
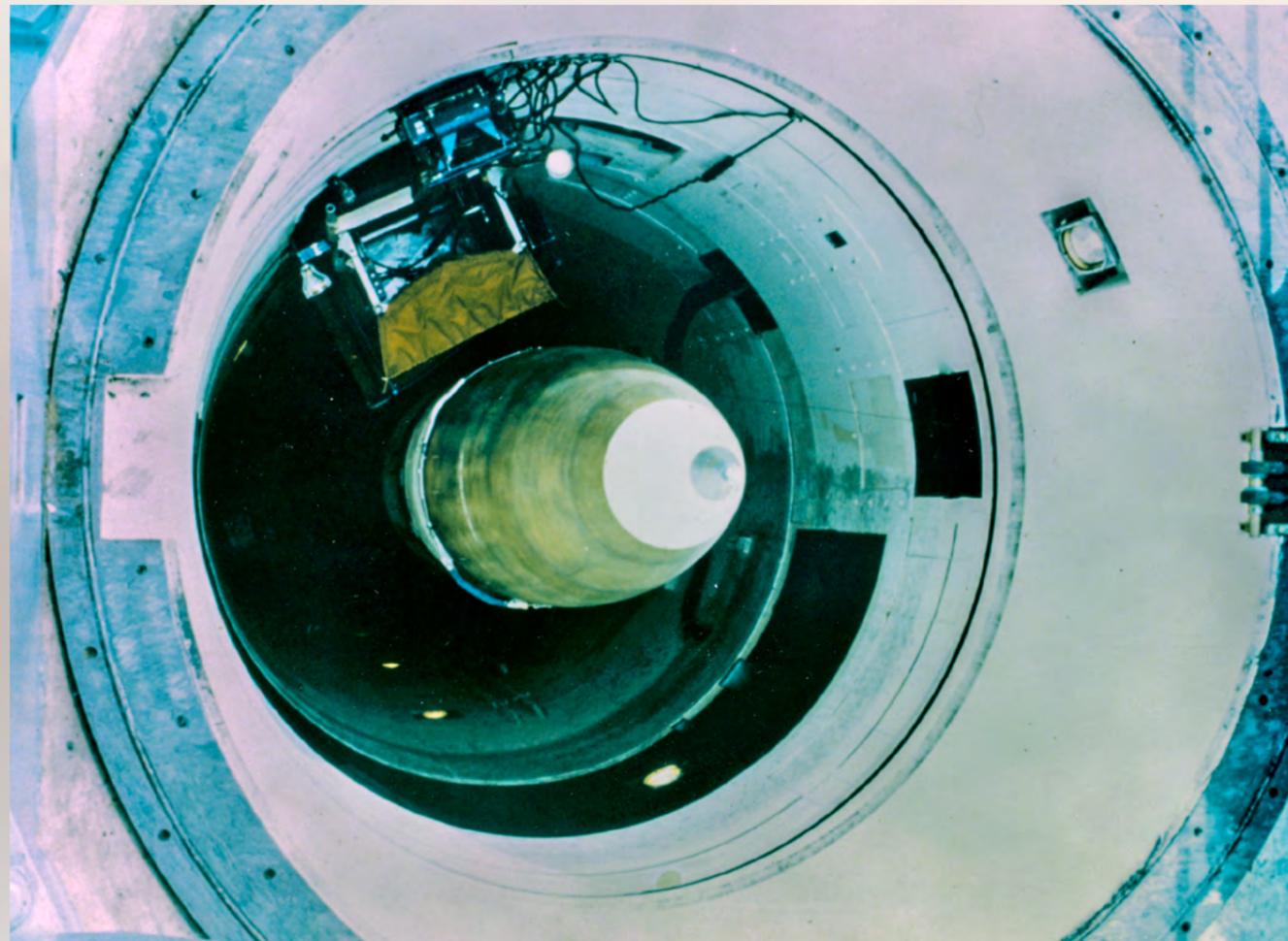
The Poseidon C-3 missile launched from a submerged submarine.

(deployed in April 1970) and the W68 warhead for C-3 (deployed in June 1970) pushed the envelope of yield-to-weight ratio, a key to the MIRV concept. They were also the first designs to include a comprehensive set of hardening features for protection against antiballistic missile (ABM) defenses. The warheads were the product of an extremely fruitful period in weapons development at the Laboratory during the 1960s.

The MIRV concept resulted from the convergence of missile technology improvements, concerns about Soviet work on ABM systems, and the desire for improved accuracy. Early in the development of Minuteman III, it became clear that a liquid-fueled fourth stage was needed for higher delivery accuracy. Further consideration led to the concept of using additional fuel in the fourth stage to independently target multiple RVs and penetration aids. Meanwhile, the ability of missile systems to deploy individual satellites through use of a post-boost control system had been demonstrated in the U.S. space program in October 1963. In December 1964, Secretary of Defense Robert McNamara approved development of a MIRV system for

Minuteman III. By early 1965, the Navy's Strategic Systems Project Office had developed baseline design requirements for the C-3 missile that would include MIRV capability.

Livermore received the assignment for both systems, and each program faced significant design challenges. The requirement to put 14 vehicles on the relatively small C-3 platform was very stressing. The W68 (in the Mk3 reentry body) was the smallest strategic warhead ever deployed by the U.S. The yield of the W62 had to be sufficient for attacking hardened missile silos, and the design of the Mk12 reentry vehicle placed stringent volume limitations on the warhead to achieve the required accuracy. In addition, both warheads included special hardening features intended to improve survivability when penetrating a threat antiballistic missile system. These features were developed with the aid of an extensive series of "exposure" nuclear tests conducted in conjunction with the Defense Nuclear Agency.

When the first MIRV systems were deployed more than 30 years ago, they marked the end to a chapter in which Livermore and the military redefined the strategic missile posture of the United States. The W62 and W68 represented such a dramatic advance in the state of nuclear design that all subsequent missile system warheads have incorporated many of their key elements. Their extensive development programs, conducted in close coordination with the U.S. Air Force and the U.S. Navy and their contractors, were a model for all subsequent generations of delivery-system design teams.

At the Frontier of Missile Defense Technology

The morning before the Cannikin event at Amchitka Island, Alaska, the test site was subjected to rain and wind gusts up to 124 miles per hour. The test crew and visiting dignitaries, including Atomic Energy Commission Chairman James Schlesinger and his family, anxiously waited. Meanwhile, the Supreme Court ruled by a 4–3 margin that the test could take place. At 6:30 am on November 6, 1971, in Amchitka, the go-ahead came from the White House on a telephone hotline. Cannikin was successfully detonated at 11:00 a.m., and the nearly 5-megaton blast generated the ground motion of a 7.0 Richter-scale-magnitude earthquake.

Cannikin was a massive undertaking involving hundreds of Laboratory employees and nearly five years of effort. Test operations overcame myriad logistics hurdles, and experimenters achieved many technical firsts. Two years of drilling produced a record-breaking emplacement hole that was 6,150 feet deep and 90 inches in diameter with a 52-foot-wide cavity mined at its bottom. The diagnostics canister was 264 feet long, and altogether 400 tons of cables and equipment were lowered downhole. Cannikin was the first test in which a laser successfully aligned diagnostics downhole and a computer system assisted field operations. A record-setting number of recording trailers, 2,000 feet from ground zero and shock-mounted to withstand a ground upheaval of 15 feet at shot time, were instrumented with 250 oscilloscopes. One hundred percent of the test data was successfully retrieved.

The experiment tested the design of the warhead for Spartan, the interceptor used in the upper tier of the U.S. Safeguard anti-ballistic missile (ABM) system. Spartan missiles were to engage clouds of reentry vehicles and decoys above the atmosphere and destroy incoming warheads with a burst of high-energy x rays. The Laboratory stepped up to the difficult challenge of designing the appropriate warhead. The Spartan warhead had high yield, produced copious amounts of x rays, and minimized fission output and debris to prevent blackout of ABM radar systems. Livermore also developed and tested the warhead technology for the second-tier interceptor, the Sprint missile. Subsequently, Los Alamos was assigned responsibility to develop the nuclear warhead for Sprint.

The Safeguard ABM system was a scaled-down version of the Sentinel system for defense of U.S. cities. Rapid evolution of offensive missile technologies (see Year 1970) made national defense impractical, and in 1972, the United States and the Soviet Union signed the ABM Treaty. However, protection against ballistic missile attack remained a noble goal and technological challenge for Laboratory researchers and was pursued with renewed vigor after President Ronald Reagan launched the Strategic Defense Initiative. Nuclear directed-energy weapons were pursued at Livermore, including experimental demonstration of x-ray lasing at the Nevada Test Site. Laboratory researchers also devised the concept of Brilliant Pebbles for nonnuclear defense against missiles in boost phase, which led to the Clementine experiment to map the Moon (see Year 1994).
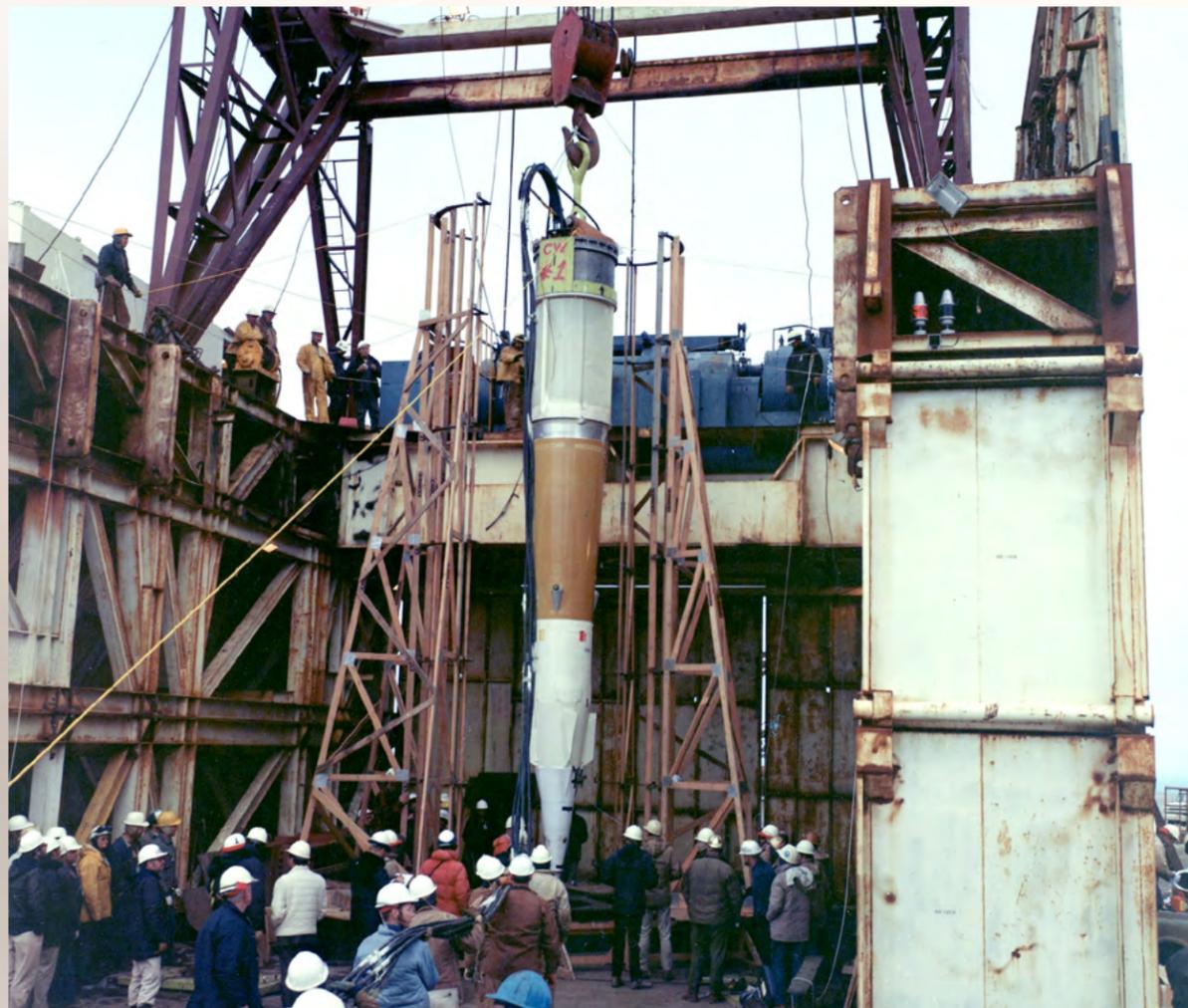
A Spartan missile body with the nuclear device is lowered downhole for the Cannikin event. The test was successfully conducted on November 6, 1971, on Amchitka Island, Alaska.

During preparation for the Cannikin event, workers—including Test Director Phil Coyle sitting on the right—ate their meals near the rigging.

Preventing Planetary Sunburn

In 1972, the Laboratory applied newly developed modeling capabilities to investigate whether human activities might degrade the stratospheric ozone layer, which screens out most of the radiation that causes sunburns and skin cancer. U.S. decision makers needed information on the potential effects of a proposed fleet of supersonic transports (SSTs)—faster-than-sound commercial jet aircraft—that would fly in the stratosphere. Concerns were raised that exhaust emissions might chemically react in ways that would thin the stratospheric ozone layer. Livermore's one-dimensional (altitude) model of stratospheric ozone, developed under Julius Chang, was one of the first simulation tools in the world used to examine ozone interactions with the SST's nitrogen oxide emissions.
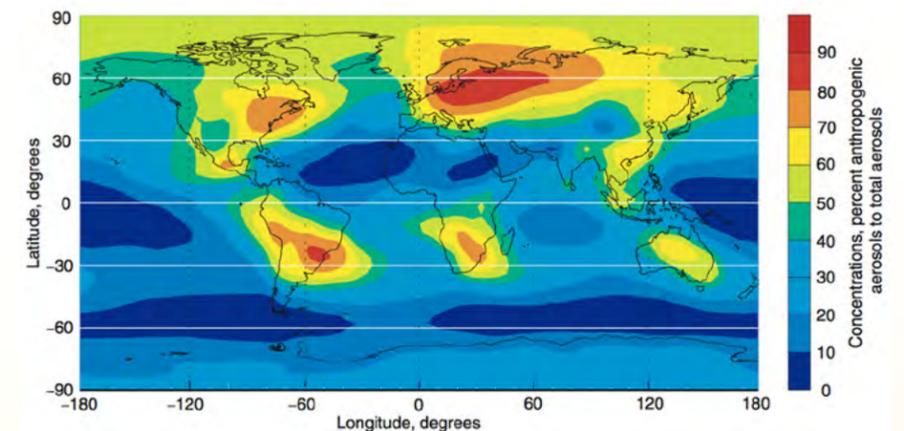
An important early test of the model was its ability to explain the observed decrease in stratospheric ozone concentrations following atmospheric nuclear testing by the United States and the Soviet Union in the early 1960s (see Year 1962). These simulations clearly indicated that use of a large number of megaton-size nuclear weapons in a nuclear war would seriously deplete stratospheric ozone—in addition to the extensive destruction caused at the surface. This finding later played a central role in a 1974 National Academy of Sciences study on the potential long-term worldwide effects of multiple nuclear weapons detonations, adding impetus for the two superpowers to reduce weapon yield and the size of their nuclear arsenals.

In 1974, the effect of chlorofluorocarbon (CFC) emissions on stratospheric ozone also became an issue. In response, Don Wuebbles and colleagues at the Laboratory developed a two-dimensional (latitude and altitude) model that predicted increasingly severe ozone depletion from continued use of CFCs in aerosol spray cans, refrigerators, and air conditioners. These results provided important input to the first international assessment of stratospheric ozone. International negotiations to limit CFCs ensued, and the U.S. prohibited their use as propellants in spray cans. Later, the research team developed a technique for calculating the Ozone Depletion Potential (ODP) of other compounds, a formulation that was included in the Montreal Protocol. Adopted in 1987, the protocol set goals for globally phasing out the use of halocarbons that have high ODP.

As computers became more powerful in the late 1990s, Laboratory researchers focused attention on improved modeling of the effects of anthropogenic aerosols on Earth's climate. In general, atmospheric aerosols have a cooling effect by directly reflecting solar radiation and seeding the formation of clouds, which also reflect radiation. Improved modeling of clouds remains a key objective of climate research at the Laboratory.

Depletion of stratospheric ozone was one of the concerns raised when development began of commercial supersonic transport aircraft. Later, use of chlorofluorocarbons was prohibited because of similar concerns about ozone depletion.

Photo credit: The Boeing Company.

A massively parallel aerosol chemistry and atmospheric chemical transport code developed at Livermore in the early 2000s provided estimates of regional concentrations of aerosols and the fractions of those concentrations from anthropogenic sources.

Less Bay Area Ozone

In the late 1960s, the Laboratory responded to a growing interest in the quality of our environment by applying its capabilities to help understand human-induced effects on the atmosphere. The rising number of excess ozone days in the Livermore Valley prompted Mike MacCracken and colleagues to adapt a new modeling technique developed at the University of Illinois for use as the core of a San Francisco Bay Area air-quality model. Results from this model and later versions served as the basis for preparing the Bay Area's Air Quality Maintenance Plan, which, with later revisions, has lowered the number of days of excess ozone from about 50 per year to just 1 or 2 days per year.

Industrial-Scale Applications for Lasers

In the early 1970s, many analysts were projecting a shortage of electricity starting in the next decade. One option was expanded use of fission energy, for which an inexpensive source of enriched uranium fuel was needed. At the same time, the inherent properties of lasers were recognized as having the potential of leading to a low-cost method for producing such fuel by selectively ionizing uranium-235 and electrostatically separating it from uranium-238. The Uranium Atomic Vapor Laser Isotope Separation (U-AVLIS) Program began at Livermore in 1973 to help maintain the U.S. market share of enriched uranium fuel for the host of nuclear power plants that would be constructed to meet the world's energy needs.

The U-AVLIS process for separating isotopes of uranium presents numerous advantages. It achieves separation in one or two passes

Livermore's plant-scale uranium separator system was one of the largest technology transfer projects in the Laboratory's history.
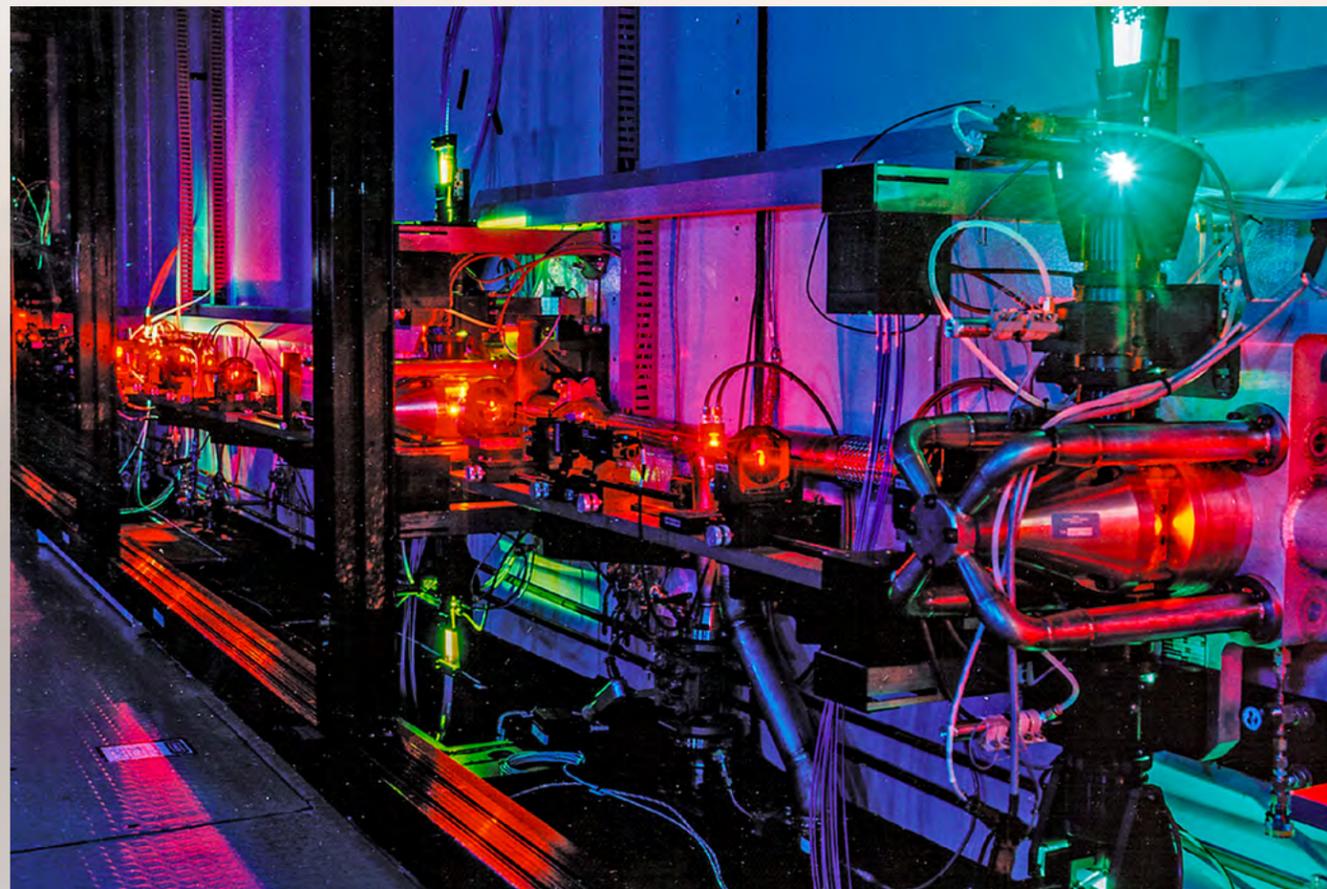
through the laser beam, rather than the hundreds of passes required in other processes. It needs only 1/20th the electrical power required by diffusion plants, producing significant cost savings. Because U-AVLIS uses uranium metal as the source material rather than uranium hexafluoride, the process is less expensive and less hazardous and produces less low-level nuclear waste.

In the early years of the program, the U-AVLIS process used copper vapor lasers to pump liquid dye lasers to effect the separation process, while in later years, more efficient solid-state lasers were developed as the pump lasers. Dye lasers were used because they could produce a broad and almost continuous range of colors. An optical system in the laser is able to "tune," or select, the laser to the precise color needed to separate the desired isotope.

Through its 25-year history, the U-AVLIS Program progressed from the Morehouse experiment that produced the first milligram quantities of enriched uranium in 1974 through the REGULIS separator in 1980, the MARS Facility in 1984, and the Uranium Demonstration System and the Laser Demonstration Facility in the 1990s. In the process, tunable laser technology was dramatically advanced, and significant scientific progress was made in the physics of laser–atom interactions. In addition, the Laboratory staff gained valuable experience in laser-based industrial production, which contributed not only to the U-AVLIS Program but also to other projects such as the Laser Guide Star (see Year 1996), the Laser and Materials Processing program, and the National Ignition Facility (see Year 1997).

Congress created the United States Enrichment Corporation (USEC) in 1992, which was a government corporation until privatized in 1998, to move the U-AVLIS program into the private sector. By the late 1990s, however, the energy economies of the world and the supply versus demand for enriched uranium had changed. USEC suspended the U-AVLIS program in 1999, retaining the rights to U-AVLIS technology for commercial applications.

A technician works with the diode-pumped solid-state (DPSS) green laser developed for U-AVLIS. The technology won LLNL an R&D 100 Award (see Year 1999), and DPSS lasers are used for precision machining and many other applications.

A clean, efficient process for producing the fuel for nuclear power plants was made possible by the Laboratory's precisely tuned, high-power lasers used for the U-AVLIS Program.

Lasers Join the Quest for Fusion Energy

With the goal of achieving energy gain through inertial confinement fusion (ICF) as its mission, the Laser Program constructed its first laser for ICF experiments in 1974. Named Janus, the two-beam laser was built with about 100 pounds of laser glass.

Under the leadership of John Emmett, who headed the Laser Program from 1972 to 1988, researchers used Janus to gain a better understanding of laser plasma physics and thermonuclear physics

The first Livermore laser for ICF research, Janus, had two beams and produced 10 joules of energy.

and to demonstrate laser-induced compression and thermonuclear burn of deuterium–tritium. It was also used to improve the LASNEX computer code developed for laser fusion predictions. Janus was just the beginning of the development, in quick succession, of a series of lasers, each building on the knowledge gained from the last, leading to the National Ignition Facility (NIF), currently performing experiments. The pace of laser construction matched the growth in ICF diagnostics capabilities, computer simulation tools, and theoretical understanding.

In 1975, the one-beam Cyclops laser began operation, performing important target experiments and testing optical designs for future


lasers. The next year, the two-beam Argus was built. Use of Argus increased knowledge about laser–target interactions and laser propagation limits, and it helped the ICF program develop technologies needed for the next generation of laser fusion systems.

The $25-million 20-beam Shiva became the world's most powerful laser in 1977. Almost the size of a football field, it delivered 10.2 kilojoules of energy in less than a billionth of a second in its first full-power firing. Two years later, Shiva compressed fusion fuel to a density 50 to 100 times greater than its liquid density. Shiva provided more power, better control over conditions, higher temperatures, and greater fuel compression than any previous laser.

The Novette laser came on line in 1983 as a test bed for the Nova laser design and an interim target experiment facility. It was used to demonstrate the efficient coupling of higher-harmonic laser light to fusion targets and to create the first soft-x-ray laser. The Nova laser (see Year 1984), 10 times more powerful than Shiva, was built the following year.

Altogether, six large fusion laser systems were engineered and built in 10 years. The next decade of ICF research was devoted to studying and demonstrating the physics required for fusion ignition and gain (fusion output greater than energy input). The work prepared the Laboratory to take the next major step, construction of the 192-beam NIF (see Year 1997), where scientists are striving to achieve fusion ignition and energy gain.
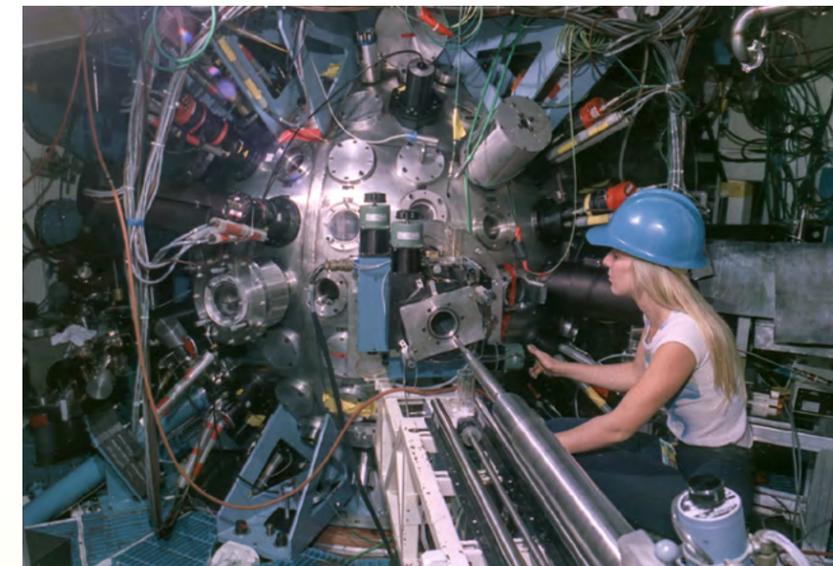
With the 20-beam Shiva laser in 1977, the Laboratory established its preeminence in laser science and technology.

Inertial Confinement Fusion

In a fusion reaction, two nuclei—deuterium and tritium—collide and fuse together, forming a heavier atom and releasing about a million times more energy than in a chemical reaction such as fossil fuel burning. The nuclei must travel toward each other fast enough to overcome electrostatic forces. Thus, the fuel's temperature must be over 10 million kelvin, and the fuel must be compressed to a density 20 times greater than that of lead. Laser beam light heats the surface of the fuel pellet and rapidly vaporizes its outer shell, which implodes the inner part of the fuel pellet and reduces it in size by a factor of 30 or more—equivalent to compressing a basketball to the size of a pea.
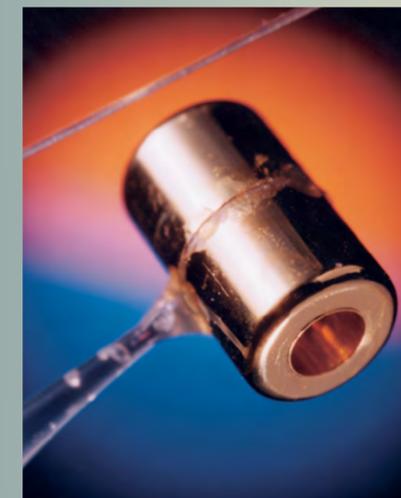
A typical hohlraum for the Nova laser is shown next to a human hair. Hohlraums for the National Ignition Facility have linear dimensions about five times greater than those for Nova.

Special-Effect Weapons for the Tactical Battlefield

In January 1975, Livermore was assigned the task of developing a new nuclear artillery shell warhead, the W79, for the U.S. Army's 8-inch howitzers. Nuclear artillery shells were part of the U.S. arsenal from the mid-1950s until 1992. They were deployed for both U.S. Army and U.S. Navy systems and provided a highly accurate, short-range (typically about 10 miles), all-weather capability using delivery systems already deployed with conventional shells.

The W79 and the W70-3 were to be the first battlefield nuclear weapons to include an "enhanced radiation" (ER) capability. ER provided a relatively high fraction of the prompt weapon output in the form of neutrons (hence the nickname "neutron bomb"). ER technology began to be developed at Livermore in the early 1960s and entered the stockpile in 1974 with the deployment of the W66 warhead for the Sprint antiballistic missile interceptor (see Year 1971).

ER weapons were developed to augment nuclear weapons assigned to NATO forces, deployed under U.S. custody. These weapons were designed to be far more effective than previously deployed battlefield nuclear weapons for blunting a Soviet armored invasion of Western Europe and hence strengthened deterrence. A lethal radiation dose to enemy troops—likely protected in armored vehicles—could be achieved with the much smaller yield of an ER weapon than with a standard nuclear weapon. ER weapons could be employed to strike enemy units much closer to urban areas while avoiding collateral damage to towns and civilians.

The W79 weapon development program led to deployment in 1981. In 1976, the Laboratory received a second related assignment—to provide an enhanced radiation modification to the Livermore-designed W70 warhead for the Army's short-range Lance missile system. This warhead, the W70-3, was also deployed in 1981. The W82, a weapon for the 155-millimeter howitzer, was also assigned to Livermore, but the development program was canceled in the mid-1980s prior to deployment.

By the time the W70-3 and the W79 were part of NATO forces, they had become the center of an international controversy. A principal concern expressed by opponents was that by virtue of the lower yield and greater utility of ER weapons, their deployment would serve to lower the threshold for nuclear war. This controversy led to a 1985 Congressional order that future W79s be built without the ER capability, and existing units were modified to remove this capability. Eventually, all U.S. battlefield nuclear weapons were retired in accordance with President George H. W. Bush's September 1991 address to the nation.
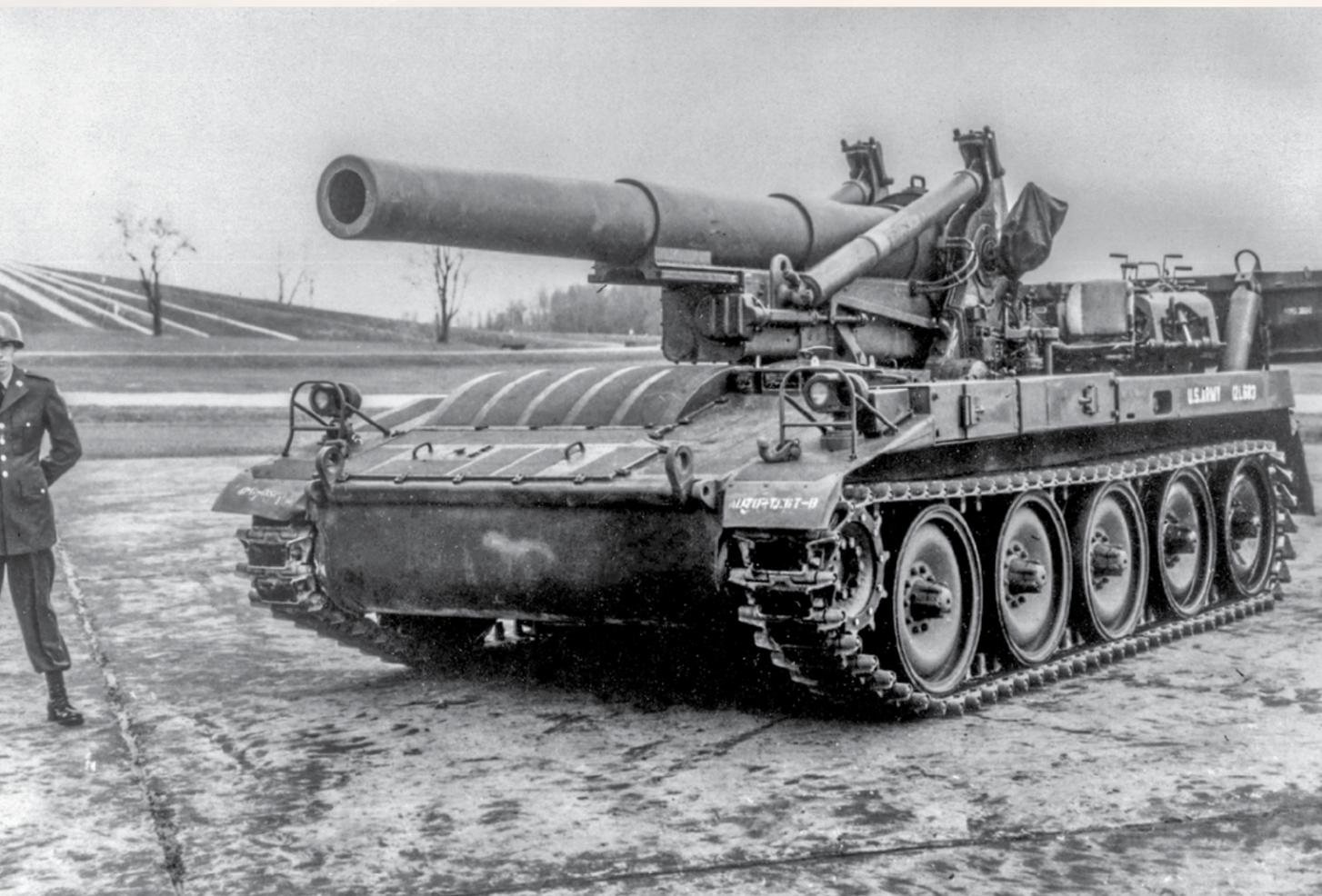

Computer models that could accommodate larger numbers and types of military units and were applicable to a wider range of scenarios, such as urban combat, were developed at the Conflict Simulation Laboratory in the 1980s. Player-interactive simulations are used by the U.S. military for training, analysis of tactics, and mission planning.

Nuclear artillery shells for the U.S. Army's 8-inch howitzers included an "enhanced radiation" capability developed at Livermore.

Conflict Simulation Laboratory

To understand the role of tactical nuclear weapons, analysts have had to take into account many factors that are not amenable to analytical models—the so-called "fog of war." In the mid-1970s, under the leadership of Don Blumenthal, the Laboratory began building high-resolution combat simulation models. A major advance occurred in 1978, when George Smith developed Mini-J, the first two-sided, player-interactive combat simulation model. The players observed their own units in real time, interactively acquired enemy units on a computer screen, and gave orders. Mini-J evolved into a model called Janus, which was successively improved at Livermore's Conflict Simulation Laboratory. The culmination of this work is the Joint Conflict and Tactical Simulation (JCATS) model, which is widely used by the Department of Defense, Secret Service, and other agencies for training and planning.

TATB Makes Nuclear Weapons Safer

In 1975, Laboratory researchers published their first report on investigations of an insensitive high explosive (IHE), TATB (triamino-trinitrobenzene). Further work to characterize the material and find improved ways of producing it has led to widespread use of IHE in nuclear weapons. Use of IHEs is one of the many important advances made over the past five decades to improve the safety and security of nuclear weapons. Its development is a demonstration of the expertise in energetic materials that resides at the nation's nuclear weapons laboratories.

First synthesized in the 19th century, TATB qualifies as an IHE because of its inherent insensitivity to shock. The material is virtually invulnerable to significant energy release in plane crashes, fires, or explosions, or from deliberate attack with small arms fire. In fact, TATB is so stable that researchers had to discover how to reliably initiate an explosion of the material. They also had to find a ready and affordable way to produce the material. Building on advances made at both nuclear design laboratories, Los Alamos researchers made a key improvement in 1967 by finding a way to prepare TATB as a molded, plastic-bonded explosive at close to theoretically maximum density.

Subsequent experiments at Livermore by Richard Weingart and his colleagues included shock-initiation, heat, and fracture tests to define the safety characteristics of plastic-bonded TATB. Other experiments helped researchers to understand how to initiate TATB reliably even in the extreme conditions that a nuclear weapon might face. A team led by physicist Seymour Sack made design advances that enabled TATB's reliable use in nuclear weapons. The first nuclear weapon systems to include TATB were a variant of the B61 bomb and B83 strategic bomb. The W87 ICBM warhead (see Year 1986) was the first design to use TATB for the explosive detonators as well as for the main explosive charge, further enhancing safety.

Use of TATB has been largely limited to nuclear weapons because it is costly to manufacture. For nuclear weapon applications, the legacy stock of this material will be depleted before production begins for the W80-4 life-extension program (LEP). Engineering development (Phase 3) of the W80-4 warhead for the U.S. Air Force's Long-Range Standoff missile is scheduled to begin in 2018. Requalification and remanufacture of the IHE to be used as the warhead's main charge is critical for program success (see Year 2016). This major undertaking is a collaborative effort involving LLNL and Sandia National Laboratories, NNSA's weapons production complex, the Holston Army Ammunition Plant, and the Department of Defense.

TATB requalification and remanufacture will draw heavily on the outstanding experimental capabilities at Livermore to synthesize, formulate, process, test, and evaluate newly manufactured explosive materials. The Laboratory has also greatly advanced the fidelity of simulations of high-explosive performance and is exploring the feasibility of additively manufacturing high-explosive materials.

Research on energetic materials at the Laboratory has led to the formulation, detailed characterization, and development for weapons use of extremely safe high-explosive materials for weapons.

Crystals of TATB (triamino-trinitrobenzene), which are shown magnified in the background, are examined under a microscope.
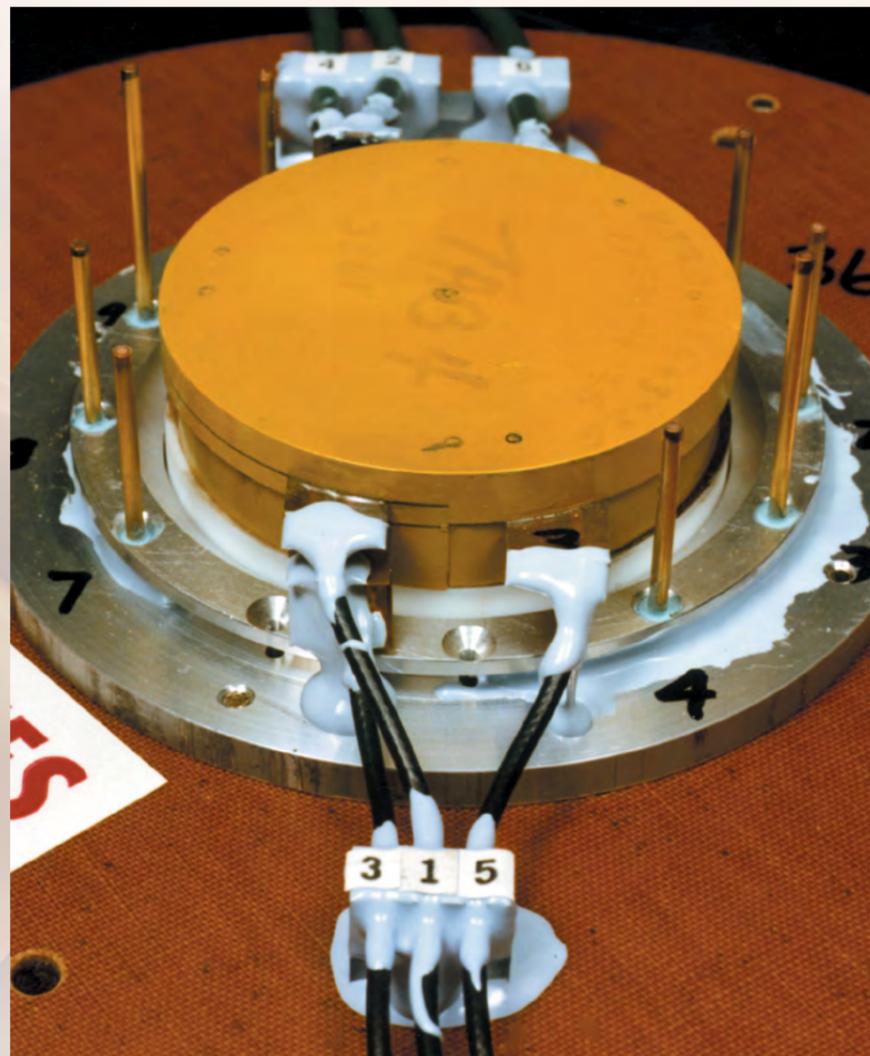
A mock W87 warhead with IHE in a Mk21 reentry vehicle is mounted on simulated upper stages of the Peacekeeper missile (in a canister) in preparation for an explosive test to determine accident environments and warhead response.
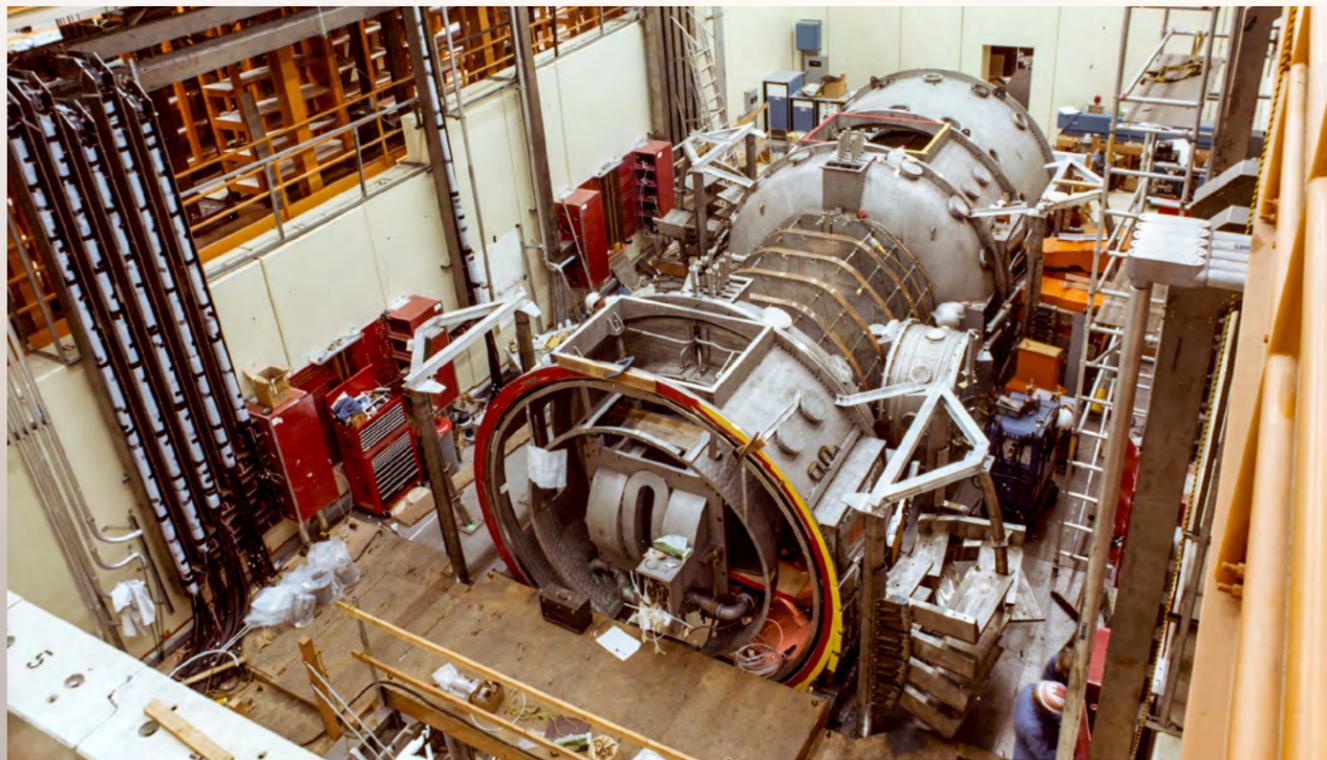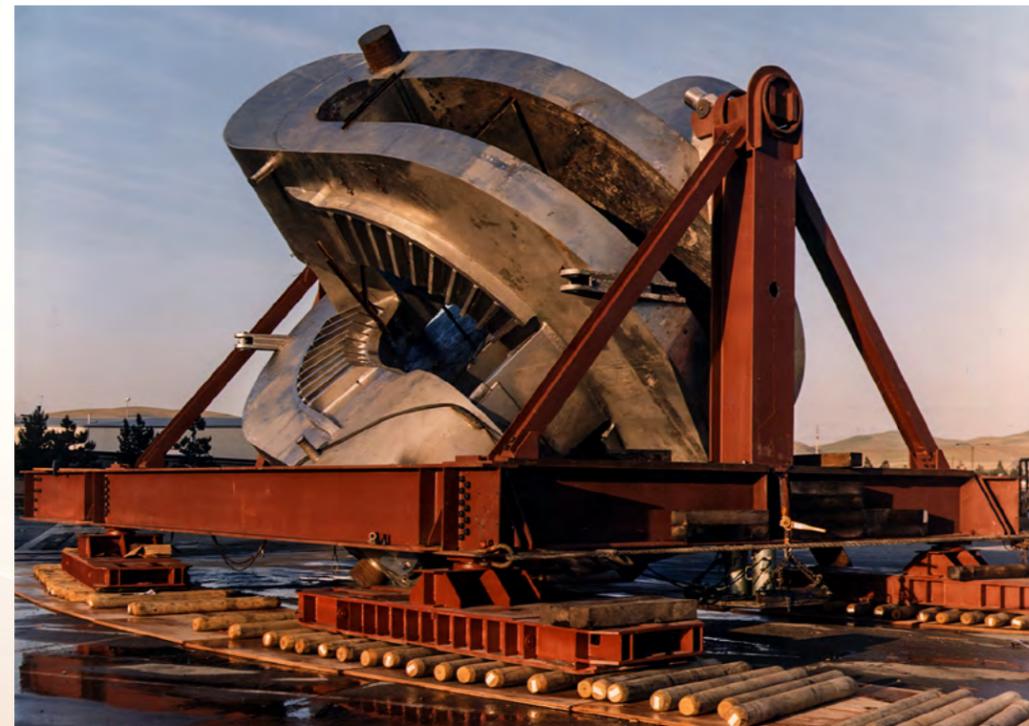
Enormous Strides in Magnetic Fusion

In 1977, Laboratory researchers were making enormous strides both in the quality of their insights into plasma physics and in the size of their experimental equipment. In the spring, the Energy Research and Development Administration approved $11 million for the Tandem Mirror Experiment (TMX),

which promised major performance improvements. That summer, researchers used an intense beam of energetic neutral atoms to generate and sustain a high-density (1014 particles per cubic centimeter), high-temperature (160 million kelvin) plasma in the 2XIIB machine, which was the

One of the yin-yang magnets for MFTF-B being moved into Building 431. The magnet system for MFTF-B was the largest superconducting system ever built.

Great success in the Tandem Mirror Experiment (TMX, above) led to TMX-Upgrade (far left and left). The vacuum vessel was enlarged, and new end coils were installed in an attempt to demonstrate the thermal barrier concept and improve performance over TMX.

single-cell mirror experiment that set the stage for TMX. And in autumn, construction began on the Mirror Fusion Test Facility (MFTF), an advanced experimental fusion device designed to be an intermediate step between the existing mirror machines and an experimental fusion reactor. The goal was to increase plasma confinement to nearly 100 times that of 2XIIB and to increase plasma temperature to more than 500 million kelvin.

Success with TMX experiments over the next several years led the Laboratory to attempt to improve plasma confinement by heating the electrons at the ends of the machine to create a thermal barrier—a change that turned out to add to instabilities. At the same time, the MFTF design was substantially modified into a large tandem mirror configuration called MFTF-B. With a 58-meter-long vacuum vessel and the largest set of superconducting magnets in the world,

MFTF-B was the Laboratory's largest construction project ($372 million) when completed in 1986. However, what could have been learned with MFTF-B will never be known because it was officially mothballed later that year. A scientific tool that had pushed the limits of engineering was turned off before it was ever turned on.

The decision was a major setback for fusion energy research at Livermore, but scientists continued work on other approaches to magnetic fusion. Laboratory researchers are collaborating in experimental studies of tokamak performance using the DIII-D tokamak at General Atomics and the NSTX-U spherical tokamak at the Princeton Plasma Physics Laboratory. One key innovation devised by a Livermore-led team is the "snowflake" power divertor, a successfully tested approach for managing safe dissipation of the power exhaust from the hot plasma in a future commercial

fusion reactor. Laboratory researchers are also providing leadership in the development and use of large-scale simulation of plasmas to carry out fusion research.

As one of its significant legacies, the large magnetic mirror fusion effort at the Laboratory led to the establishment of the nation's first unclassified national supercomputing center to provide magnetic fusion researchers nationwide with the computing horsepower that was then available only to nuclear weapons designers. When it opened at Livermore in 1974, the computer center pioneered many practices: remote access by thousands of users; high-performance data storage and retrieval; online documentation; and around-the-clock support for users. In the 1980s, the center became the National Energy Research Scientific Computing Center (NERSC). It is now located at Lawrence Berkeley National Laboratory.

When Satellites Go Bad

Cosmos 954 started losing orbital altitude in December 1977. The North American Aerospace Defense Command (NORAD) thought it would burn up in the Earth's atmosphere on reentry, but not much was known about the Soviet satellite—its size, its weight, and most important, the amount of nuclear material in its reactor. A month later, the Laboratory was quietly notified to get ready. NEST—the Nuclear Emergency Search Team— was prepared to find the satellite, wherever it landed.

After the first meeting at the Laboratory on January 18, 1978, two Livermore computer scientists were provided the exclusive use of a CDC-7600 computer, and they spent the next few sleepless days refining calculations of the trajectory and figuring out how wide an area—called the footprint—would result from the impact of variously sized pieces of Cosmos, including perhaps 100 pounds of nuclear fuel. The exact time and place of reentry would not be known until the final orbit.

Meanwhile, the Laboratory's NEST contingent—a group of health physicists, chemists, nuclear physicists, and engineers—left for the Las Vegas NEST office to wait. They had packed every type of clothing because they had no idea where they would ultimately end up. Radiation detectors, liquid nitrogen, sample containers, power generators, what passed for portable computers then, and even a helicopter were loaded into a C-141 aircraft—all to look for anything that survived reentry.

The final orbit occurred on January 24. Cosmos fragments scattered across a 30-mile-wide, 500-mile-long swath of the Northwest Territories of Canada, a desolate area populated by caribou and a few Inuit hunters. Within

Not Exactly California Weather

During Operation Morning Light, Livermore's Tom Crites was at the Baker Lake site, where the temperature hovered around –40°F, or around –120°F with the wind-chill factor. The Canadians had outfitted every team member with the latest survival gear. Crites needed it all. The hydraulically powered helicopter failed one day, requiring the stranded team to build snow igloos and keep fires going. They endured a subzero night before a plane rescued them. A few people lost fingers and toes to frostbite. Crites has put his experience to good use leading Boy Scout camping trips in the Sierras. "Besides," he says, "where else can you look south to see the Northern Lights?"

six hours, the official request for help came from Canada, and Operation Morning Light began. The Canadians were depending on the Laboratory team to help find Cosmos pieces, identify the reactor fuel, and estimate the fission product inventory.

Soon, planes with radiation detectors were surveying the frozen landscape. The first radioactive pieces were found on January 26. Radioactivity ranged from a few milliroentgen to 100 roentgens per hour. No single piece was much larger than a small trash can, and tiny bits of radioactive fuel dotted the landscape. Hotspots were concentrated in a few places in the snow-packed forest and in the middle of frozen lakes. Because of the intense cold, team members could work only for short periods.

Operation Morning Light officially ended on April 18. At the peak of its operation—the first two weeks— 120 U.S. personnel worked alongside the Canadians. Of that number, 39 were from the Laboratory with an additional 80 people back at Livermore supporting the team. Today, Laboratory personnel are still part of NNSA's Nuclear Emergency Support Team (a revised name for the restructured NEST organization), ready to deploy at a moment's notice anywhere in the world.

NEST members from Livermore join the search for Cosmos 954, a fallen Soviet satellite. They found small pieces of the satellite and its nuclear reactor on frozen Baker Lake in the Northwest Territories of Canada.

Responding to Nuclear Emergencies Worldwide

On March 29, 1979, Marv Dickerson and Tom Sullivan were at a meeting to secure an agreement with the U.S. Air Force Global Weather Center to supply information to the Atmospheric Release Advisory Capability (ARAC) at Livermore. ARAC, which had recently begun pilot operations under the sponsorship of

DOE, would use that information as part of its integrated system. The two scientists received a call: "There's been an accident at the Three Mile Island nuclear power plant. Could ARAC help, and how soon?"

Over the course of the next 10 days, ARAC scientists worked 24 hours a day, 7 days a week to

predict possible levels and areas of radioactive fallout. Working with a private contractor that was taking aerial radioactivity measurements during flyovers of the area, Livermore scientists used meteorological and topographical information to determine where the plume of radioactive materials was located and where it would travel.

When it started in 1973, ARAC was a research and development project with a goal to track any radioactive accident that happened at a DOE facility and assess its effect on the surrounding community. But with the meltdown at Three Mile Island, ARAC became a household name within the group of federal agencies responsible for responding to nuclear

accidents. The group included the Environmental Protection Agency, DOE, the Department of Defense, the Nuclear Regulatory Commission, and even the Federal Emergency Management Agency.

ARAC has since changed its name to the National Atmospheric Release Advisory Center (NARAC) because of its expanded role to respond to nuclear, radiological, chemical, or natural hazardous material releases. The center's central system, now in its third generation, uses automated software to build 3D models of the area under scrutiny using worldwide meteorological and geographical databases. With information added about the characteristics of the hazardous materials in question,

NARAC scientists and engineers—often within 15 minutes—generate dispersion and fallout models' predictions of dose, air, and ground contamination, blast damage zones, and health risks.

The center has responded to hundreds of alerts and incidents since operations began. Key events include the 1980 Titan II missile explosion in Damascus, Arkansas; the Chernobyl nuclear power plant meltdown in 1986; the Kuwaiti oil fires during and after the Persian Gulf War in 1991; the 1991 Mount Pinatubo eruption; an industrial cesium-137 release in Algeciras, Spain, in 1998; and the Fukushima disaster in 2011 (see box).

ARAC scientist Marv Dickerson keeps members of the media informed about the status of radioactive releases from the Chernobyl nuclear power plant meltdown in 1986.

Response to the Fukushima Dai-ichi Nuclear Power Plant Disaster

NARAC was activated on March 11, 2011, after a massive tsunami hit the east coast of Japan and knocked out power to the Da-ichi Nuclear Power Plant's reactor cooling systems, resulting in damage to reactor cores and the release of radioactivity. NARAC personnel provided critical support to agencies in the United States and Japan responding to the disaster. The team generated a steady stream of up-to-date atmospheric dispersion predictions, plume projections, and radiation dose estimates. During the height of the crisis, the center operated around the clock for 22 days. By the time active operations ended in mid-May, NARAC had logged more than 5,000 person-hours and produced more than 300 projections and analyses.

The Eighties

New Leadership

John H. Nuckolls
(1988 • 1994)

All major programs at the Laboratory have relied on the interplay between computer simulations and experiments to increase scientific understanding and make dramatic engineering improvements. In the 1980s, the combination of testing and simulations greatly contributed to the development of new strategic weapons, such as a nuclear bomb that could be delivered at low altitude, to help win the Cold War. The combination was also critically important to scientific exploration of x-ray lasers and the complexities of intense laser light interacting with matter. Major new experimental facilities were constructed, such

Simulations and experiments

as the Bunker 801 complex at Site 300 for hydrodynamic testing, the Nova laser, and the High Explosives Applications Facility; and the first three-dimensional simulation codes were developed.

In the late 1980s, Laboratory researchers began to explore the feasibility of using multiple parallel processors for scientific computing—now a key component of efforts to maintain the nation's nuclear weapons stockpile. Since Livermore opened, the need for ever more powerful simulations for nuclear weapons design has guided industry's development of supercomputers, and the Laboratory has helped industry make prototype machines ready for a wider range of users.

Addressing the Challenges of Nuclear Waste
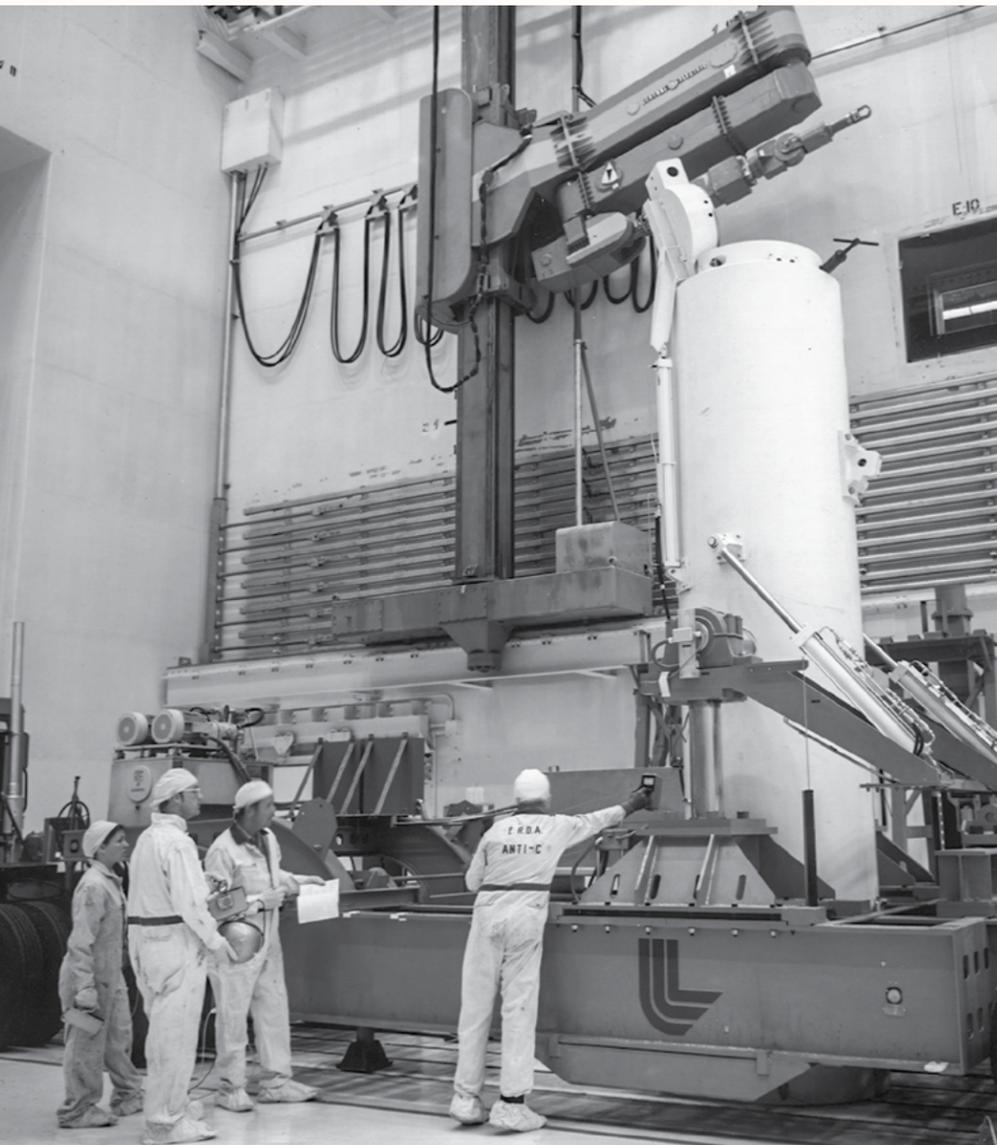
At the Nevada Test Site, each spent-fuel canister was moved over paved roads from the hot-cell facility to the mined test facility in a specially designed surface cask mounted on a low-boy trailer. The cask was upright for loading and almost horizontal for travel.

In 1980, the Laboratory placed spent nuclear fuel 420 meters underground at the Nevada Test Site beneath the floor of a tunnel in Climax granite. In this experiment, Spent Fuel Test–Climax (SFT–C), researchers measured thermal loads from 11 canisters of spent fuel, 6 electrical heaters designed to mimic fuel canisters, and 20 electrical heaters in adjacent tunnels. The combined measurements of the three-year-long test simulated the thermal behavior of part of a large geologic repository for nuclear fuel.

SFT–C was a significant large-scale field test for demonstrating essential technologies and revealing unexpected effects of high-level nuclear waste disposal in geologic repositories. Nuclear waste issues were looming on the horizon long before 1980, but Congress did not pass the Nuclear Waste Policy Act to deal with the problem until 1982.

Opportunities for testing at full scale were very limited this early in the U.S. nuclear waste management program. Livermore undertook SFT–C to demonstrate the feasibility of spent-fuel handling and retrieval from an underground repository and to address technical concerns about geologic repository operations and performance. The test was part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project for the Department of Energy.

Operational objectives included packaging, transporting, storing, and retrieving highly radioactive fuel assemblies in a safe and reliable manner. In addition to emplacement and retrieval operations, three exchanges of spent-fuel assemblies between the SFT–C tunnel and a
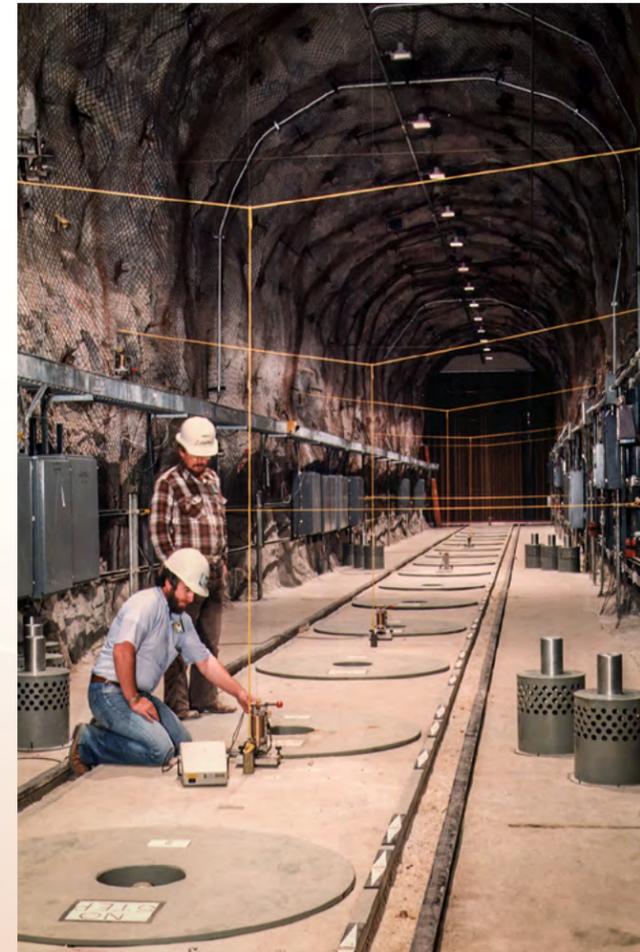
Scientists perform an instrumentation checkout in the tunnel at the Nevada Test Site. The purpose of Spent Fuel Test–Climax was to determine the issues involved with storing and retrieving nuclear wastes underground.

Cannisters of spent nuclear fuel were entombed 1,400 feet below the surface as part of the DOE National Waste Terminal Storage Program. They were placed in holes drilled in the Climax granite formation and retrieved three years later.

surface storage facility were part of this demonstration.

SFT–C technical objectives required a measurements program with nearly 1,000 field instruments and a computer-based data acquisition system. The system had to be robust enough to withstand the vagaries of the Nevada Test Site's power grid, shaking from nuclear weapons tests, and high temperatures caused by the thermal load—a major challenge for 1980s technology. When the Laboratory requested bids for a computer for logging the test data, only one

company (Hewlett-Packard) answered the call. Undaunted, Livermore scientists and engineers designed most of the instruments, installed the system, and recorded geotechnical, seismological, and test status data on a continuing basis for the three-year storage phase and six months of monitored cool-down.

The SFT–C experiment demonstrated the feasibility of deep geologic storage of spent nuclear fuel from commercial nuclear power reactors. SFT–C also showed the Laboratory's strong capabilities in

materials science, nuclear science, earth science, advanced simulations, and engineered systems. The test's success provided a foundation for subsequent collaborations with nuclear waste disposal programs in other countries. More directly, as NNWSI evolved into the Yucca Mountain Project (YMP), SFT–C helped prepare Livermore researchers for their role as experts in addressing YMP waste form, waste package, near-field environment, and repository performance issues.
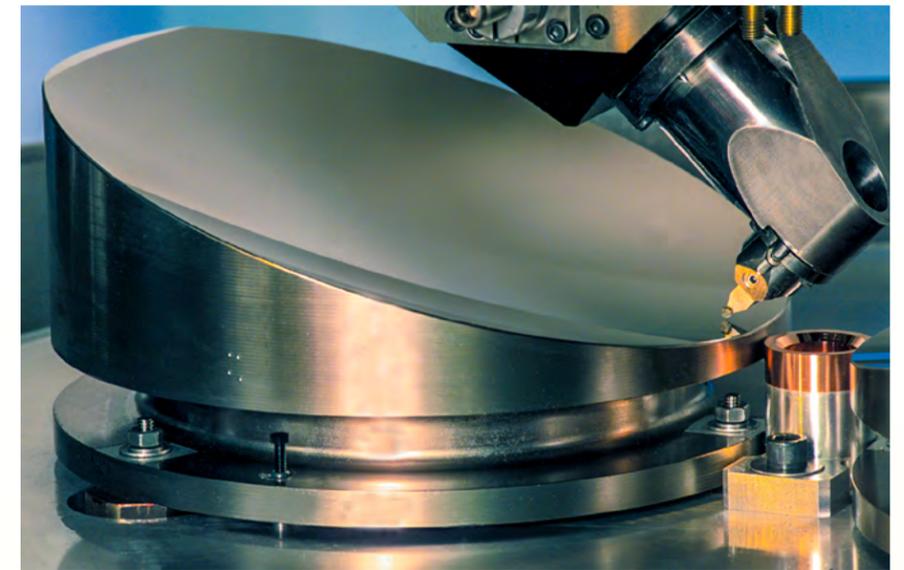
The Art of Precision Machining

It has been called the world's most accurate lathe, the world's most precise large machine tool. With the groundbreaking for the Large Optical Diamond Turning Machine (LODTM) in 1981, the Laboratory solidified its place at the top of state-of-the-art precision machining. LODTM opened in 1983, two years after its groundbreaking, and remained in service for two decades.

The machine's precision was such that LODTM (pronounced "load-em") outperformed the measurers—the National Institute of Standards and Technology could not corroborate the accuracy of its work. LODTM machined metal to a mirror-smooth accuracy within one-millionth of an inch—1,000 times more accurate than conventional machine tools. It handled a workpiece with a diameter up to 1.65 meters, a height up to 0.5 meters, and a weight up to as much as 1,360 kilograms.

Like a lathe, LODTM spun a workpiece as a tool cut the revolving surface. But the similarity ended there, because LODTM left behind a gleaming reflective surface that often needed no further polishing. During its service life, LODTM was the tool of choice for contractors making lenses for heat-seeking missiles and other weaponry, exotically shaped optics for lasers, and mirrors for powerful telescopes such as Keck in Hawaii and NASA's space-based lidar-system, SPARCLE. When the Shoemaker–Levy comet collided with Jupiter in 1994, it was witnessed in real time, thanks to mirrors turned on LODTM and then installed at Keck.

Almost since its inception, the Laboratory has been among the leaders in the development of advanced techniques for precision measurement and manufacture to meet the demands of programmatic work. Livermore's first diamond turning machine was built in the late 1960s, and by the early 1970s, one-millionth of an inch precision was achieved. The idea of the LODTM arose later in the decade when researchers began considering the development of powerful lasers as an element of missile defense. The laser system's optics had to be extremely large, exotically shaped, and fabricated with a precision that corresponded to a small fraction of the wavelength of light. No machine had those needed capabilities.

Livermore's Precision Engineering Program, under the guidance of Jim Bryan, Jim Hamilton, Jeff Klingmann, Dennis Atkinson, and others, designed LODTM. The culmination of previous Laboratory research in machine tool accuracy, LODTM incorporated exhaustive analysis and elimination of factors that caused errors in machine tools—from the heat of the human body to the vibration from a heavy truck passing by.

Precision engineering continues to be an exceptional strength of the Laboratory and an essential feature of many programmatic activities ranging from targets and optics for the National Ignition Facility to biocompatible neural-interface microelectronics for biomedical research.

Machining metal up to 1.65 meters in diameter and at a precision of 2 micrometers was possible with LODTM.

The Large Optics Diamond Turning Machine was the first machine able to produce an aspherical mirror.

A Hero of U.S. Manufacturing

Literally billions of dollars worth of machine tools have been tested with a small measuring device invented by Jim Bryan, who made wide-ranging contributions to metrology and precision machining in 32 years of service at the Laboratory. In the 1980s, Bryan reworked an old British invention called a fixed ball bar by adding a telescoping arm to the instrument. Today, versions of Bryan's ball bar are used around the world to test machine tool performance quickly. For this invention and other achievements, which include leading the design and construction of record-breaking diamond turning machines in the 1970s, Bryan was recognized in 2000 by Fortune magazine as one of six "Heroes of U.S. Manufacturing."

Technology Transfer with DYNA3D

In 1982, a growing list of users benefited from the publication of the first User's Manual for DYNA3D. This three-dimensional computer code was developed by Laboratory mechanical engineers to meet the needs of the nuclear weapons program, and it grew to become a remarkable "swords to plowshares" story. Interest in DYNA3D rapidly expanded from a manual to an international conference on the code's applicability to a wide range of structural analysis problems. The computer code has been used by industry for making everything from safer planes, trains, and automobiles to better beer cans.
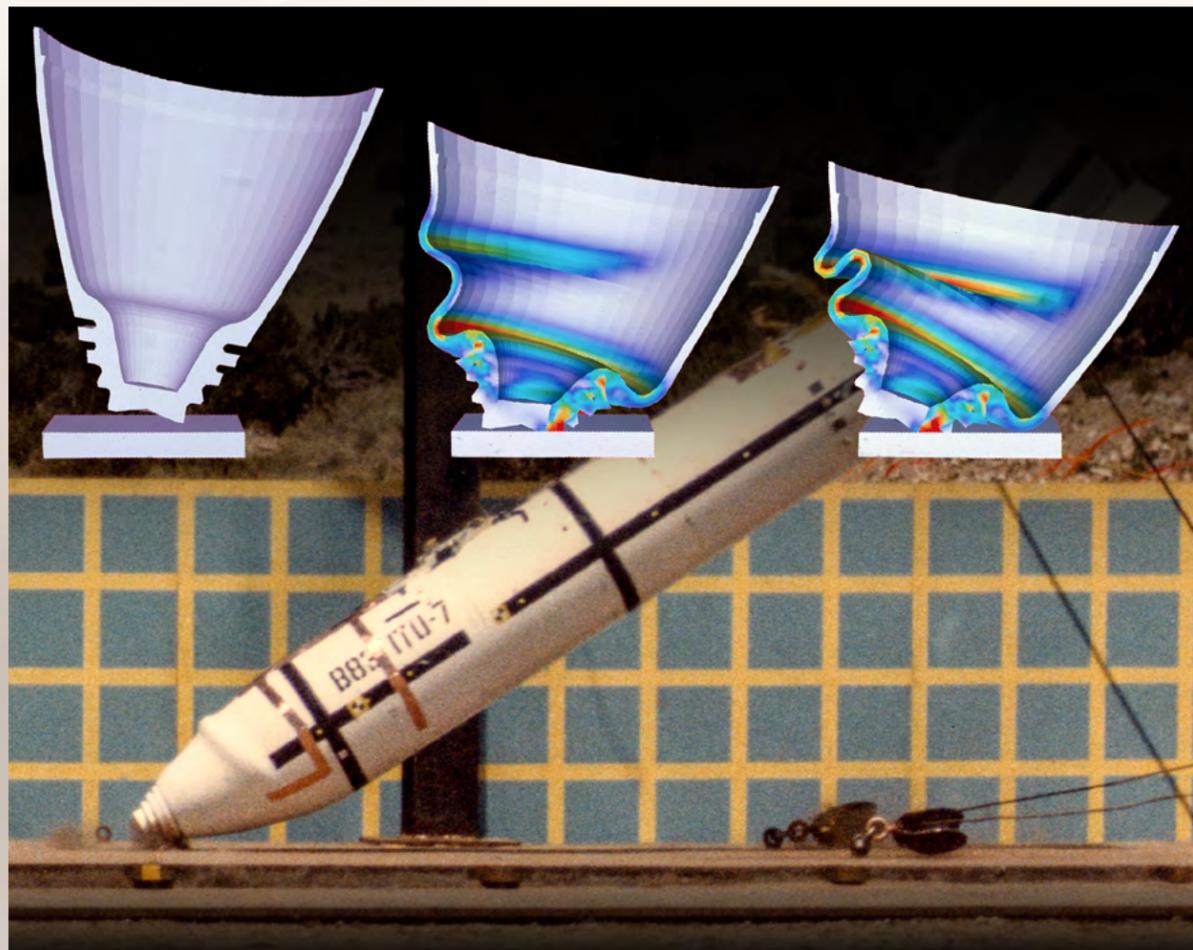
Much of the early incentive to develop DYNA3D, short for dynamics in three dimensions, arose from challenges presented by the B83 program. The B83 nuclear bomb was to be released from a low-flying aircraft, and even though it was to be slowed by a parachute, the bomb would have to survive an impact with the ground or whatever irregular structure it hit at up to 75 miles per hour. Lawrence Livermore and Sandia national laboratories needed an affordable program of tests and simulations to design the B83 and certify its crashworthiness. DYNA3D was used to model the structural performance of the B83, a complex design using a wide variety of materials, and it saved millions of dollars and years of time.

An unclassified code, DYNA3D soon began spreading to private industry in one of the Laboratory's best examples of software technology transfer. The list of early industrial users of DYNA3D reads like a "Who's Who" of major firms—General Motors, Daimler-Chrysler, Alcoa, General Electric, Lockheed Missiles and Space, General Dynamics, Boeing Commercial Airplane Group, Adolph Coors Co., Rockwell International, and FMC Corp. DYNA3D's developer, John Hallquist, founded Livermore Software Technology Corporation in 1987 and moved DYNA3D "off campus" as LS-DYNA. Altogether, more than 2,500 companies worldwide have reaped benefits in cost savings and safety advancements with LS-DYNA's stress and deformation prediction capabilities.

In particular, use of LS-DYNA has been nothing short of revolutionary for the automotive industry. Crash simulations to predict vehicle
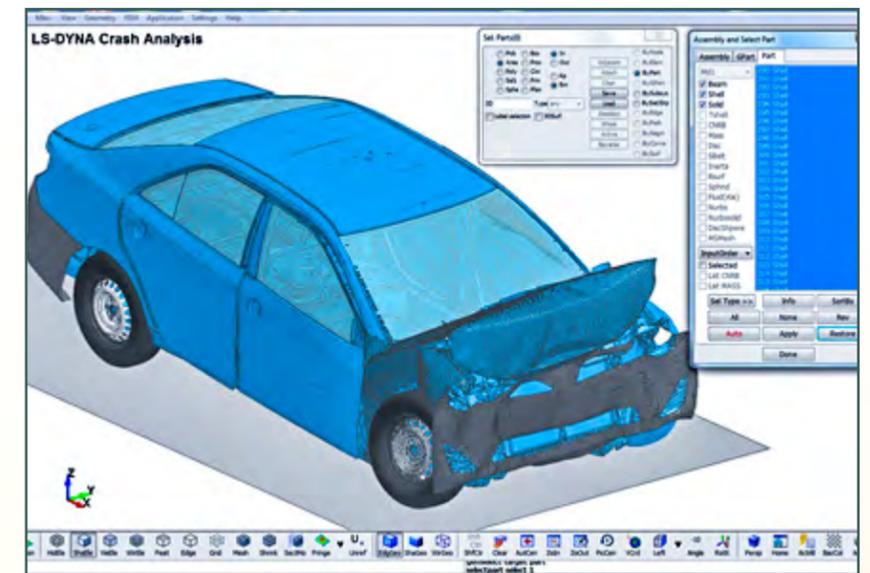
The automotive industry has used LS-DYNA to make great leaps in safety research. This crashed car was simulated with more than 1.5 million points. (Image courtesy of computerhistory.org)

Mitigating Traumatic Brain Injury

Soldiers could reduce the severity of traumatic brain injury by wearing one-size-larger military helmets fitted with thicker pads. In a study conducted for the U.S. Army and the Joint IED Defeat Organization, Livermore researchers used experiments and ParaDyn simulations to examine the response of various helmet pad systems to battlefield-relevant blunt and ballistic impacts. Increasing current pad thickness by a quarter inch can make a large difference in reducing head accelerations. How this difference influences brain response and possible injury is a complex issue and still being studied.

behavior in collisions reduce the need for expensive tests with real cars. Seatbelts, airbags, and other specialized vehicle components are also designed with the help of LS-DYNA. The industry has seen multi-billion-dollar savings over the last three decades.

Since work started on it in 1976, DYNA3D has blossomed from a small 5,000-line computer code

into a 150,000-line package. In the late 1990s, Livermore researchers developed a version for parallel computers, called ParaDyn, which has undergone continuous improvement since 2000. Among its many applications, ParaDyn has been used to estimate debris fields from satellite collisions in space and to improve the design of helmets for U.S. military forces to reduce traumatic brain injury.

A DYNA3D calculation shows the crush-up of a B83 strategic bomb's nose cone upon impact. Simulations were in excellent agreement with the results of experiments, such as this drop test with a B83 test unit landing on a rigid steel plate. Use of DYNA3D accelerated the B83 development program and lowered costs by reducing the number of actual crash-test experiments needed.
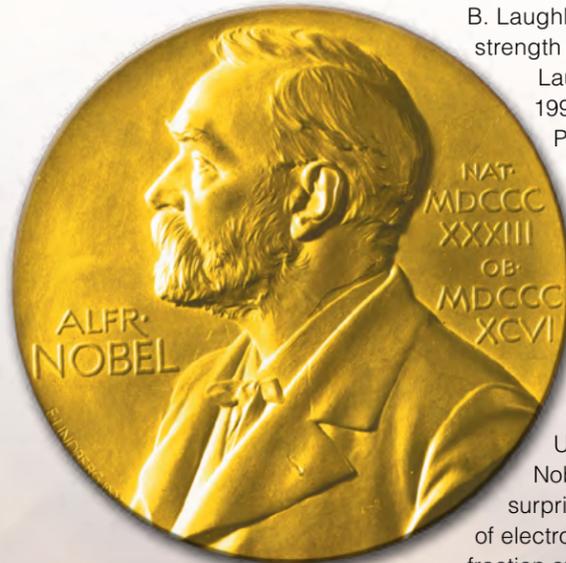
Award-Winning Science and Technology

The road to the Laboratory's Nobel Prize in physics was a 15-year journey, one that winner Robert B. Laughlin credits to Livermore's strength in team science.

Laughlin earned his Nobel in 1998, but it was in 1983 that Physical Review Letters published his elegant theoretical work explaining the so-called fractional quantum Hall effect. The effect had been experimentally discovered in 1982 by Horst Stormer of Columbia University and Daniel Tsui of Princeton University, who shared the Nobel with Laughlin. Its key surprise is that collective motions of electrons can behave like a fraction of the electrical charge for one electron. Previously, the only example of fractional charges in nature had been quarks.

By the time Laughlin's research was lauded in ceremonies held in Stockholm, Sweden, on December 10, 1998, Laughlin had become a professor of physics at Stanford University. But the work that led to that Nobel Prize was born in the Laboratory's condensed matter physics division. It was there that Laughlin, a solid-state postdoctoral physicist, benefited from Livermore's multidisciplinary approach to science— first championed by Laboratory cofounder and Nobel winner Ernest O. Lawrence.

Laughlin learned the ins and outs of plasma physics and the mathematics of classical hot liquids from physicists such as Hugh DeWitt, David Young, Marvin Ross, and Forrest Rogers. While waiting for his security clearance, he passed time by learning Monte Carlo simulation methods, studying the experimental literature of fluids, and making computer models of fluids. While thinking of the possibilities for the quantum Hall wave function, Laughlin realized "it was a fluid problem." He believes that he would not have seen that if he had not been interacting with fellow H-Division physicists, who understood fluids. Although some experts think the fractional quantum Hall effect research could lead to advances in computers or power generation, Laughlin sees the main value of his work as revealing fundamental insights into quantum mechanics.

Laughlin has the distinction of being the first national laboratory employee ever to win the Nobel Prize. He is the 71st winner who worked or conducted research at a DOE institution or whose work was funded by DOE, and he is the 11th University of California employee to receive a Nobel Prize in physics.

As a professor at Stanford University, Laughlin continued his association with the Laboratory. His work stands as the hallmark of the world-renowned science conducted at Livermore, work that has earned hundreds of other scientists, like Laughlin, Ernest O. Lawrence awards, Teller medals, distinctions from every worldwide scientific society, and even the Nobel Prize.

(AP photo/Jonas Ekstromer)
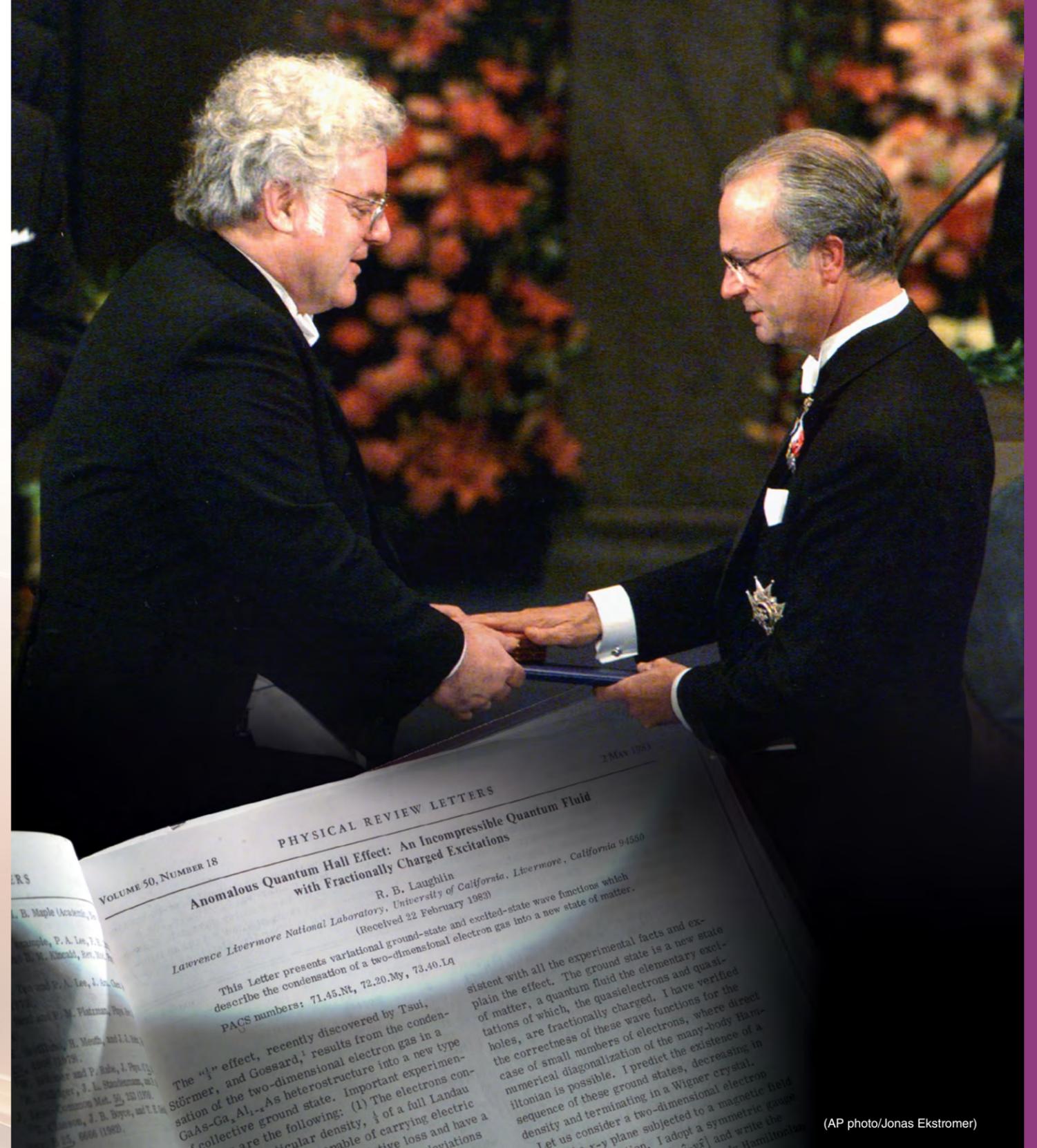
Robert Laughlin (left) received the Nobel Prize for physics from Swedish King Carl XVI Gustaf at the ceremonies in Stockholm, Sweden, on December 10, 1998.

Breakthrough Laser Science and Technology

In the early 1980s, researchers were exploring how to produce x-ray laser beams initiated by nuclear explosives at the Nevada Test Site. At the same time, success was achieved creating a a soft x ray (with a wavelength of about 200 angstroms) laser in a laboratory setting using the Novette laser, which was a test bed for the design of Nova. In December 1984, Nova became operational, enabling further groundbreaking research in x-ray lasers and many other areas of laser science and technology.

Ten times more powerful than Shiva, its predecessor, Nova was the world's most powerful laser. Its 10 beams produced laser pulses that delivered up to 100 trillion watts of infrared laser power for a billionth of a second. For that brief instant, its power was 25 times greater than the total produced by all U.S. power plants. Unlike Shiva, Nova included crystal plates to convert the infrared light to ultraviolet light—needed for inertial confinement fusion (ICF) experiments.

In 1986, Nova ICF experiments produced a record-breaking laser fusion yield of 11 trillion fusion neutrons. The following year, Nova compressed a fusion fuel pellet to about 1/30th its original diameter, very close to that needed for high gain (fusion output greater than energy input). The laser exceeded its maximum performance specifications in 1989 when Nova generated more than 120 kilojoules of laser energy at its fundamental infrared wavelength in a 2.5-nanosecond pulse. In addition, in 1996, one arm of Nova was reconfigured as the world's first petawatt laser (see the box).

About 30 percent of Nova's shots were used by the nuclear weapons program. When the United States ceased nuclear testing, laser facilities became even more important for defense research, and the portion of Nova shots dedicated to the weapons program increased considerably. Researchers using Nova continued obtaining high-temperature data necessary to validate the computer codes used to model nuclear weapons physics.

Livermore also developed increasingly sophisticated diagnostic instruments to measure and observe what was happening with the laser beam, in the target, in the interaction between the laser light and the plasma, and in the fusion process.

In 1984, when it began operation, Nova was the world's most powerful laser. Laser pulses were produced with 10 beams (right), which were directed to a 5-meter-diameter target chamber (below left). Inside the chamber (below right), the laser light was focused on BB-sized targets.
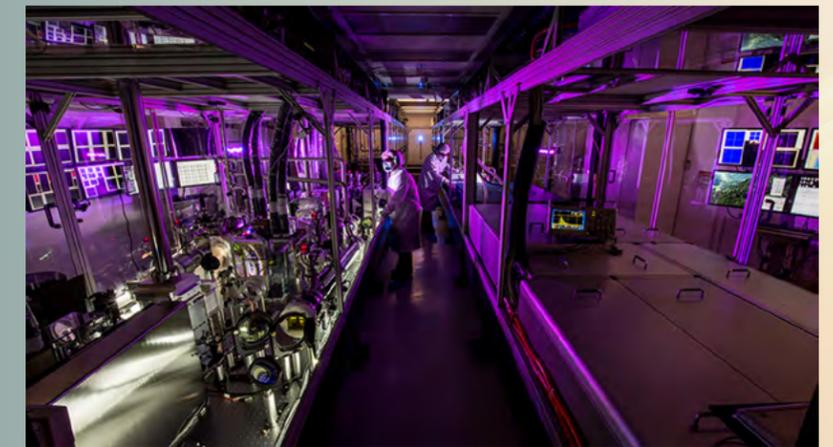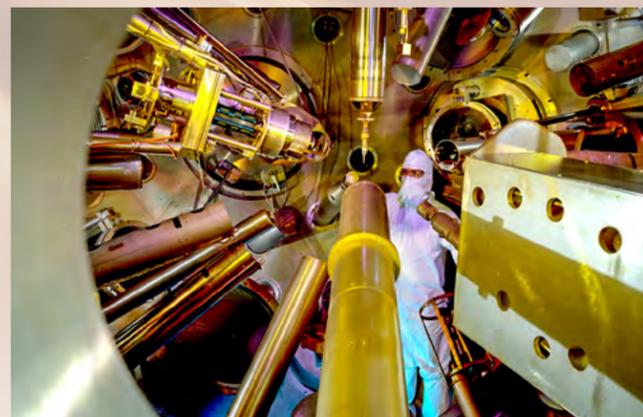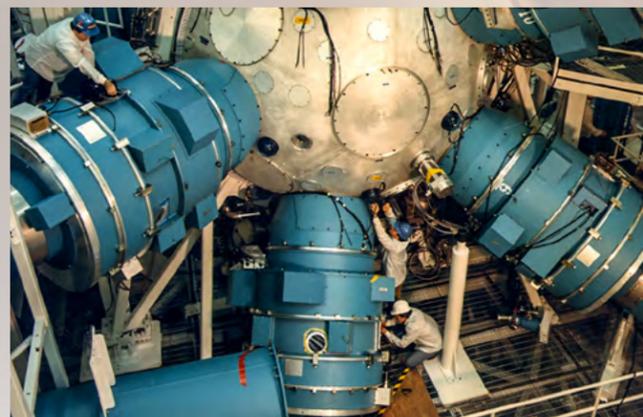

Pioneering the Petawatt Laser

LLNL researchers reconfigured one arm of the Nova laser to achieve a highly significant advance in laser technology: a petawatt laser. In 1996, the petawatt laser set a power record of 1.25 quadrillion (a million billion) watts—more than 1,200 times the U.S. power generating capacity—for a duration less than a trillionth of a second. The laser's ultrashort pulses and extremely high irradiance opened up entirely new physical regimes to study. Experiments have split atoms, created antimatter, and generated a well-focused, intense proton beam—all firsts for a laser.

In 2016, the Laboratory set new records with the High-Repetition-Rate Advanced Petawatt Laser (HAPLS) system, which is designed to generate 10 pulses per second, each 30 quadrillionths of second long with greater than one petawatt peak power. The system includes many breakthrough technologies, including the use of laser diodes as flashlamps, which reduces system size and power requirements. HAPLS has been delivered to the Extreme Light Infrastructure (ELI) Beamlines facility in the Czech Republic, where it will provide experimenters with unique opportunities to advance their understanding of the fundamental nature of energy and matter.

Some of the technologies provided spin-off advances, such as improved medical technologies, femtosecond laser machining, and techniques for using extreme ultraviolet light for lithography to produce smaller, faster computer chips (see Year 1999).

Nova served as the proving ground for the 192-beam National Ignition Facility (NIF). Achievements on Nova helped scientists to convince the Department of Energy of the viability and probable ultimate success of achieving thermonuclear ignition on NIF (see Year 1997). In May 1999, Nova fired its last shot after 14 years of operation and more than 14,000 experiments.
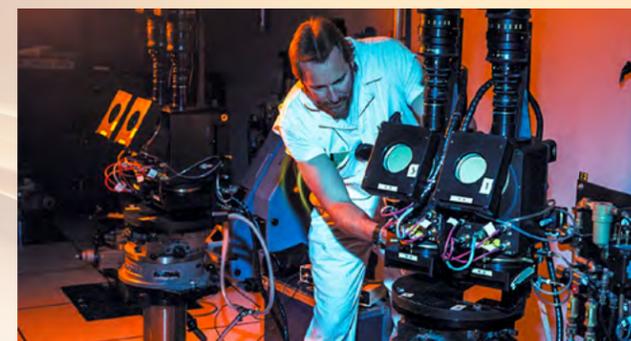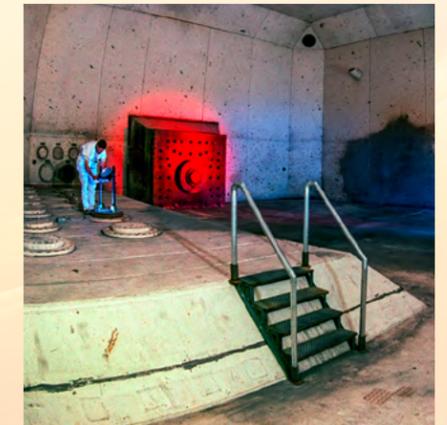
1985 Bunker 801

Improving Implosion Images

In 1985, Livermore completed the Bunker 801 project to upgrade what was the very first facility (then called Bunker 301) at Site 300, the Laboratory's remote test site. The newly refurbished bunker—a complex of protected enclosures, largely underground—became a fully modernized hydrodynamic test facility to gather data crucial for assessing the operation of a nuclear weapon's primary stage. Until project completion, weapon designers relied largely on technologies from the 1960s for much of their hydrodynamics experimentation.

After the upgrade, Bunker 801 contained the most modern diagnostics available. They included a Fabry–Perot interferometer to measure the velocity of explosion-driven surfaces, 10 high-speed cameras to capture the progressive movement of a pit's outer surface, and an electrical-probe diagnostics system for recording data from hundreds of shorting pins that time the arrival of the interior surface. Additionally, an important diagnostic tool was the Flash X-Ray (FXR) machine, a 16-megaelectronvolt linear-induction accelerator (see Year 1960). Electrons from the FXR strike a target to produce an intense burst of x rays, which are used to image a mock nuclear weapon primary as it implodes. Built between 1978 and 1982, FXR produced five times the x-ray dose of previous machines in one-third the pulse length. Much denser objects could be radiographed and with less blur because of the shorter pulse.

Continual upgrades to Bunker 801 since 1985 have kept the facility equipped with the most modern capabilities. For example, in the 1990s, Laboratory scientists and engineers improved the beam quality of the FXR so that a higher overall x-ray dose is produced. In addition, the Laboratory developed a gamma-ray camera to record the radiographic images. With these upgrades, scientists in 1998 were able to carry out the first "core punch" experiments on mock pits for two stockpiled weapons—the W76 submarine-launched ballistic missile warhead and the B83 strategic bomb. In core punches, images are obtained of the spherical symmetry of the gas cavity inside a highly compressed pit. In 2017, FXR carried out its first double-pulse imaging experiment, enabling researchers to follow the time evolution of the implosion process. This added capability was the result of a multilaboratory collaboration that entailed numerous upgrades to FXR and its diagnostic systems.

In 2001, Bunker 801 became the Contained Firing Facility through a major upgrade, the addition of a firing chamber to the complex. This addition allows debris from test explosions to be contained in a more environmentally benign manner than ever—dramatically reducing particle emissions and minimizing the generation of hazardous waste, noise, and blast pressures. With walls up to 2 meters thick and protected by steel plating, the firing chamber is designed to withstand repetitive tests that use up to 60 kilograms of high explosives.

Before completion of the Contained Firing Facility in 2001, tests at the Bunker 801 complex were conducted outdoors (top). Now the complex (middle left) includes an indoor firing chamber (middle right), which contains debris and minimizes the environmental consequences of tests that use up to 60 kilograms of high explosives. The facility is equipped with the latest diagnostics, including electronic image-converter framing cameras (bottom).

1986 W87

ICBM Warheads with Modern Safety Features

In March 1986, the first production unit of the W87 warhead for the Peacekeeper intercontinental ballistic missile (ICBM) was completed at the Pantex Plant in Amarillo, Texas. This event culminated a four-year advanced development program executed by the Laboratory in close coordination with Sandia National Laboratories and the U.S. Air Force and its contractors, particularly AVCO, which was responsible for the Mk21

reentry vehicle. Peacekeeper was designed to carry 10 independently targetable Mk21 reentry vehicles with W87 warheads.

The W87 design is unique for strategic ballistic missile systems in its use of an insensitive high explosive (see Year 1976) and a fire-resistant pit design. Both features help to minimize the possibility of plutonium dispersal in the event of an accident. First incorporated in Livermore's

Engineering tests supported the development of the W87 warhead for the Peacekeeper missile, which carried 10 Mk21 reentry vehicles with W87s. Through a stockpile life extension program completed in 2004, W87 warheads were refurbished to extend their long-term use on Minuteman III ICBMs.

Studies of MX Basing

In 1982, President Reagan set up a commission led by Professor Charles M. Townes (University of California at Berkeley) to evaluate basing options for the MX missile. The commission sought input from a variety of sources, including weapon systems analysts from Livermore's D Division.

Upon conclusion of the study, Townes wrote to University President David Saxon: "It was clear that most of the industrial organizations were quite cautious about giving information or making conclusions which would be contrary to Pentagon policy. I was personally impressed that the many persons who helped us from Livermore seemed completely objective in examining the technical facts, in investigating what needed to be looked into, and in being willing to state plainly, though diplomatically, where they did not agree… I make the above point because I think, contrary to some opinions, Laboratory personnel are often important in giving helpful perspective and ameliorating U.S. nuclear policy, and that this is partly because they are protected by the management structure from the obvious pressures to which commercial or governmental laboratories are subjected."

W84 warhead design for the ground-launched cruise missile, a fire-resistant pit includes in the weapon primary a metal shell that is able to keep molten plutonium contained. Both the W84 and W87 also include detonator strong links that provide additional safety assurance.

The enhanced safety design features of the W87 were incorporated

at an early stage of the development program when Air Force plans called for Peacekeeper, at that time known as MX, to be based in the Multiple Protective Shelter mode. To improve missile survivability in an attack, many moderately hardened shelters would be built, and the ICBMs would be clandestinely shuttled among them, forcing an attacker to target all shelters

or to guess which held a missile. This plan was later abandoned in favor of basing the missile in Minuteman silos.

With the signing of the START II treaty, the U.S. chose to retire Peacekeeper ICBMs and to deploy a large fraction of its W87 warheads on Minuteman III missiles.

To prepare for long-term continuing deployment of the W87, a life extension program (LEP) for the W87 was initiated in 1995 to make some mechanical modifications. The first refurbished warhead under this program was produced in 1999. Extensive ground and flight testing together with detailed calculations using the newly available Blue Pacific supercomputer preceded formal certification of the refurbished W87s in April 2001. Certification without nuclear testing was an important early demonstration of new capabilities developed under the Stockpile Stewardship Program. Work finished on the final unit in November 2004, marking the Stockpile Stewardship Program's first successful conclusion of an LEP.
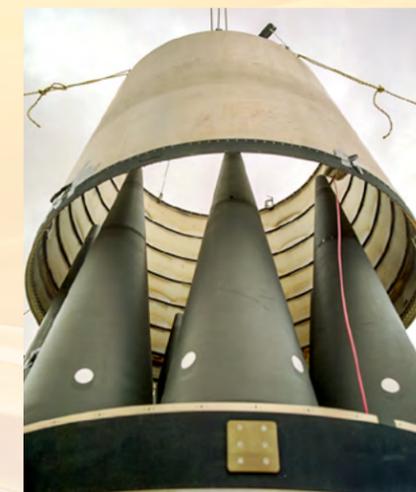
Deciphering the Human Genetic Code

In 1987, Livermore biomedical researchers joined a DOE initiative that would determine the entire sequence of DNA that makes up the human genome. Chromosome 19 became the focus of a new Human Genome center at Livermore. At the same time, Los Alamos began work on chromosome 16 and Lawrence Berkeley chose chromosome 5. The intensive work of decoding had begun and grew to be an international industry.

Livermore's involvement in genetic research stretches back almost to its first biological program, chartered in 1963 to study the human health consequences of environmental radiation exposure (see Year 1963). A natural extension was to explore how radiation and chemicals interact with human genetic material, mutating DNA and leading to cancers and other adverse effects. The Laboratory's experiments to study repair of DNA damaged by radiation focused on chromosome 19 (see the box). By 1984, Livermore and Los Alamos were working together to build human chromosome-specific gene libraries. Advanced chromosome-sorting capabilities, essential to the genome initiative, had been developed at both laboratories.

In 1984, DOE's Office of Health and Environmental Research (OHER) cosponsored a meeting in Alta, Utah, that highlighted the value of acquiring a reference sequence of the human genome. Leading scientists were invited by OHER to a subsequent international conference, held in March 1986 in Santa Fe, New Mexico. Participants at this landmark meeting concluded that mapping and then sequencing the human genome were desirable and feasible goals, and DOE became the first federal agency to commit to these goals by launching its Human Genome Initiative. This decision was endorsed in an April 1987 report by a DOE Biological and Environmental Research Advisory Committee, which noted that DOE was particularly well-suited for the task because of its demonstrated expertise in managing complex, long-term multidisciplinary projects.

In 1990, DOE joined with the National Institutes of Health and other laboratories around the world to kick off the Human Genome Project, the largest biological research project ever undertaken. Thanks to the commercial development of automated, high-throughput sequencing machines, a rough-draft sequence of the entire 3 billion base pairs of human DNA—all 23 chromosomes—was completed in 2001, several years ahead of schedule. DOE's Joint Genome Institute (JGI), a sequencing production facility in Walnut Creek, California, sequenced chromosomes 5, 16, and 19. JGI combined the efforts of Lawrence Livermore, Lawrence Berkeley, and Los Alamos national laboratories. The institute is now operated by Lawrence Berkeley with participation by LLNL.

Shortly after JGI had completed the human genome, microbial genome sequencing became the next exciting area for research in both medical and environmental areas. Because of improvements in sequencing technology and the small size of microbial genomes, microbiology experienced a renaissance. The research provided a step toward the Laboratory's current focus on applied genomics in support of important national problems in public health, biosecurity, and energy security (see Year 2011).

In the late 1990s, the sequencing process at the Joint Genome Institute (JGI) had numerous steps, four of which are shown here: Colonies of cells containing human DNA are selected from a cell culture plate (right). The CRS robot system (upper right) places a DNA sample plate onto a plate washer for purification of the DNA. A JGI researcher (lower right) removes a plate of purified DNA from a plate washer. A JGI research technician (far right) reviews the sequencing data produced by one of JGI's 84 DNA capillary sequencers.
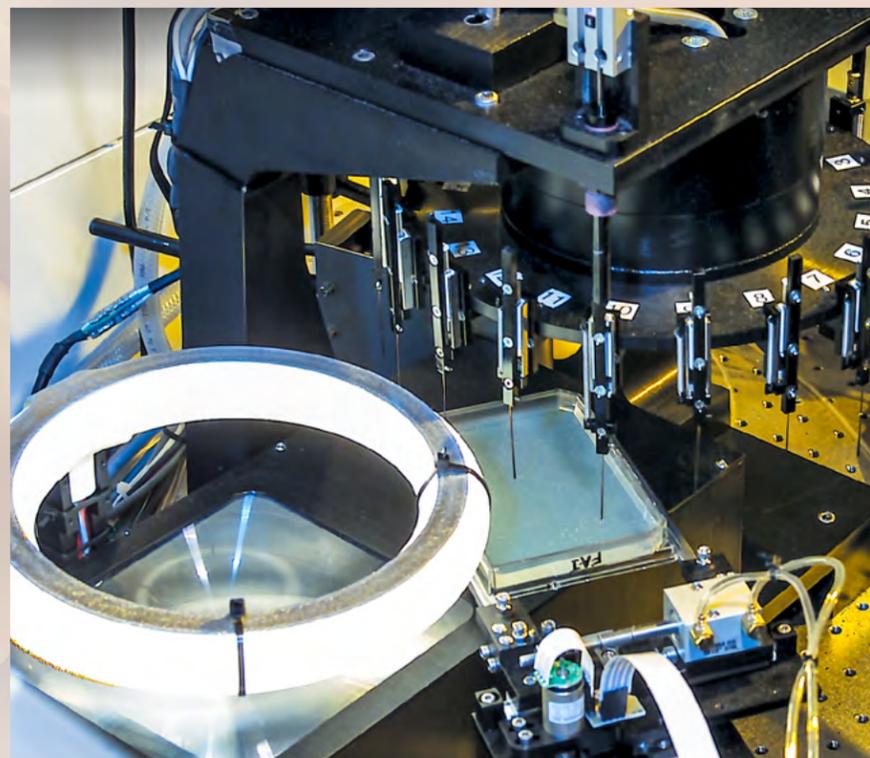
LLNL's Long History with Chromosome 19

In their investigations in the early 1980s, Livermore researchers chose chromosome 19 to study because evidence suggested that it had a relatively high concentration of genes. That hunch proved to be correct. The gene density is more than twice the genome-wide average. Chromosome 19 codes for more than 1,400 genes, most of which are important for general human health. Many of these genes are associated with diseases such as insulin-dependent diabetes, myotonic dystrophy, migraine, Alzheimer's, elevated blood cholesterol, and prostate-specific antigen (PSA). In work spanning two decades, LLNL completed the difficult task of mapping and began the enormous task of sequencing chromosome 19—work that was completed at JGI. Important ensuing studies focused on understanding the function, regulation, and evolution of the genes.

1988 Joint Verification Experiment

Reducing the Nuclear Threat

In 1988, a landmark event in U.S.–Soviet relations occurred when Soviet and U.S. teams for the first time conducted measurements of nuclear detonations at each other's nuclear testing sites. The event, called the Joint Verification Experiment (JVE), allowed Soviet and U.S. scientists to become more familiar with characteristics of the verification technologies that were proposed to monitor compliance with the Threshold Test Ban Treaty and the Peaceful Nuclear Explosions Treaty. The intent of both treaties was to limit the yield of nuclear explosions to no more than 150 kilotons.

Planning for the JVE took place in Geneva, Switzerland, and at the two nations' nuclear test sites. A U.S. delegation made a familiarization visit to the Semipalatinsk Test Site early in January 1988, and a Soviet delegation visited the Department of Energy's Nevada Test Site (NTS) a short while later.

Russian scientists were on hand to witness the Kearsarge event that was detonated August 17, 1988, on Pahute Mesa at NTS. As a symbol of international good faith and cooperation, the Soviet Union flag was raised to the top of the emplacement tower next to the U.S. flag. Nearly 150 people from the U.S. traveled to the Semipalatinsk test site to participate in the preparation of the Shagan test on September 14, 1988. Forty-five U.S. personnel witnessed the event, standing just 4 kilometers from the test ground zero. Both nuclear tests were in the yield range of 100 to 150 kilotons of explosive power. Livermore personnel were heavily involved in fielding the two explosions, with the Laboratory contributing equipment, instrumentation, and technical advice.

For each of the two tests, both sides made hydrodynamic yield measurements in the emplacement hole and in a satellite hole located about 11 meters from the emplacement hole. U.S. scientists measured nuclear yield based on close-in observations of the velocity of the shock wave generated by the nuclear explosion using a technology called CORRTEX (continuous reflectometry radius versus time experiment). The Soviets also made CORRTEX-like measurements as well as a hydrodynamic measurement using switches. The satellite holes at the test sites were drilled by U.S. personnel with U.S. equipment because of a professed Soviet lack of such capability.

Many American–Russian friendships were forged during the JVE, which was a turning point in Soviet relations with the West. The more open atmosphere preceded the collapse of the Soviet Union and prevailed for nearly two decades. When diplomatic conditions permitted, Laboratory scientists were frequent travelers to Russia and the newly independent states. They monitored and assisted the progress of arms reductions; pursued cooperative efforts to better protect, control, and account for nuclear materials; and collaborated with scientists on nonweapons-related projects.

Heralding an emerging period of cooperation, U.S. and Soviet flags fly side by side atop the experiment tower at the Nevada Test Site during the first of two Joint Verification Experiments.

Associate Director J. I. Davis leads a tour of the Nova laser for senior managers from Arzamas and Chelyabinsk (the Russian counterparts to Los Alamos and Livermore) as part of a groundbreaking series of U.S.–Russian laboratory visits in 1992.

HEU Transparency Program

In 2013, after 20 years of operation, the U.S.–Russia Highly Enriched Uranium (HEU) Purchase Agreement achieved its goal of converting more than 500 metric tons of HEU to safer low-enriched uranium for use in American nuclear power plants (shipping containers are shown). Livermore researchers supported the HEU Transparency Program by serving on and coordinating the U.S. monitoring team. They provided advanced equipment such as an LLNL-developed portable nondestructive assay system and maintained a repository of the collected monitoring data.

Photo credit: U.S. Enrichment Corporation.

Exploring the Future of Scientific Computing

In October 1989, the Laboratory Directed Research and Development office funded the ambitious Massively Parallel Computing Initiative (MPCI), which cut across directorates at the Laboratory and helped redefine high-performance computing as massively parallel computing. The exploratory work performed as part of the initiative—and comparable efforts at Los Alamos and Sandia national laboratories—paved the way for the Accelerated Strategic Computing Initiative (or ASCI, now the Advanced Simulation and Computing (ASC) Program), which is a vitally important part of the Stockpile Stewardship Program.

Led by Eugene D. Brooks III, the three-year initiative explored the relevance to Laboratory computer applications of then-accelerating trends in commercial microprocessors. Advances in very-large-scale integration had increased both computer chip speed and reliability so much that massive, coordinated clusters of microprocessors were sometimes rivaling the performance of custom-designed supercomputers. For example, early tests here with radiation transport codes (used in weapons simulations) suggested a factor of 20 advantage for the massively parallel approach.
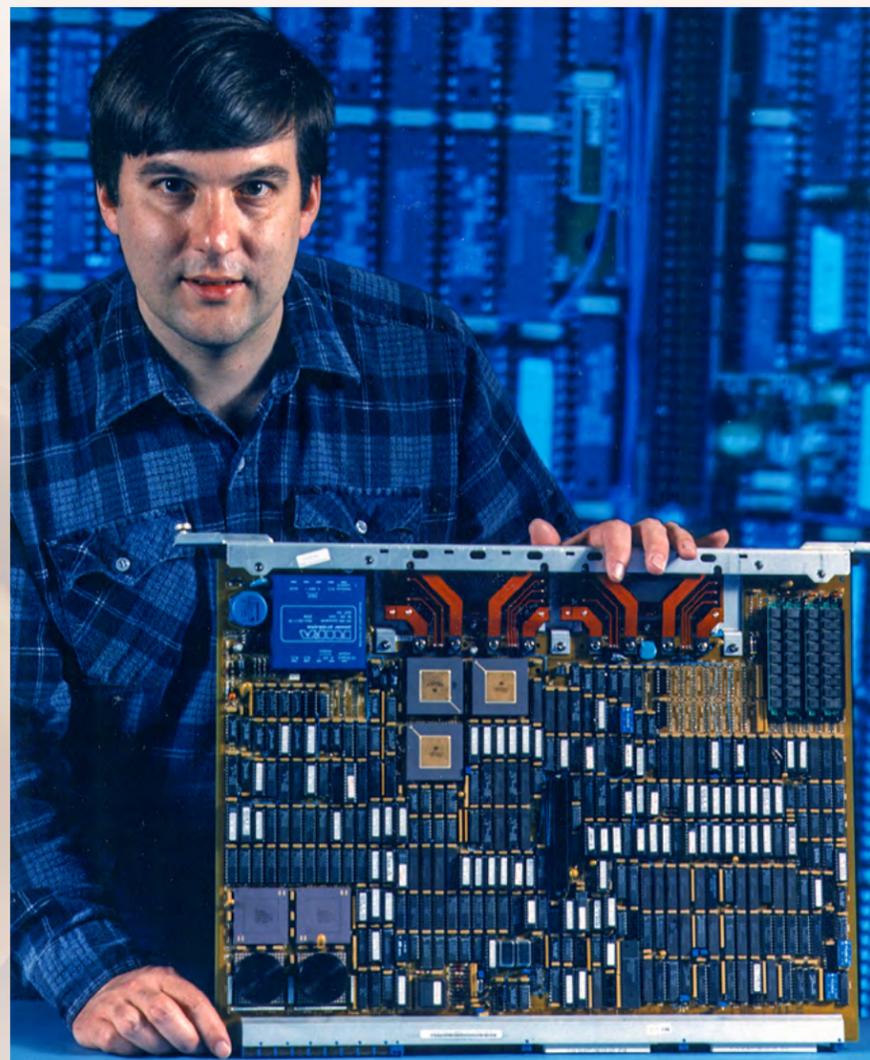
In 1990, the MPCI project acquired Livermore's first substantial, onsite massively parallel resource, a 64-node BBN-ACI TC-2000 machine that was upgraded to a full 128-node configuration a year later. Scientists from across the Laboratory's technical directorates probed the software development challenges of effectively using this new architecture by running a variety of computer problems on the MPCI machine. By 1992, early results were already available in such diverse areas as particle-physics event simulation, multidimensional numerical analysis, parallel graphics rendering algorithms, and sedimentation modeling. Each MPCI annual report not only encouraged use of this new approach to scientific computing but also summarized the latest trial programming techniques and output evaluations for Laboratory researchers.

One rewarding long-term effect of the early MPCI work was a heightened desire to widely share centrally managed massively parallel computing resources among many unclassified projects at the Laboratory. In 1996, a formal Multiprogrammatic and Institutional Computing (M&IC) initiative began providing fast, high-capacity

Eugene D. Brooks III, leader of early Laboratory efforts to explore potential benefits of parallel computing, displays a cluster of processors used in the BBN-ACI TC-2000.

First available from Bolt, Beranek and Newman Advanced Computers, Inc., in 1989, the BBN-ACI TC-2000 had a multiprocessing architecture that allowed individual processors to be partitioned into clusters and dynamically reallocated. Because data could be shared within and between clusters, the computer was able to integrate distinct segments of a complex calculation.

CIAC: Keeping Cyber Space Safe

On February 1, 1989, DOE formed the Computer Incident Advisory Capability (CIAC) at Livermore. A continuous stream of security incidents had begun the previous year, affecting computer systems and networks throughout the world. Crackers and intruders made bold headlines with their stealthful entry into government computers, commercial equipment, and telephone systems. The world of computers was proving to be a dangerous one and clearly something needed to be done. CIAC's primary mission has been to help protect the DOE computer community, currently by providing crucial support to the DOE Joint Cybersecurity Coordination Center.

parallel computers to researchers throughout the Laboratory and their collaborators. Supported by institutional funding and managed by the Livermore Computing program, M&IC procures the computing hardware and covers operational costs—leveraging ASCI/ASC investments in high-performance computing.

The Laboratory's continued investment in M&IC has repeatedly enabled groundbreaking unclassified simulations that have advanced scientific discovery and Laboratory missions. Software innovations at Livermore developed for use on parallel computational resources have made possible quantum molecular dynamics simulations based on first-principles physics (see Year 2003), greatly improved modeling of laser–plasma interactions in fusion ignition experiments and enhanced studies to quantify the key uncertainties that influence the predictions of global climate simulations.

The Nineties

New Leadership

C. Bruce Tarter
(1994 • 2002)

The Berlin Wall came down in 1989, the Cold War ended, and significant reductions were being made in strategic arsenals. Both the Soviet Union and the United States entered a nuclear testing moratorium in 1993 while recognizing an important continuing role for nuclear weapons in the post–Cold War world. The United States formally began its Stockpile Stewardship Program to maintain a safe, secure, and reliable nuclear deterrent in 1995. As a National Nuclear Security Administration laboratory, Livermore is a principal contributor to the program.

In the post–Cold War world, the Laboratory broadly

Focus on national security

contributes to the nation's science and technology base, but its defining mission remains national security. That mission is broader than stockpile stewardship. The invasion of Kuwait in 1990 and the subsequent discovery of aggressive Iraqi programs to develop weapons of mass destruction made clear that the world remained a dangerous place—complicated by the uncertain status of nuclear weapons and materials in a fragmented Soviet Union. Livermore responded by quickly expanding its analysis and technology-development program to prevent proliferation at its source, detect and reverse proliferant activities, and respond to the threat or use of weapons of mass destruction.

Detecting One in a Quadrillion

Standing next to the Center for Accelerator Mass Spectrometry's tandem electrostatic Van de Graaff accelerator, physicist Jay Davis explains the center's operations and the many applications of AMS.

In 1990, soon after the Center for Accelerator Mass Spectrometry (CAMS) started operations, the first biomedical experiment using AMS was performed at Livermore. It measured the effects on rat DNA of a suspected carcinogen that results from cooking meat. From the beginning, CAMS has proved to be a highly versatile research facility, contributing to the success of a wide range of Laboratory programs and the research projects of many external users.

AMS is a sensitive technique for measuring concentrations of specific isotopes in very small samples— able to seek out, for example, one carbon-14 isotope out of a quadrillion (a million billion) other carbon atoms. The technique enables Laboratory researchers to diagnose the fission products of atomic tests and monitor the spread of nuclear weapons by detecting radioisotopes in air, water, and soil samples. In addition, AMS supports studies in environmental

quality, climate change, seismology, archaeology, biomedical science, and many other areas of scientific research.

The opportunity for a multiuser AMS capability was recognized by Jay Davis, at the time a division leader, who lined up support for the new accelerator facility from programs throughout the Laboratory. Research efforts benefited from one of Livermore's first large-scale initiatives in its Laboratory Directed Research and Development program. In addition, funding from the University of California (UC) helped to support construction and continuing use of CAMS by UC faculty. To help lower costs, the designers used as many spare components as they could find. The accelerator came from the University of Washington, and a couple of the largest magnets had previous lives in an electron beam accelerator at Stanford University.

Established in 1988, CAMS was unique from the start because of the use of high-quality beam optics and a computer-control system that allows large numbers of high-precision measurements to be taken. The capabilities exceeded those of other AMS facilities because of the programmatic need to measure a diverse array of isotopes. An initial optimistic projection was that someday 5,000 to 10,000 measurements could be handled each year. CAMS quickly exceeded that goal. As the the world's most versatile and productive AMS facility, CAMS performs more than 25,000 analyses per year.

In 1999, the National Institutes of Health (NIH) awarded Livermore a Biotechnology Center grant to make AMS available to the biosciences community. CAMS became the first National Resource for Biomedical

CAMS began operation in 1989 and now processes about 25,000 samples per year for its users (above). With support from the National Institutes of Health, the Laboratory has added a smaller AMS capability (not shown) dedicated to biomedical analyses.

AMS. The facility provides biomedical researchers—currently from more than 60 institutions—the ability to accurately measure very low levels of carbon-14 and other radioisotopes used in tracer studies. Numerous technology upgrades have enhanced the Laboratory's biomedical AMS capabilities, including the installation of a $3-million, NIH-funded, dedicated

bioAMS system and the development of much-simplified and faster processes for sample preparation. LLNL researchers are also working to develop and validate a totally new type of spectrometer that will be smaller, less expensive, and simpler to operate and could be more widely deployed in biomedical research laboratories.
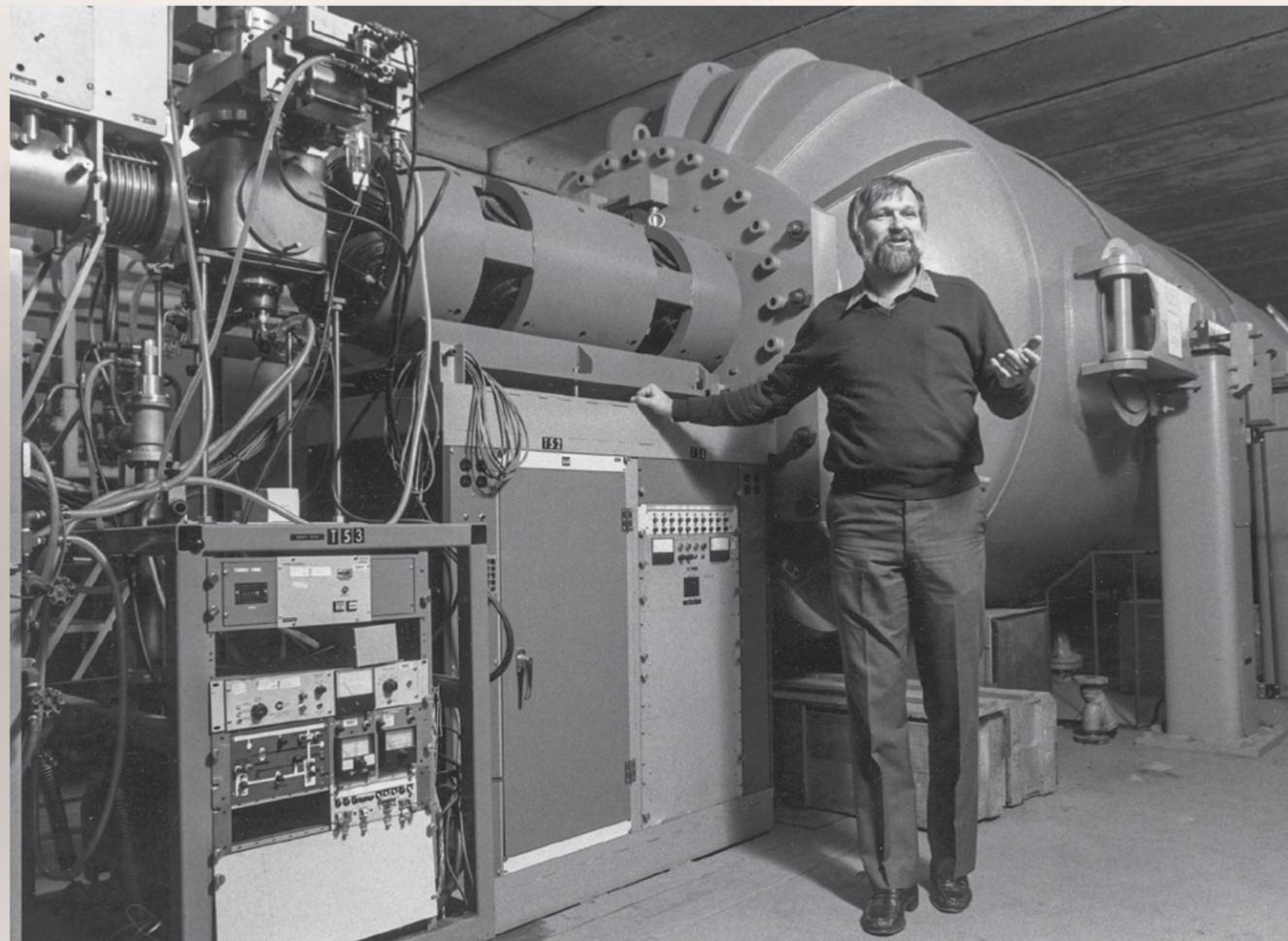
Inspecting for Weapons of Mass Destruction

Laboratory engineer Bill Nelson inspects the bombed-out reactor and nuclear research facilities at Tuwaitha (just outside Baghdad) during the first inspection after Desert Storm.

At the end of Operation Desert Storm, the world was full of rumors about Iraq's nuclear capabilities and how much of them remained following an intense bombing campaign. In May 1991, a specially selected team, under the auspices of the United Nations Special Commission (UNSCOM) and the International Atomic Energy Agency (IAEA), was assembled for the first inspection of Iraqi nuclear facilities under UN Security Council Resolution 687. Laboratory engineer Bill Nelson was a member of that team.

The first and subsequent UNSCOM/IAEA inspections uncovered evidence of an advanced Iraqi nuclear program, code-named Petro-Chemical Project 3. At Tarmiya, inspectors uncovered Project 946, a uranium enrichment

Iraqi Calutrons

Laboratory physicist Jay Davis, twice a member of UNSCOM/IAEA inspection teams, found the Iraqi isotope separation technology was similar to that developed at the University of California (UC) at Berkeley in the late 1940s to enrich uranium for the first atom bomb. Called the calutron because of its UC origin, the technology was abandoned by the United States because of cost. However, it was an excellent choice for Iraq in that calutrons required few outside resources. Davis estimated the Iraqi Manhattan Project–style effort at between $6 and $8 billion and noted that the quality of work was "every bit as good as we could do today."

production facility that the Iraqis attempted to hide by removing railings from the floor of the building, pouring a new layer of concrete, and putting rubble on top. They had developed a first-class electromagnetic isotope separation capability with supporting research and industrial infrastructure. Production of 10 to 30 kilograms of highly enriched uranium, a key component of nuclear weapons, might have occurred within two years.

Perhaps the defining moment came in September 1991, when UNSCOM/IAEA Team 6 discovered a large cache of documents. Two Laboratory scientists were on the team; another was at the UN supporting the operation. For five days, a standoff occurred in Baghdad between the team of inspectors, which wanted to remove the documents from where they were found, and hundreds of

heavily armed Iraqi soldiers. Sleeping on pieces of cardboard in the building's parking lot and sometimes without even water, the group refused to leave without the papers they considered to be the smoking gun. The documents indeed proved critical in establishing a knowledge baseline of the Iraqi program.

Iraqi facilities were inspected for any evidence of weapons of mass destruction—not just nuclear, but also chemical and biological weapons and ballistic missiles. The teams seized, had destroyed, or subjected to monitoring impermissible equipment. In all, more than a dozen Laboratory researchers took part in various inspections until the UN removed all personnel in 1998 because of an increasingly hostile atmosphere. Livermore scientists also developed, installed, and maintained sophisticated inspection and monitoring equipment in Iraq, such as automated

cameras and microwave communication links for remote surveillance of facilities that could be used in missile production.

Livermore continues to provide technology, analysis, and expertise to help prevent the spread or use of weapons of mass destruction. Soon after the Iraq inspections began, Laboratory Director John Nuckolls formed the Nonproliferation, Arms Control, and International Security (NAI) Directorate. The new directorate merged into a comprehensive program of research activities pertaining to nonproliferation, including proliferation prevention, detection, and reversal, and response to potential proliferant states and terrorists. NAI evolved into the Global Security Principal Directorate.

Better Global Climate Models and Analysis

In 1992, Laboratory atmospheric scientist Larry Gates issued The Validation of Atmospheric Models, the first of a continuing series of reports that would radically alter global climate 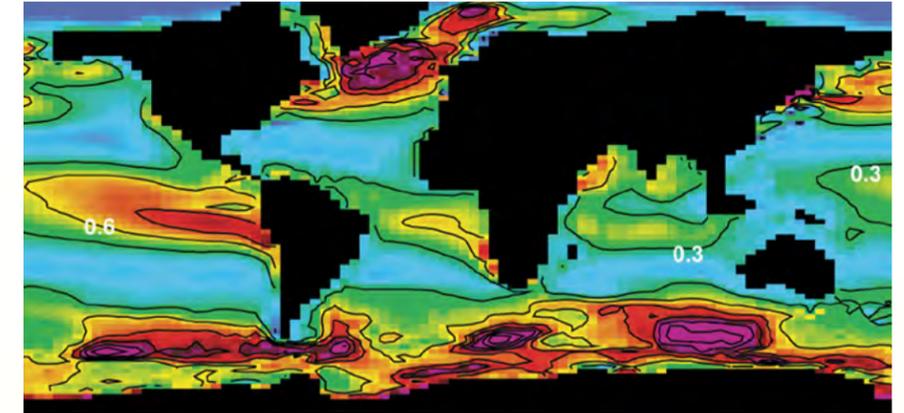change research and the way models characterize climate. The report came five years after Gates, an atmospheric science professor at Oregon State University, had come to Livermore and stayed. In 1989, Gates and fellow atmospheric scientists formed a new group at the Laboratory called the Program for Climate Model Diagnosis and Intercomparison (PCMDI).

Livermore quickly became an internationally recognized institution for climate model analysis. PCMDI's earliest joint studies were conducted with scientists from the Department of Commerce's Geophysical Fluid Dynamics Laboratory, the National Science Foundation's National Center for Atmospheric Research, Oregon State University, and the State University of New York at Stony Brook. Research groups from Canada, China, Germany, Japan, and the United Kingdom also participated. A selected set of climate models was transferred to a supercomputing facility at Livermore. PCMDI researchers worked to devise a common format and processing protocol for output, assemble databases for model evaluation, and develop diagnostic methods to illuminate the effects of model assumptions and approximations.

At the time, the need for standards in both modeling and analysis were becoming increasingly apparent as more complex models were developed. The disagreements among models and between models and observations were significant and poorly understood. A persistent need exists to account for, in a systematic fashion, the nature and causes of differences among models and between simulations and observations to continually improve climate prediction studies in support of global climate change research.

PCMDI integrates the talents of physical (atmospheric) scientists and computer scientists, following the approach of other interdisciplinary programs at Livermore. The program's mission is not to make new models but rather to set a standard by which all climate models adhere so as to lend validity to to modeling efforts. The major goals are to develop improved methods and tools for the diagnosis, validation, and intercomparison of global climate models and to conduct research on a variety of problems in climate modeling and analysis. PCMDI's software system is recognized around the world for its efficiency and flexibility.

Atmospheric scientists at PCMDI have also been key participants in international efforts examining the evidence for climate change due to human activities. Ben Santer, who received the prestigious MacArthur Foundation "genius award" in 1998, served as lead author for Chapter 8 ("Detection of Climate Change, and Attribution of Causes") of the 1995 Second Assessment Report of the Intergovernmental Panel on Climate Change. The report concluded that "the balance of evidence suggests a discernible human influence on global climate." PCMDI's work continues and contributed to the selection of the winners of a Nobel Peace Prize (see Year 2007).
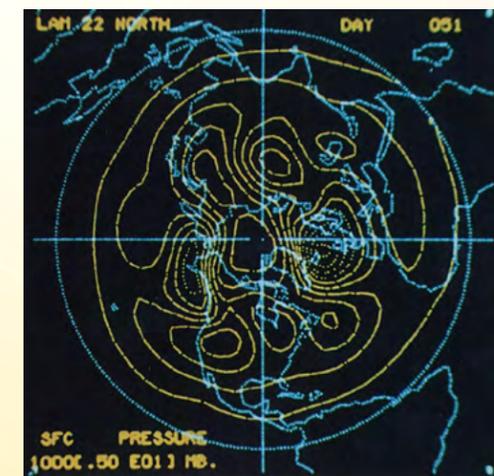
W. Lawrence Gates, an internationally known climate scientist from Oregon State University, became the Chief Scientist and first leader of PCMDI. He set as the goal of the program's first studies "to identify the model improvements needed to enable more reliable regional climate predictions to be made over the next decade."

Studies conducted in the 1990s used ocean circulation models to study northerly movement of the carbon dioxide soaked up by cold water in the Southern Ocean. Efforts are under way to develop an integrated climate and carbon-cycle model.

In the late 1950s, Laboratory physicist Cecil "Chuck" Leith and his group applied numerical methods used for weapons physics to develop the first global general circulation model, which was able to simulate the behavior of large weather systems. Results were displayed in a movie (left) of the model's weather on a map centered at the North Pole.

The Founding of PCMDI

In July 1989, a Laboratory press release announced: "Lawrence Livermore National Laboratory has begun a program to improve the quality of models for predicting potential climate change due to the so-called 'greenhouse effect.'"

"The new effort—a collaborative one involving research groups across the nation—is called the Program for Climate Model Diagnosis and Intercomparison. …The Chief Scientist of the new program, Lawrence Gates, said that the major task for the program in its first few years of operation will be to work with the various national and international modeling groups to diagnose and compare a series of increasingly stringent numerical 'experiments' with the models."

Hot Technology Removes Contamination

If the Laboratory had used conventional methods in 1993 to clean major leaks from its underground gasoline tanks, the project would still be under way. Estimates had pegged the time at 30 to 60 years to remove thousands of gallons of gasoline that had leaked into the soil beneath the shipping and receiving area north of East Avenue. But instead of decades or even years, the 7,600 gallons of gasoline were mopped up in about four months using remediation technologies developed by Laboratory scientists Roger Aines, Robin Newmark, and John Ziagos in collaboration with a University of California at Berkeley researcher.

The technique, called dynamic underground stripping, involves injecting steam to heat the ground.

Dynamic underground stripping cleans up underground hydrocarbon spills. The method is used in combination with other Livermore-developed monitoring and remediation technologies to rapidly remove contaminants from groundwater or destroy them in place.

Contaminants are vaporized and driven to extraction wells, where they are easily removed from soil and water. The heat and forced air chemically break down many contaminants in place, leaving harmless compounds. Electric currents heat soils that are too impermeable for steam to penetrate. The treatment of contaminants is even more effective when dynamic underground stripping is combined with two related remediation technologies subsequently pioneered by Livermore researchers: electrical resistance tomography, for monitoring an underground clean up in real time; and hydrous pyrolysis/oxidation, which destroys pollutants where they are found underground.

The technology achieved remarkable success cleaning a Superfund site in Visalia, California, between May 1997 and June 2000. For nearly 60 years up to 1980, Southern California Edison had treated utility power poles with carcinogenic wood preservatives such as creosote and pentachlorophenol, some of which leaked into the ground. Using older cleanup methods at Visalia, about 275 pounds of contaminants had been removed in one nine-month period. However, with the use of the Livermore technology, Southern California Edison, working with the Laboratory and a licensee, was able in a similar nine-month period to extract about 540,000 pounds of pollutants—almost 2,000 times more.

During the entire three-year Visalia cleanup, about 1.2 million pounds of contaminants were removed from the four-acre site using the dynamic underground stripping technology, and the residual contaminants continued to degrade after operations ceased. Further cleanup was augmented by installation of a system to enhance natural biological degradation processes. After the Environmental Protection Agency issued a Final Close Out Report in May 2009, the Visalia site was removed from the National Priorities List.

In addition to the Visalia cleanup project, dynamic underground stripping technologies were successfully used at DOE's Savannah River Site, Pinellas Plant, and Portsmouth facility. For example, in 2000–2001 more than 65,000 pounds of contaminant were removed from an area at Savannah River where chlorinated solvents were stored (with considerable spillage and leakage). The technology was applied again in 2006 for groundwater cleanup in an adjacent area.
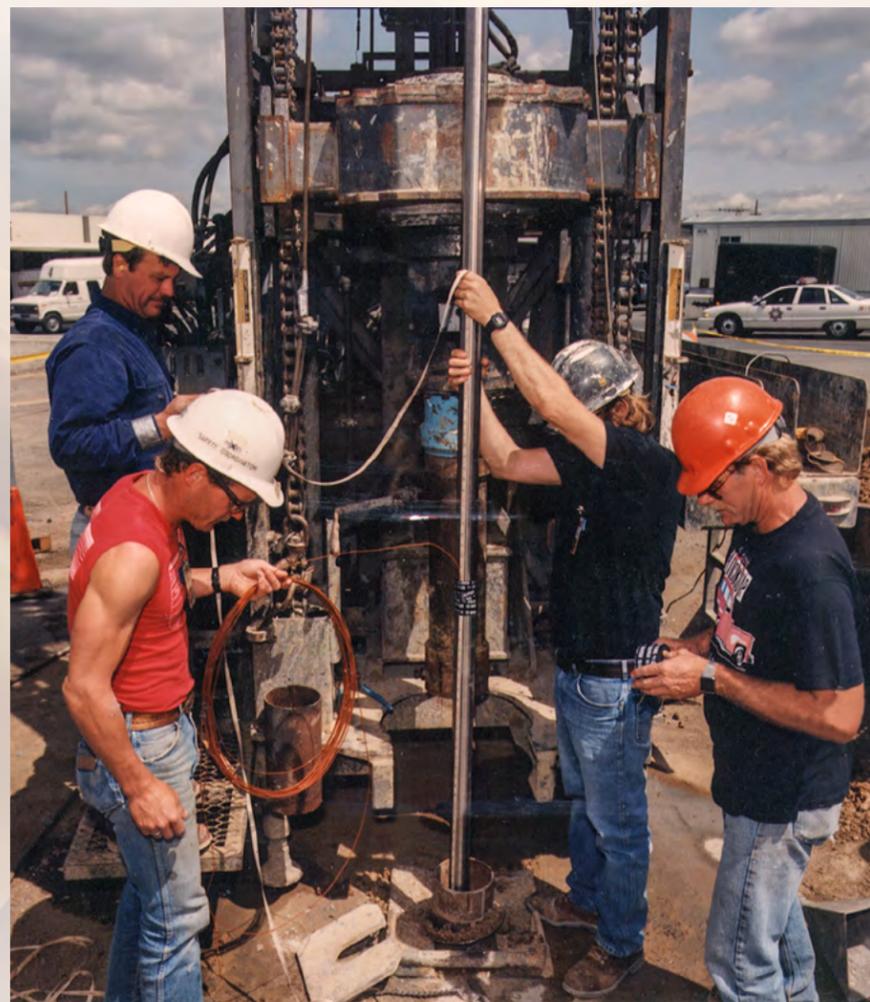

Two complementary technologies pioneered at Livermore have successfully cleaned up contaminated groundwater and soil at facilities in several states. Hydrous pyrolysis/oxidation combined with dynamic underground stripping destroys contaminants in situ and brings them to the surface at 5,000 times the rate of conventional technologies.

Advanced Sensors Map the Moon

The Clementine Deep Space Experiment, sponsored by the Ballistic Missile Defense Organization, was launched on January 25, 1994—22 months after the effort began. At a mission cost of less than $100 million, it was the first U.S. spacecraft to visit the moon in over two decades. The Clementine mission collected over 1.7 million images during its two months in lunar polar orbit. The data has enabled global mapping of lunar-crust rock types and the first detailed investigation of the geology of the lunar polar regions and the lunar far side.

The Clementine spacecraft included new advanced technology sensors and space component technologies that provide the basis for a next generation of lightweight satellites for
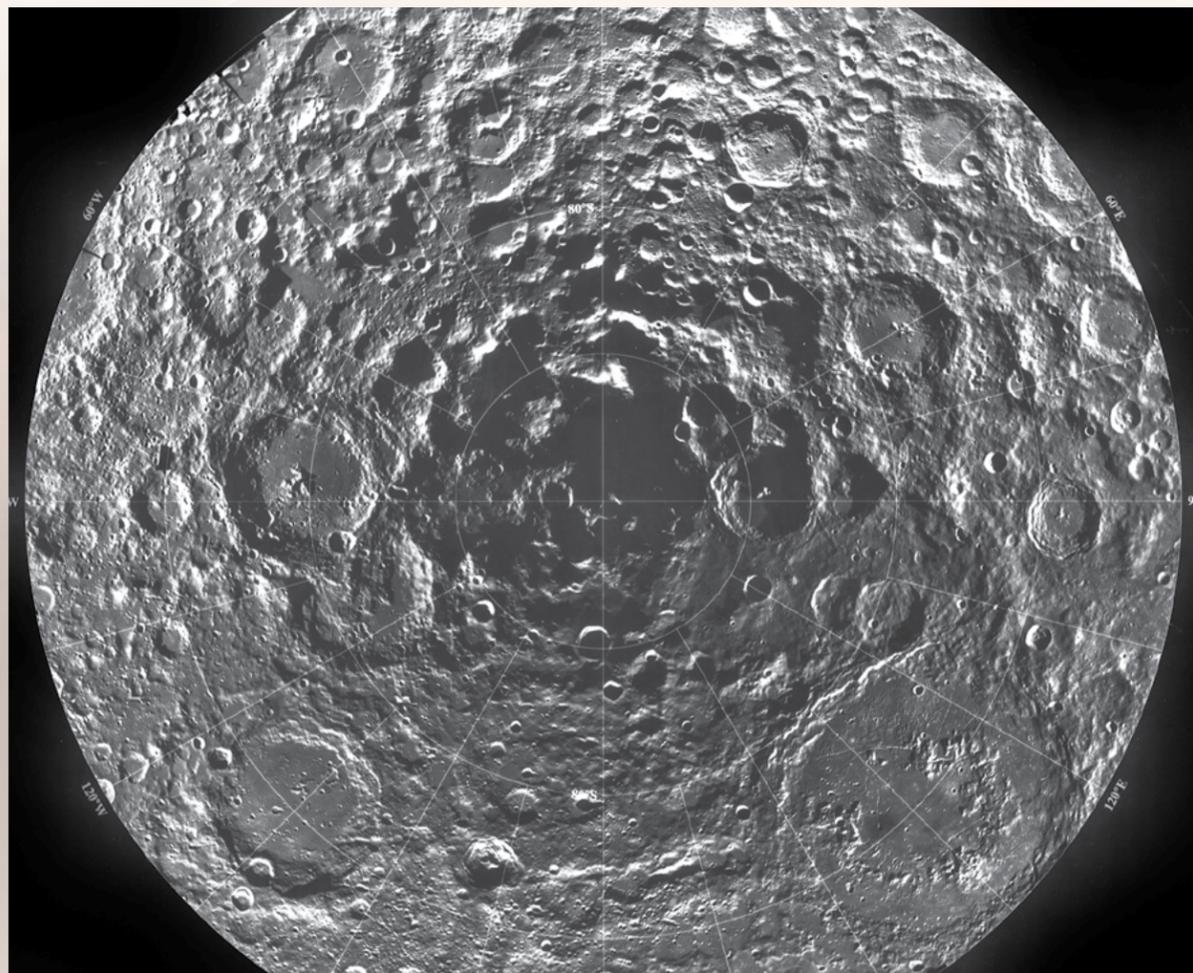
A mosaic of 1,500 images taken by Clementine reveals for the first time a 300-kilometer-wide depression near the Moon's lunar south pole.

Using six on-board cameras designed and built at the Laboratory, the Clementine satellite mapped the entire surface of the Moon in 1994 at resolutions never before attained.

civilian and military missions. It had a dry mass of only 500 pounds and incorporated 23 advanced subsystem technologies. The spacecraft's payload consisted of an advanced sensor suite weighing less than 16 pounds that was designed, fabricated, integrated, and calibrated by Laboratory scientists and engineers with the support of industrial contractors. The Naval Research Laboratory designed, integrated, and operated the spacecraft. NASA provided mission design and operational support.

Clementine carried an ultraviolet-visible camera, a shortwave infrared sensor, a longwave infrared sensor, an imaging lidar (light detection and ranging) instrument, and two Star Tracker cameras. These instruments successfully mapped the entire lunar surface in 11 spectral bands. By laser ranging, the lidar system also generated a global topographical data set. The topography of the moon's many ancient impact basins was measured, and a global map of the thickness of the lunar crust was derived. In addition, bistatic radar measurements made over the Deep South polar depression indicated the presence of frozen water on the moon.

Clementine's sensor system technologies were derived from Livermore's space-based interceptor development program. The Strategic Defense Initiative Organization (SDIO) funded related research beginning in 1985, and in November 1987, the Brilliant Pebbles effort formally commenced. The concept was to deploy a constellation of sophisticated, inexpensive, lightweight spacecraft in low Earth orbit—Brilliant Pebbles—that could detect and hunt down missiles over distances of thousands of kilometers without external aid. In the summer of 1989, Brilliant Pebbles was adopted by SDIO as the new baseline for the space-based segment of a national missile defense system.

A wide variety of projects to develop state-of-the-art sensor technologies at the Laboratory have built upon the success of the Clementine program. An immediate follow-on was the development of a large-format digital camera system that uses charge-coupled device detectors. Astronomers used the 16-million-pixel cameras in the search for massive compact halo objects (MACHOs), a form of dark matter.

O Group

Under the leadership of physicist Lowell Wood, O Group pursued a variety of imaginative research projects in the late 1970s and the 1980s. O Group included many extremely talented young scientists, some of whom came to the Laboratory as Hertz Foundation fellows. An exceedingly ambitious early project was the design of the S-1 supercomputer, an effort which led to the development of computerized design methods, including Structured Computer-Aided Logic Design (SCALD), which successfully spun-off from the Laboratory. O Group pioneered the development of x-ray lasers and gave birth to the concept of Brilliant Pebbles.

Lowell Wood presented President George H. W. Bush with a conceptual model of Brilliant Pebbles when the president visited the Laboratory in 1990.

Understanding the Details of Nuclear Weapons Performance

In 1995, the Stockpile Stewardship Program formally began when President Bill Clinton reached two critical decisions that established the course for future nuclear weapons activities in the United States. At the time, both the U.S. and Russia were reducing the size of their nuclear arsenals, both nations had been observing a moratorium on nuclear testing for three years, and the U.S. had halted its programs to develop new nuclear weapons.

First, on August 11, 1995, the president announced that the U.S. would pursue a Comprehensive Nuclear-Test-Ban Treaty. In making that decision, he also reaffirmed the importance of maintaining a safe and reliable nuclear weapons stockpile. Then, on September 25, 1995, the president directed necessary programmatic activities to ensure continued stockpile performance. Under the leadership of Vic Reis, Assistant Secretary for Defense Programs, the DOE national security laboratories and the weapons production facilities worked with DOE Defense Programs and the Department of Defense to formulate the Stockpile Stewardship Program.

The program was launched as an ambitious effort—not without risks— to significantly improve the science and technology base for making informed decisions about an aging nuclear weapons stockpile without relying on nuclear testing. All aspects of weapons must be understood in sufficient detail so that weapons experts can assess the performance of the nation's nuclear weapons with confidence and make informed decisions about refurbishment, remanufacture, or replacement of weapons as needs arise.

To succeed, the three DOE national security laboratories, now part of the National Nuclear Security Administration, needed much more advanced experimental and computational capabilities. At Livermore, construction of the National Ignition Facility soon began (see Year 1997), and the Advanced Simulation and Computing Initiative (ASCI) prodded the development of next-generation supercomputers (see Year 2000). As new capabilities have come online, they have contributed to surveillance of stockpiled weapons to determine their condition, assessment of weapon safety and reliability, activities to extend the lifetime of weapons, and certification of refurbished warhead systems. The new experimental and computational capabilities also serve to train and evaluate the skills of next-generation stockpile stewards, who must recognize and deal with issues as they arise to sustain the nuclear stockpile.

The Stockpile Stewardship Program made excellent technical progress in its first decade. For example, researchers made dramatic improvements in their understanding of the properties and aging of materials in weapons, and the sophistication and resolution of 3D simulations of weapons performance rapidly increased. In addition, Livermore successfully completed engineering development work on its first stockpile life-extension program (see Year 1986). However, then as now, tougher challenges likely lie ahead as weapons continue to age. The long-term success of stockpile stewardship depends on a continuing strong national support for the program and on the skills and capabilities of future generations of weapons experts at the nuclear weapons laboratories.
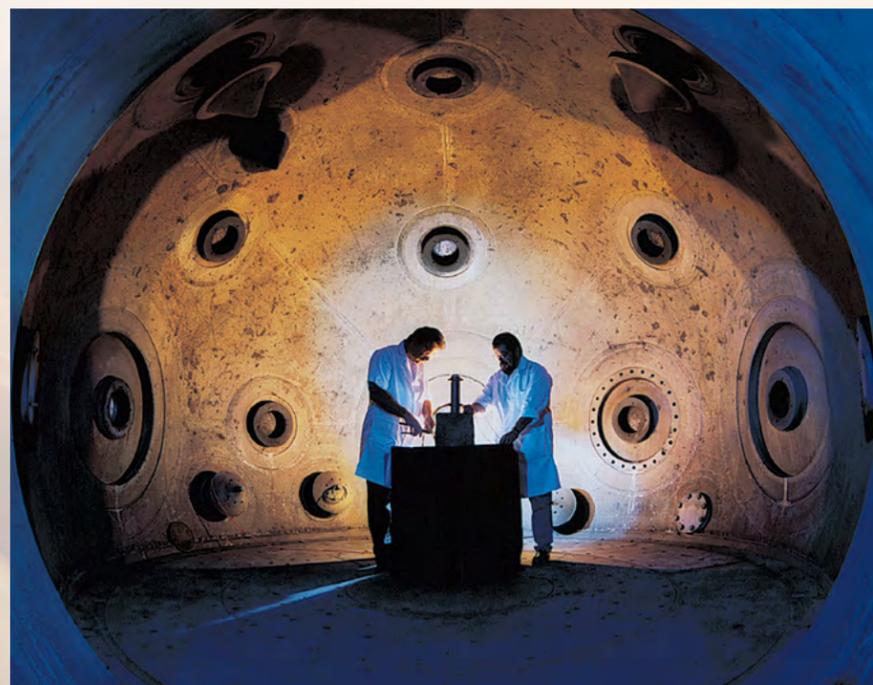
Established in 1989, Livermore's High Explosives Applications Facility (HEAF) is an NNSA Center of Excellence supporting stockpile stewardship. Researchers at HEAF develop, characterize, and test high explosives and other energetic materials. Specially designed containment vessels (above and left, arriving in August 1988) are used to safely detonate explosives in quantities as large as 10 kilograms of TNT-equivalent. Larger scale tests are staged at the Contained Firing Facility at Site 300.

Vic Reis, DOE Assistant Secretary for Defense Programs, provided exceptional leadership in defining the "science-based" Stockpile Stewardship Program, working with program leaders from Livermore, Los Alamos, and Sandia national laboratories. Reis formulated and clearly articulated to government decision makers a key major premise: the core of any long-term stewardship program was a set of world-class scientific and technical laboratories with expertise in all aspects of nuclear weapons.

Heralding a New Era in Astronomy

In September 1996, observers at the University of California's Lick Observatory, atop Mount Hamilton near San Jose, California, obtained their first image that was significantly improved through use of a laser guide star and adaptive optics. The event heralded a new era in astronomy.

The Shane telescope's Livermore-developed adaptive optics subsystem (below and bottom) was the first such laser system on a major astronomical telescope. Adaptive optics were installed on the Keck II telescope (left) in 1998, and in 2001, a laser guide star system was added.

Photo credit: John McDonald/Canada-France-Hawaii Telescope Corp.

Atmospheric distortions, which cause stars to twinkle and have haunted astronomers since Galileo, no longer greatly limit the performance of Earth-based telescopes.

Two years earlier, a Livermore-designed adaptive optics system was installed on Lick's 3-meter Shane telescope. To correct for atmospheric turbulence, an adaptive optics system uses a large number of computer-controlled actuators to precisely adjust the shape of a deformable mirror up to several hundred times per second. The technology has benefited from the efforts of many researchers, including the team at LLNL, which developed adaptive optics for use as part of the Atomic Vapor Laser Isotope Separation (U-AVLIS) Program (see Year 1973). Adaptive optics are also central to the design of the lasers for the National Ignition Facility (see Year 1997) and the search for extrasolar planets (see Year 2005).

The adaptive optics system alone benefits astronomers only if the object being studied has a sufficiently bright nearby star that can be used to determine the atmospheric distortions that must be corrected. In most cases, no such star exists, and one has to be created—a "laser guide star." The team of Laboratory and University of California (UC) researchers working on the Lick project, led by Livermore's Claire Max, installed a laser guide star system at Lick in 1996. A 15-watt dye laser system, a technology developed as part of the U-AVLIS Program, was retrofitted onto the Shane telescope. Light from the laser reflects off a layer of sodium atoms in the upper atmosphere (about 100 kilometers altitude), creating the needed artificial star.

Subsequently, a team from Livermore, UC, and the California Institute of Technology installed adaptive optics and a laser guide star system on the telescopes at Keck Observatory in Hawaii. Since the first observations in 1998, the adaptiv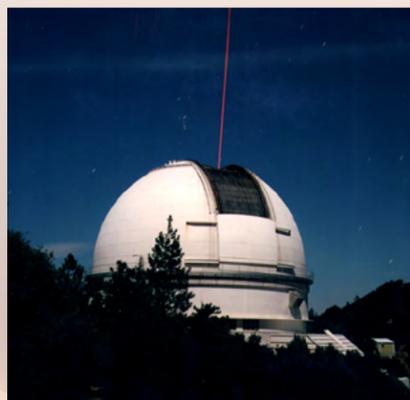e optics have enabled astronomers to obtain infrared-light images of unprecedented resolution—four times better resolution than the Hubble Space Telescope. Early successes included detailed studies of Uranus and its rings and the observation of hundreds of young stars in very fast orbit around an unseen, incredibly massive object—a black hole—at the center of our galaxy.

In December 2001, "first light" was achieved with a newly installed laser guide star system on the 10-meter Keck II telescope. Science observations using the system began in late 2004. The first images of a distant planet were taken at Keck, and a picture of Eris and its moon contributed to Pluto's demotion from planetary status.

Astrophysics at Livermore

Because astrophysics and nuclear weapons physics have many similarities, it is not surprising that the Laboratory has a long history of contributing to the advancement of scientific understanding about our universe and developing instrumentation used by astronomers. Pioneering work in the 1960s includes seminal papers on gravitational collapse and supernova explosions by Laboratory researchers including Stirling Colgate, Montgomery Johnson, Michael May, Richard White, and James Wilson. Current interests range from development of instrumentation for planetary imaging (see Year 2005) and x-ray astronomy to observation and experiments of high-energy-density astrophysical phenomena (see Year 2009).

Thermonuclear Physics and Matter at Extreme Conditions

Groundbreaking for the stadium-sized 192-beam National Ignition Facility (NIF) took place in May 1997. An extremely ambitious and technically challenging project, NIF construction was the culmination of a series of increasingly larger lasers built over the prior 30 years. Dedicated in 2009 (see Year 2009), NIF is the world's most energetic laser. With NIF, scientists perform vitally needed high-energy-density (HED) physics experiments. The facility is a cornerstone in the U.S. nuclear weapons Stockpile Stewardship Program to ensure the safety, security, and effectiveness of the nuclear deterrent. NIF serves as a national and international user facility for studying the physics of matter under conditions of extreme temperature, energy density, and pressure and pursuing inertial confinement fusion (ICF).

NIF is designed to deliver 192 laser beams with a total energy of 1.8 million joules of ultraviolet light to the center of a 10-meter-diameter target chamber. This energy, when focused into a volume less than a cubic millimeter, provides unprecedented energy densities in a laboratory setting. Scientists use NIF to obtain valuable data for stockpile stewardship and other national security applications, and they re-create astrophysical phenomena and extreme conditions that exist inside planets. In ICF experiments, NIF's laser beams converge on a target containing a peppercorn-sized capsule of deuterium–tritium fuel, causing the capsule to implode and create fusion reactions. The goal is to achieve ignition and sustained thermonuclear burn (see Year 2013).

In June 1999, after two years of construction, the 132-ton aluminum target chamber was transported from its assembly building to the target bay where it is now aligned to better than a millimeter accuracy. While excellent progress was being made on all technical fronts and construction continued on the $270-million conventional facility, the NIF project was rebaselined to enhance the planned method for assembling the lasers and to ensure that strict cleanliness requirements would be met.

In September 2001, conventional facility construction was completed on schedule and on budget. Inside the building, the beampath infrastructure for the first 48 beams was completed the next month. This significant milestone was 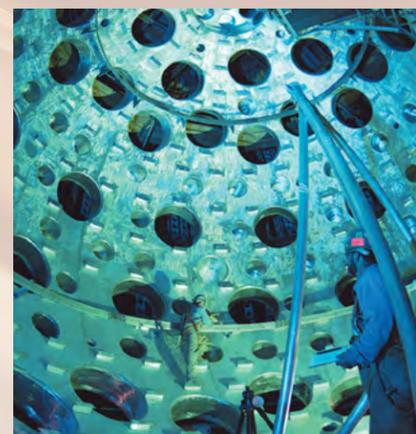accomplished through the successful partnership of the installation contractor, Jacobs Facilities, Inc., Laboratory staff, and the local building trades.

Another key milestone, NIF Early Light, occurred in December 2002 with activation of the first "quad"—the first four laser beams. Early Light demonstrated that the integrated laser system worked and that the laser beams met all performance criteria. Using the first quad, researchers conducted NIF's first physics experiment in August 2003. The ensuing experimental campaign engaged scientists from Livermore and Los Alamos national laboratories and the United Kingdom's Atomic Weapons Establishment.

In 2001, construction of the conventional facility was completed (top). The 10-meter-diameter target chamber (above and right) had been moved into the facility in 1999.

Target Chamber Construction

The 10-meter-diameter target chamber was assembled from 18 four-inch-thick aluminum sections fabricated by Pitt-Des Moines, Inc., of Pittsburgh, Pennsylvania, in a special-purpose building adjacent to the National Ignition Facility. After verifying that the vessel was leak-free in June 1999, the 132-ton vessel was hoisted by one of the largest cranes in the world and carefully installed onto its support pedestal in the target building. Surprisingly, this breathtaking event took only about 30 minutes. The seven-story walls and roof of the target bay were then completed, and the target chamber was coated with a special 16-inch-thick neutron shielding concrete shell. Now weighing about 1 million pounds, the complete target chamber was precision aligned to better than 1-millimeter accuracy.

Material Properties from Atomic to Large Scales

For years, scientists have longed for computer simulations that could accurately predict materials' performance from atomic to engineering scale. In 1998, researchers at the Laboratory began to make great strides toward this goal, developing experimentally verified, three-dimensional simulations that bridge these extreme scales. The first simulations focused on the mechanical behavior of molybdenum, using information generated at the atomic scale (measured in nanometers) to model phenomena occurring at the scale of micrometers.

The results of these microscale simulations—the strength properties of molybdenum—were then passed on to codes that model phenomena at larger scales. Researchers validated their codes by comparing their simulations to experimental results.

The multiscale modeling approach only became possible with the advent of powerful, multiprocessor supercomputers in the 1990s. Using the massively parallel computers of of NNSA's Advanced Simulation and Computing Initiative (see Year 2000), Livermore researchers launched a concerted effort to model material behavior over length scales ranging from nanometers to meters and time scales ranging from billionths of a second to tens of years.

Through multiscale modeling and experiments, scientists have gained a better understanding of the effects of radiation damage on materials. The issue is of particular importance to scientists in the Stockpile Stewardship Program, who are concerned about the aging of materials in nuclear weapons (see Year 2006). In 2000, a Livermore team headed by materials physicist Tomás Díaz de la Rubia used multiscale modeling and experiments to demonstrate for the first time the underlying connection between radiation damage (in crystalline metals), which occurs at ultrasmall scales (nanometers and picoseconds), to degradation over time of the material's mechanical properties.

Multiscale material modeling has dramatically improved as computing power increased and simulation tools grew more sophisticated. Livermore researchers pioneered the development of first-principles molecular dynamics and quantum molecular dynamics simulation models (see Year 2003). At larger scales, LLNL scientists developed ParaDiS, a code for studying how dislocations in crystal structures harden materials under strain. State-of-the-art experiments complement and validate simulations. Notably, Livermore scientists and engineers developed techniques such as dynamic x-ray diffraction to study the response of shocked crystalline materials. They also developed tools such as the dynamic transmission electron microscope (DTEM) to produce multiple digital images of ultrafast material processes on the billionth-of-a-meter scale.

Many research activities at the Laboratory are benefiting from the work. At the National Ignition Facility (NIF), scientists are applying experimentally verified multiscale modeling to predict the lifetime of optics subjected to NIF's high-intensity laser light. The multiscale approach is also being used to model biochemical processes and "designer materials" for applications ranging from supercapacitors for energy storage to advanced radiation detectors.

Livermore materials simulations are closely coupled to a program of laboratory experiments. Researchers measure the atomic transport properties of radiation damage defects in metals, including plutonium. The data are used to refine codes that simulate and predict the performance of stockpiled nuclear weapons.

DTEM takes snapshots of the dynamics that occur in samples of material undergoing change, creating a visual record of microstructural features as they rapidly evolve. Its use has validated simulation models and provides new levels of scientific understanding of nanostructure growth, phase transformations, and chemical reactions.
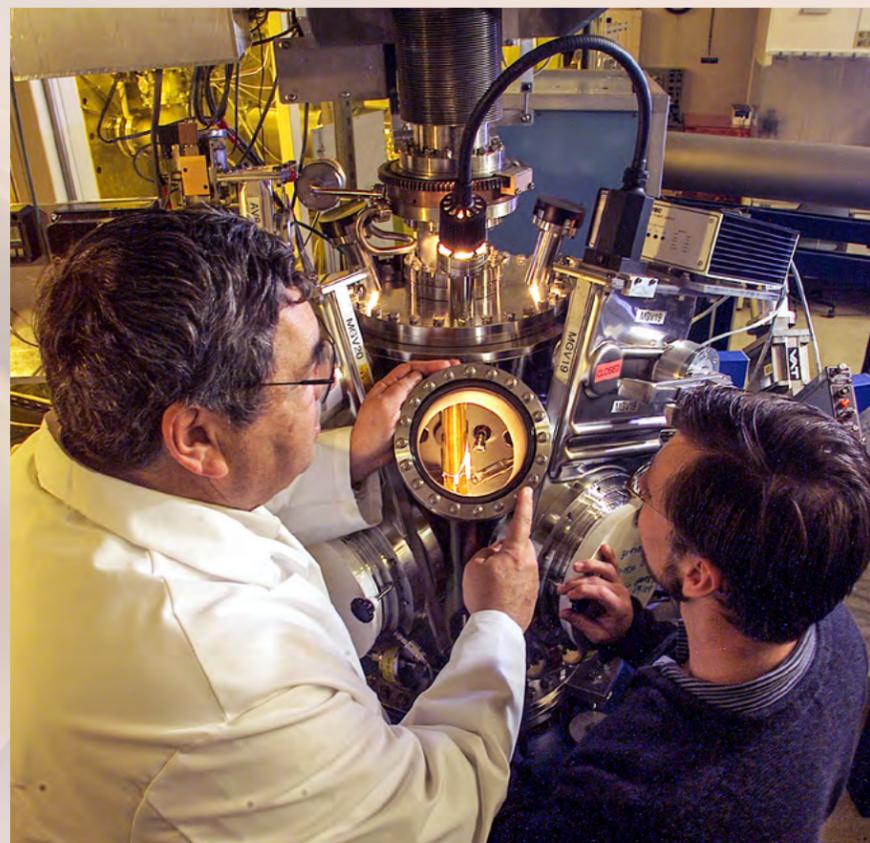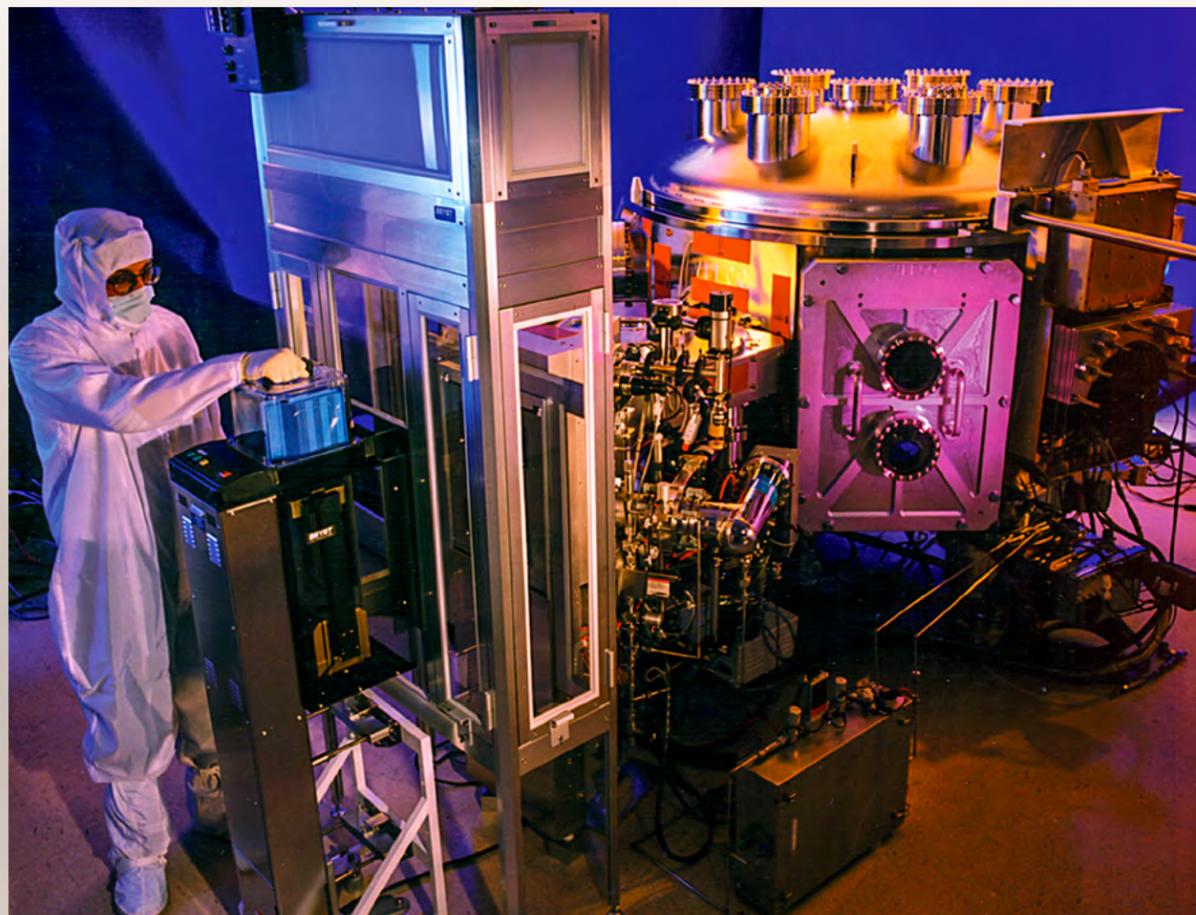
Delving into Radiation Damage

Inherently a multiscale phenomenon, radiation damage can occur over a scale of 100 nanometers and in a small fraction of a second, but the effects build up over decades. Radiation damage can produce unacceptable changes in the plutonium used in nuclear weapons, shorten the lifetime of pressure vessels in nuclear power plants, and limit the choice of materials for fusion energy research. Livermore's scientists have a long-standing interest in the topic; the Livermore Pool-Type Reactor, which operated on site from 1957 to 1980, provided neutrons to study radiation damage to materials (see Year 1952).

Technologies Spin Off to Industry

In 1999, R&D Magazine recognized Livermore with six of the 100 awards it grants annually for the most technologically significant new products and processes; the prior year Laboratory researchers won seven awards. The annual R&D 100 Awards competition recognizes important technological advancements that can be commercialized and that promise to improve people's lives. With these and later successes, Livermore has won 158 of these coveted awards through 2016. That large number is a credit to the outstanding science and engineering work at the Laboratory as well as to Livermore's excellent track record in working with industry.

Two of the awards in 1998–1999 are indicative of the Laboratory's wide variety of partnerships with U.S. industry and how technologies developed for national security applications often lead to broader societal benefits. In some cases, such as the 1998 award-winning Lasershot Peening System, the commercialization comes quickly. This new technology provided a way to harden and extend the service lifetime of metal parts, such as aircraft fuselages and engine fan blades, faster and more effectively than conventional means. The commercialized technology, now part of Curtiss-Wright Surface Technologies, has been used since 2008 by the Boeing Company to manufacture wing panels for 747-8 aircraft.

One of the R&D 100 Awards in 1999 was for a multilayer, thin film deposition system, a technology that is key to the development of extreme ultraviolet (EUV) lithography. Development of EUV lithography was being pursued by a unique industry–government collaboration that began in 1997. It involved Lawrence Livermore, Lawrence Berkeley, and Sandia national laboratories and a consortium of semiconductor companies called the EUV Limited Liability Company (LLC). The consortium committed $250 million to the project and then extended the cooperative research and development agreement with the laboratories to 2005.

At the time, the goal of computer chip manufacturers was to print circuit lines at least as narrow as 30 nanometers (1/3,000th the width of a human hair) to extend the pace of innovation described by Moore's Law. Industry saw EUV lithography as a possible solution, but that goal was reached by advancing technologies already widely used by manufacturers. In 2017, IBM announced a major breakthrough: the first 5-nanometer silicon chip, which was manufactured using EUV lithography. Future supercomputers at LLNL might be powered by processors made possible by EUV lithography.

These award-winning technologies further advanced unique, critical skills in laser and optical technology and precision engineering that support the Laboratory's national security missions. Among many other applications, those skills contribute to development of diagnostics and targets at the National Ignition Facility as well as the extremely powerful High-Repetition-Rate Advanced Petawatt Laser System for the European Union's Extreme Light Infrastructure Beamlines facility (see Year 1984).

Former Laboratory employees and members of the LLNL Entrepreneurs' Hall Fame Lloyd Hackel (left) and Brent Dane stand with a robot used in laser peening to strengthen critical parts for aviation and other industries. The duo successfully commercialized the Lasershot Peening System—used around the world for aircraft parts and turbines for electric power generation.

The Ultra Clean Ion Beam Sputter Deposition System, developed at Livermore, produces precise, uniform, highly reflective masks in the lithographic process of printing features on computer chips. In many strategic partnership projects, Livermore supplies expertise in optics, precision engineering, and multilayer coatings.

Livermore Valley Open Campus

In June 2011, the High-Performance Computing Innovation Center (HPCIC) opened for business in the Livermore Valley Open Campus (LVOC). It is the first new facility at LVOC, a 110-acre collaborative open, unclassified research and development space on the eastern edge of Lawrence Livermore and Sandia/California national laboratories. The HPCIC serves as a focal point for collaborations among LLNL experts in the application of HPC and partners in industry and academia. HPCIC has partnered with such companies as IBM, Intel, Cisco, Baker Hughes, and GE on far-reaching research efforts.

In 2016, a new supercomputing facility, adjacent to LVOC, opened to meet a rapidly growing demand for unclassified HPC for Laboratory researchers and their collaborators. Construction also began at LVOC on the Advanced Manufacturing Laboratory for LLNL employees to work with industry and academic partners.

The Aughts

The Laboratory entered its 50th year of operation as a recognized national resource, with an essential and compelling core mission in national security and the capabilities to solve difficult, important problems. Livermore's responsiveness to national needs was vividly demonstrated after September 11, 2001. Ongoing research and expertise, prototype development, and field-testing enabled Livermore to respond quickly to the terrorist attacks. The Laboratory's advanced technologies such as radiation and pathogen detectors have strongly contributed to homeland security and counter the proliferation of weapons of mass destruction.

A national resource

An exceptional scientific and technical staff made use of the Laboratory's special facilities and capabilities to resolve a key issue about the nation's nuclear weapons stockpile by finding that plutonium pits in weapons are aging gracefully. In addition, construction of new facilities further strengthened stockpile stewardship. The National Ignition Facility was dedicated in 2009 and the Terascale Simulation Facility ushered in a new generation of supercomputers that have enabled first-principles simulations of nature at the scale of atoms.

As a national resource, Livermore's science and technology have broad impact. LLNL researchers are at the forefront of understanding our planet's likely future climate and discovering distant planets.

New Leadership

Michael R. Anastasio
(2002 • 2006)

George H. Miller
(2006 • 2011)

ASCI White Arrives

During the summer of 2000, 28 moving vans carried the pieces of the world's fastest supercomputer, called ASCI White, from IBM's development facilities in Poughkeepsie, New York, to Livermore. To accommodate the sheer physical size of this massively parallel machine, together with its wiring and cooling system demands, the Laboratory had doubled the size (and the underfloor space) of the computer room in Building 451.

This latest addition to the Laboratory's computing resources was deployed in three parts, all of which shared versions of IBM's RS/6000 SP hardware technology. ASCI White consisted of 8,192 central processor units clustered into 512 nodes. Intended for large, highly parallel batch jobs, the machine demonstrated a processing speed of 12.3 teraops (trillion operations per second), about three times more than any other available computer at that time.

ASCI White's arrival marked the successful third step in a five-stage plan by the Department of Energy to sponsor development of a 100-teraops supercomputer by 2004. Launched in 1995 as the Accelerated Strategic Computing Initiative (ASCI), this collaboration of Livermore, Los Alamos, and Sandia national laboratories with U.S. industry and academia was later renamed the Advanced Simulation and Computing Program. The goal was to significantly improve capabilities to simulate with high resolution the performance of weapons in the nation's nuclear stockpile. The White machine, as the latest ASCI advance, became one of the cornerstones of NNSA's Stockpile Stewardship Program.

Effective use of a computer like ASCI White required sophisticated software and network support. Laboratory innovations to transfer and store the massive data sets generated by ASCI White simulation runs—and to analyze that data visually—enhanced the practical value of this machine. Locally designed tools enabled the efficient parallel storage of vast output files. And local software (called a terascale browser) displayed data visualizations on wall-sized screens to allow faster interpretation of results and bug detection.
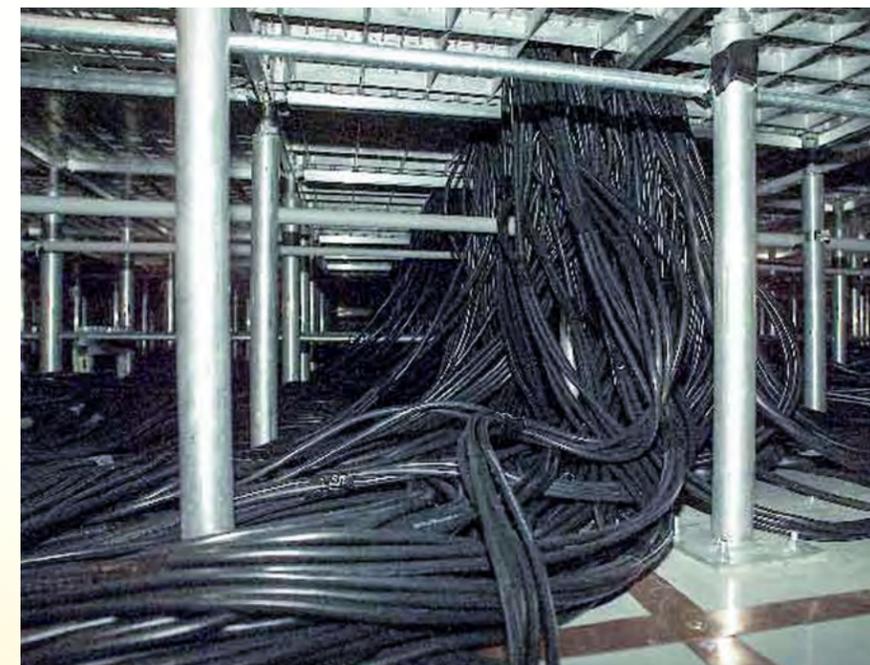
The ASCI White supercomputer needed a floor with an extra 2 feet underneath it to accommodate airflow, switches, and 40 miles of cable connecting all the computer nodes.
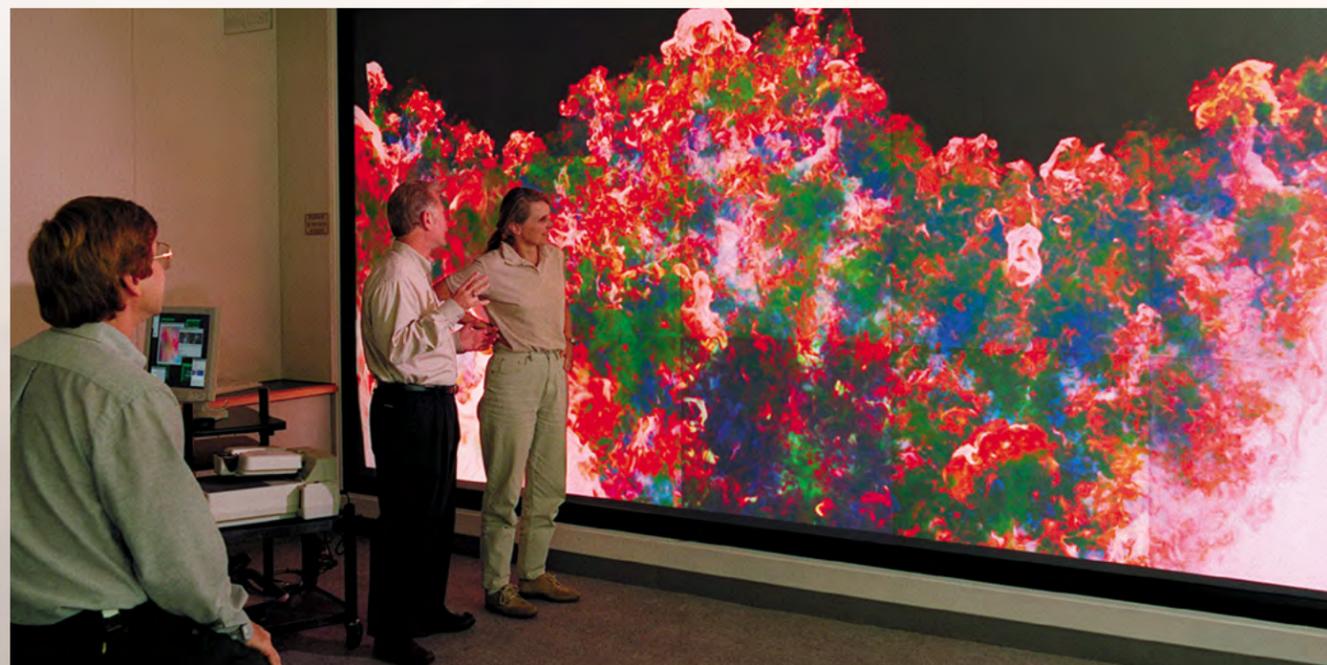
An array of 15 projectors (far left) was used to display the results of ASCI computer simulations in unprecedented detail on the Powerwall (above), a nearly 20-million-pixel screen. Scientists also used arrays of flat panel displays (left) in their work centers and individual offices to visualize the results of ASCI calculations.

ASCI White's benefits were soon evident. Use of the machine for pioneering scientific simulations began even as component upgrades continued on ASCI White's nodes. By the spring of 2002, scientists at Livermore and Los Alamos, using separate approaches to parallel code development for ASCI White, successfully completed two of the most refined computer simulations ever attempted, the first full-system three-dimensional modeling of a nuclear weapon explosion. Livermore's simulation alone used more than 1,024 processors and took 39 wall-clock days to run.

The Los Alamos work, executed remotely at Livermore by using a secure network connection to New Mexico, took over 120 days. High-bandwidth connections to Los Alamos and Sandia, coupled with extensive user support services at Livermore, allowed this machine to be used effectively by all three laboratories until it was retired in 2006.

Defending against Terrorism

The events of September 11, 2001, lent new urgency to the Laboratory's efforts to apply its technologies, tools, and expertise to better prepare the nation to defend against terrorist use of weapons of mass destruction (WMD). The prospect of a devastating bioterrorist attack became even more real a few weeks later when a terrorist sent anthrax through the mail, killing five people and sickening 17. Livermore researchers were able to provide immediate help because they had begun addressing the threat of WMD terrorism long before

September 11. Since the formation of the Nonproliferation, Arms Control, and International Security Directorate in 1992, the Laboratory had been effectively organized to take a comprehensive, multidisciplinary approach to emerging WMD threats. LLNL was developing technologies and tools to counter threats and working closely with response agencies to ensure that the technological solutions met real-world operational needs.

The Laboratory provided post-9/11 analysis and assessments

as well as information tools and expert personnel to the Intelligence Community. LLNL's Nuclear Threat Assessment Center operated seven days a week to evaluate numerous smuggling incidents and nuclear-related threats. In addition, the Counterproliferation Analysis and Planning System (CAPS), developed at Livermore and extensively used by the Department of Defense, supported U.S. military efforts to counter WMD threats.

As the anthrax mail cases illustrated, the U.S. is vulnerable to bioattack. Developments in DNA detection technologies are at the core of the nation's biodefense capabilities. The LLNL's miniaturized DNA analysis device was commercialized by Cepheid Inc., as the Smart Cycler. It was based on polymerase chain reaction (PCR) technology breakthroughs in biodetection instrumentation made by Laboratory researchers, who pioneered the miniaturization and ruggedization of DNA identification devices. In 1998, the technology was successfully demonstrated in field tests at Dugway Proving Ground, Utah, and an early version of the handheld instrument was delivered soon after to selected users.

In addition, the Biological Aerosol Sentry and Information System (BASIS), developed jointly by by Livermore and Los Alamos, was deployed to Salt Lake City, Utah, as part of the overall security strategy for the 2002 Winter Olympic Games. Smart Cycler biodetectors are the heart of the BASIS field laboratory. Because biodetectors require unique antibodies or DNA sequences to identify and characterize pathogens, LLNL set out to develop "gold standard" DNA

LLNL has developed an array of DNA pathogen signatures against which a biological-agent detector matches gathered samples. DNA signature development involves microbiologists, molecular biologists, biochemists, geneticists, and informatics experts.

Specialists from Livermore and Los Alamos national laboratories deployed the Biological Aerosol Sentry and Information System (BASIS) for the 2002 Winter Olympics in Salt Lake City, Utah. BASIS was developed under the sponsorship of NNSA's Chemical and Biological National Security Program.

The Forensic Science Center

The Laboratory's Forensic Science Center (FSC) is one of the two U.S. laboratories to be internationally accredited by the Organisation for the Prohibition of Chemical Weapons to analyze suspect chemical-warfare agents. Created in 1991, the center combines state-of-the-art science and technology with expertise in chemical, nuclear, biological, and high-explosives forensic science to provide 24/7 counterterrorism support to federal agencies. FSC researchers also advance the state of the art in forensic science. In 2016, an LLNL-led tem developed the first-ever biological identification method that exploits the information encoded in proteins of human hair—a potential game-changer for forensics.

signatures and assay protocols, which are then validated by the Centers for Disease Control and Prevention (CDC) and distributed by the CDC to the public health community.

The Laboratory has continued to make major advances in capabilities to detect pathogens for biosecurity, disease control, and other health

applications (see Year 2011). For example, almost exactly one decade after 9/11, Laboratory scientists announced an advance in PCR technology that makes possible near-instantaneous DNA analysis that could be deployed in research laboratories and doctors' offices around the world.

2002 Celebrating and Breaking Ground

Reflecting on the Past and Groundbreaking for the Future

Anniversaries are a time to reflect on one's accomplishments, learn from and be reinvigorated by them, and look to the future. The Laboratory celebrated 50 years of "Making History, Making a Difference" through panel discussions, special conferences and publications, and events such as the dedication of a time capsule and a Family Day weekend to conclude the festivities. This look to the future in 2002 was underscored by the selection of a new Laboratory director, Michael Anastasio, and groundbreaking ceremonies on April 4, 2002, for two mission-critical facilities.

Shown rising on the banks of Lake Haussmann, the $91-million Terascale Simulation Facility was completed in 2004 ahead of schedule and under budget. It initially housed two of the world's most powerful computers, BlueGene/L and the 100-trillion-operations-per-second ASCI Purple machine.
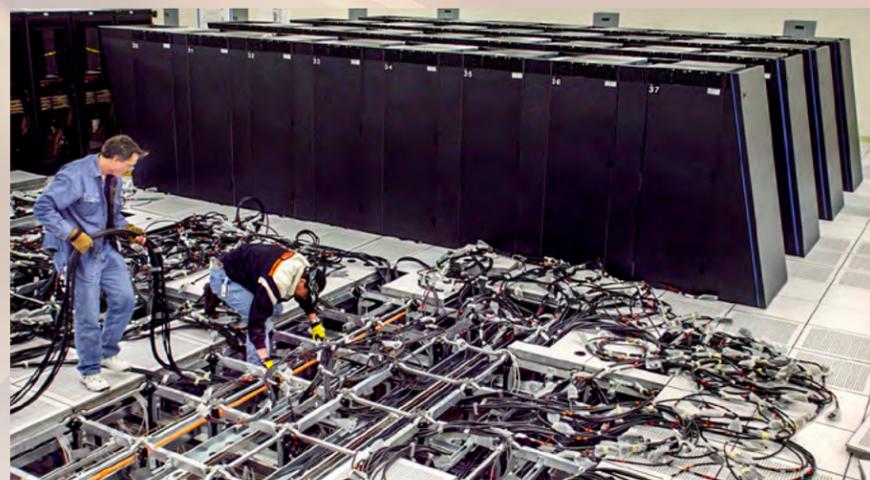
Installation at TSF of BlueGene/L's 64 racks, air-cooled cabinets with 1,024 nodes (2,048 processors) each, was completed in summer 2005. The 65,536-node system clocked 280 teraflops, a record-breaking benchmark speed. The astonishingly successful system was later expanded to 106,496 nodes and achieved 480 teraflops.

Construction began on the Terascale Simulation Facility (TSF), a $91-million world-class supercomputing facility. With 48,000 square feet of floor space for machines, TSF was designed to usher in a leap in supercomputing capability as part of DOE's Accelerated Strategic Computing Initiative (ASCI). In November 2002, DOE announced that IBM would develop for TSF the two fastest machines in the world: the 100-teraflops (trillion floating-point operations per second) ASCI Purple, designed to be a workhorse for stockpile stewardship, and a research machine called BlueGene/L. The latter was an innovative, scalable supercomputer based on energy efficient "system-on-a-chip" technology.

Blue/Gene L proved to be the future of supercomputing. It topped the list of the world's most powerful computers for four years, ultimately achieving 480 teraflops peak speed. The peak performance of its Blue/Gene Q successor, Sequoia, is nearly 20,000 teraflops (20 petaflops). Sequoia is sited in the Livermore Computing Complex, known as TSF before supercomputing outgrew the building's name. The next leap in capability is Sierra (see Year 2017). Plans are in the works for a facility upgrade to accommodate delivery of a 1,000-petaflop-scale (exascale) supercomputer in the next decade.

On the other side of the Laboratory, a groundbreaking ceremony also began construction on the International Security Research Facility (ISRF). ISRF was necessary, in part, to accommodate growth within the Laboratory's Intelligence Program (see Year 1965) following the events of September 11, 2001. The two-story, 64,000-square-foot building houses LLNL's work in support of the Intelligence Community. In the mid-2000s, the Intelligence Program (Z Program) started the Cyber, Space, and Intelligence Initiative, which focused on cyber defense and network intelligence, space security, intelligence analysis, and persistent surveillance.

Z Program continues to provide technical solutions and assistance to defend U.S. government networks and secure critical infrastructure, assess foreign cyber threats, and support information operations efforts. The program also provides innovative analysis to anticipate new and developing terrorist threats involving the use of chemical, biological, radiological, nuclear, and explosive (CBRNE) weapons and investigate opportunities to counter them. Z Program also works to understand the state of foreign weapons of mass destruction (WMD) programs; informs U.S. counterproliferation decisions, policies, and efforts; and develops supporting technology solutions to dissuade or prevent states from acquiring WMD-related technologies, materials, and expertise.

At a 50th anniversary panel discussion, directors Michael Anastasio, Bruce Tarter, John Nuckolls, Michael May, John Foster, and Herbert York reflect on the Laboratory's past, present, and future. Harold Brown participated via teleconference, and Edward Teller gave a video presentation. Roger Batzel passed away in 2000.

At a 50th-anniversary event for the local community, former astronaut and U.S. Senator John Glenn enclosed a memento thanking the Laboratory for its service to the nation and helped seal a time capsule, which is to be recovered at the 100th anniversary.

Simulating Nature at the Scale of Atoms

In 2003, a team of LLNL researchers, the Quantum Simulations Group, launched a Laboratory Directed Research and Development project to make practical "first-principles" molecular dynamics simulations. Such calculations were possible for small problems, but practicality required the development of new algorithms and numerical methods combined with the emergence of highly parallel terascale computing.

First-principles simulations are ideal tools for examining the atomic and electronic structure of materials, from the simple hydrogen atom to complex biomolecules and nanostructures. The simulations are based on the laws of quantum mechanics with no fitted parameters as input. As a result, they are well suited to predict highly complex and unexpected states of matter. They have many applications relevant to LLNL's national security mission: calculations of the properties of high explosives, equation of state of molecular liquids, shock simulations, biochemistry, and nanotechnology.

The Quantum Simulations Group successfully addressed the major challenge of achieving linear scaling. With this improvement, the computational complexity is proportional to the number of atoms rather than the cube of the number. In addition, the simulations were modified to run efficiently on a large number of processors in parallel. The researchers used some of the Laboratory's largest computers at the time to demonstrate the use of large-scale first-principles molecular dynamics simulations on a wide range of problems. This work opened the door to numerical simulations of physical processes occurring on length scales of several nanometers, which was previously inaccessible.

Successful development and application of Qbox, a practical first-principles molecular dynamics code, earned LLNL researchers and collaborators the 2006 Gordon Bell prize, a prestigious award for innovations in high-performance computing. The simulation, run on BlueGene/L, studied the behavior of 1,000 molybdenum atoms (a high-Z metal) under immense pressure. The ability to validate experiments and understand and predict material performance at the nanoscale under extreme conditions is especially important to LLNL's nuclear stockpile stewardship mission and experiments at the National Ignition Facility.

Broader mission areas also benefit. Qbox, now a high-performance open-source software infrastructure, is increasingly used as a predictive tool in the exploration of properties of new materials for batteries, solar energy conversion, light-emission devices, dielectric materials, and phase-change materials for optical storage. For example, in one project LLNL researchers simulated the solid-electrolyte interfaces in lithium–ion batteries. Using Qbox and even more advanced tools, they were able to locate key reactions and provide a detailed, microscopic view of the interface of chemistry and dynamics.

Livermore researchers used quantum simulations to discover a new class of cheap and efficient catalysts to facilitate the process of splitting water to make zero-emission hydrogen fuel. They found that the surfaces of the new materials actively produce hydrogen, whereas only the edges are active for other similar (layered metal dichalcogenide) catalysts. Their results were experimentally validated by collaborators.
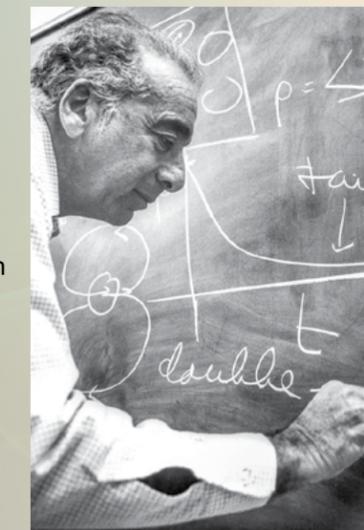

Record-setting molecular dynamics simulations on BlueGene/L won Gordon Bell Prizes in 2005 and 2006. First, physicist Fred Streitz (shown) led a team performing a 524-million atom simulation of the solidification of tantalum at extreme conditions. Computer scientist François Gygi then led a team using Qbox to study the properties of molybdenum under high pressure.
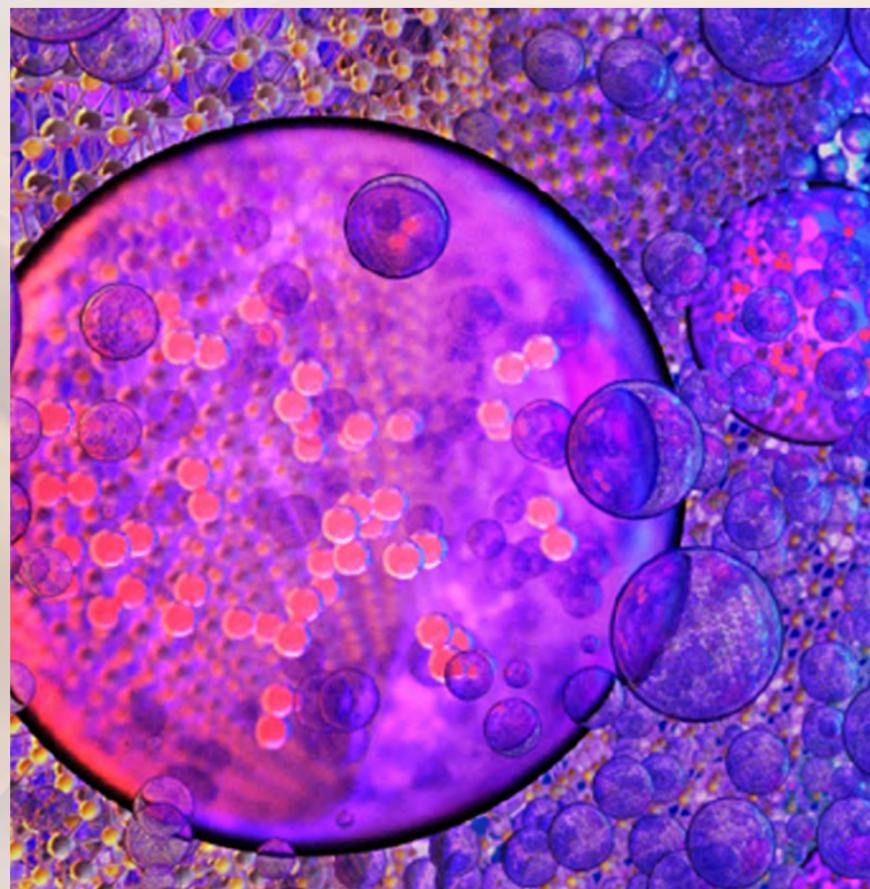
Berni Alder, Father of Molecular Dynamics Simulations

In August 2015, the Laboratory honored Berni Alder at a special symposium to celebrate his 90th birthday and his illustrious 60-year research career at Livermore. Alder saw the opportunity to use supercomputers to simulate the properties of materials and joined the Laboratory in 1955. He invented computational molecular dynamics and helped develop Monte Carlo methods. Alder and his colleagues at Livermore have made pioneering advances in the field ever since. In 2009, Alder received the National Medal of Science, the highest honor bestowed by the U.S. government upon scientists, engineers, and inventors.

Now LLNL scientists explore "extreme chemistry" with quantum molecular dynamics simulations of thousands of atoms. Classical molecular dynamics models are much larger. The Laboratory's Gordon Bell Prize winner in 2005 was a 524-million-atom simulation of resoldification of tantalum.

Predictive simulation tools play an increasingly important role in LLNL's basic materials research. Progress in quantum simulations of condensed and molecular systems, combined with advances in high-performance computing, has created the possibility of using truly predictive simulation tools to address the complexity of materials—both natural and designed for special applications—at the nanoscale.

For Enhanced National Security—and Space Exploration

Years before the events on 9/11, Laboratory researchers began to focus their research efforts to counter the threat of weapons-of-mass-destruction use (see Year 2001). The attacks that day redoubled attention to nuclear threats that might not arrive in the form of missiles launched from abroad. A new generation of portable radiation detection devices were needed by military, law enforcement, and first responders to easily and quickly identify radioactive materials and distinguish among them.

LLNL researchers brought to bear their expertise in nuclear physics, micro- and nanotechnologies, and materials science to develop innovative systems to more reliably detect and distinguish special nuclear materials (uranium and plutonium) from other sources of radiation. They quickly developed a portable gamma-ray spectrometer, now commercialized as ORTEC's Detective.

Detective was licensed to ORTEC, a unit of AMETEK, Inc., in June 2003— only 21 months after 9/11. Gamma

An R&D 100 Award winner in 2009, the GeMini gamma-ray spectrometer uses a germanium crystal kept at low temperature by an innovative ultraminiature cooling system. The spectrometer flew to the planet Mercury and has been commercialized as an affordable, portable instrument for accurately detecting and identifying nuclear materials.

Inspectors at the Comprehensive Nuclear-Test-Ban Treaty Integrated Field Exercise in Jordan in 2014 identified sources of interest using the Detective instrument.

LLNL researchers have developed improved scintillator materials (left) to better detect and distinguish special nuclear materials from other sources of radiation and a novel technology for detecting thermal neutrons from plutonium shielded to evade detection (right).
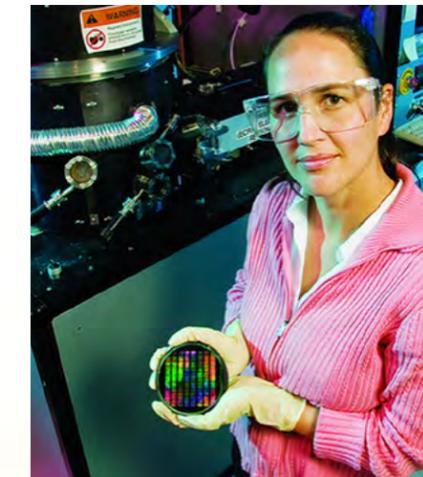
rays come from many sources, so it is important to count only those at the precise energies that are emitted by special nuclear materials. High-purity germanium crystals cooled to –280°F are ideal for this application. LLNL researchers invented ways to make this possible in a small package. Detective features a miniaturized electromechanical refrigeration system, uses sophisticated artificial-intelligence-based radionuclide identification algorithms, and weighs only 15 pounds. The battery-powered device can be operated by workers or first-responders with minimal training. This miniaturized detector technology was also sent into space (see the box).

More than 1,200 Detective instruments have been acquired for use at border crossings, cargo ship docks, transportation terminals, and other locations to differentiate between potentially dangerous radioactive materials and otherwise harmless radiation sources.

During the Fukushima Dai-ichi Nuclear Power Plant crisis in 2011, Detective radiation detectors were used to ensure that American citizens at the embassy and on military bases were safe, help Japanese governmental authorities determine

who should be evacuated or sheltered in place, and identify agricultural areas of radiological concern.

Finding highly-enriched uranium is especially difficult. A more effective, yet still very challenging, approach is to detect and discriminate neutrons from background gamma rays. Improved detection requires effective, affordable materials to use as scintillators, which convert the radiation to measurable flashes of light. Currently used crystal

scintillators are difficult to grow in large sizes and are expensive. Materials science experts at the Laboratory made a breakthrough widely thought to be impossible: They developed inexpensive plastic materials that are almost as effective as crystal scintillators. Further research has led to much faster and cheaper ways to grow large crystal scintillators as well as a novel approach to detecting low-energy neutrons using scintillators with nanoengineered features.

A Mission to Mercury

A key instrument aboard NNSA's MESSENGER mission to Mercury was the Laboratory's gamma-ray spectrometer. Launched on August 3, 2004, the spacecraft journeyed more than 4.88 billion miles over six-and-a-half years to reach the planet. The germanium crystal had to be cooled to –330°F in the presence of the extreme heat from the Sun and re-radiating from Mercury's surface. The instrument, which orbited the planet for four years, collected data to help determine the elemental mineral composition of Mercury's surface. The information gathered is forcing researchers to rethink theories about how the planet was formed. A later, newer version of the MESSENGER instrument, called GeMini, also was licensed by ORTEC—and a still later version, GeMini Plus, is being developed to fly on a NASA mission to the asteroid Psyche.

Discovering and Studying Distant Worlds

LLNL engineer Lisa Poyneer and Stanford University astrophysicist Bruce Macintosh (previously at Livermore) stand in front of the Gemini Planet Imager, which is mounted on the Gemini South telescope in Chile (bottom left). To correct for atmospheric turbulence, the imager uses a small deformable mirror (top left) made of etched silicon with 4,096 actuators.
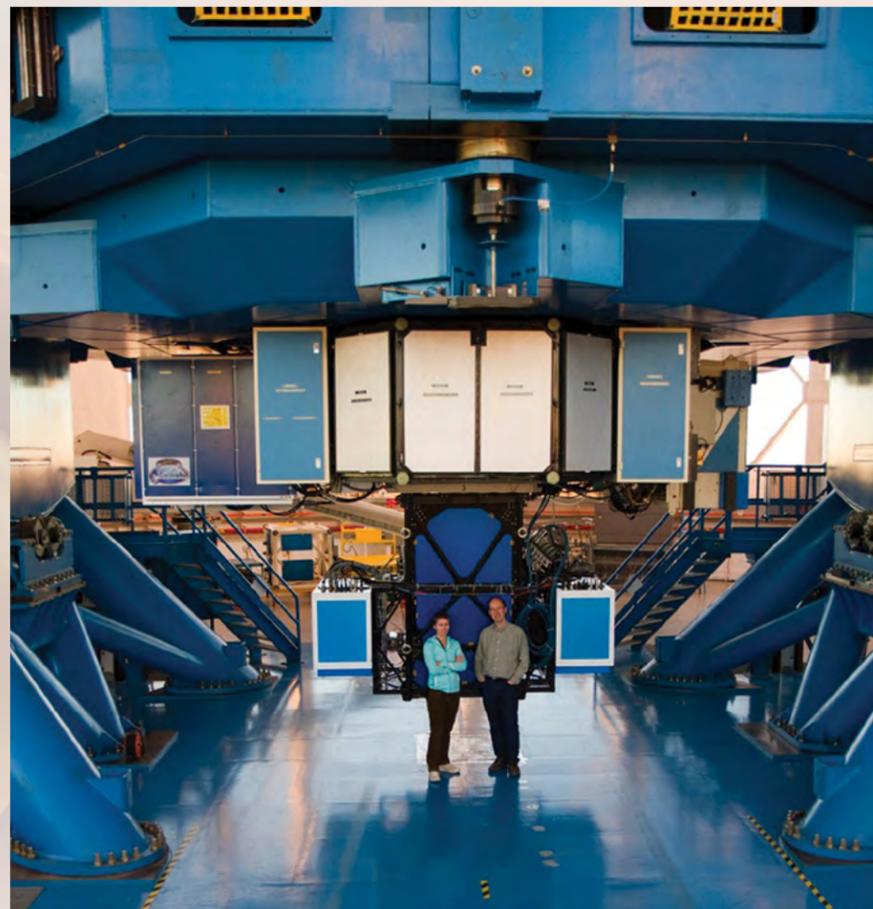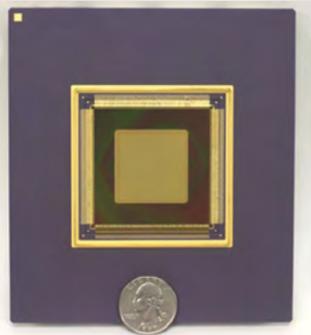
In 2005, a team of Laboratory scientists and collaborators launched an effort to greatly advance the state of the art in adaptive optics (see Year 1996) to directly image extrasolar planets. It was the birth of the Gemini Planet Imager (GPI) project. Meanwhile, an international team including another Laboratory scientist discovered the first Earth-like extrasolar planet, using a network of telescopes across the globe and a technique pioneered by LLNL, called microlensing. Microlensing astronomy began with an international effort, launched by the Laboratory and applying technologies developed for Clementine (see Year 1994) to look for Massive Compact Halo Objects (MACHOs).
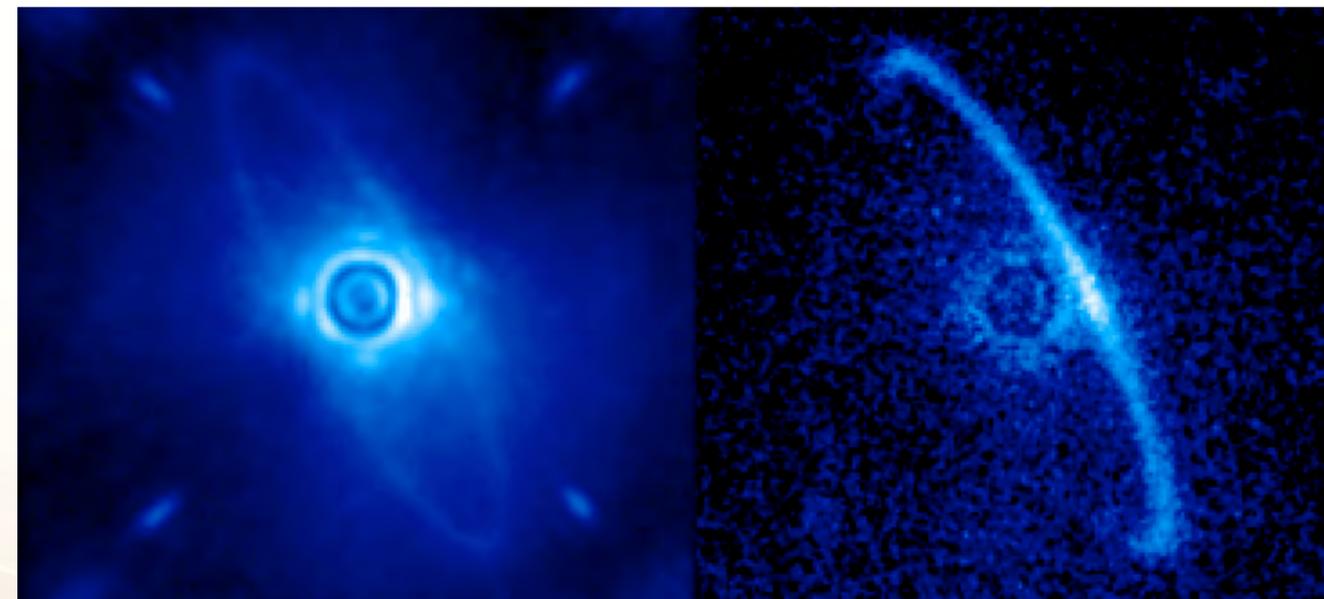
Images of the young star HR4796A revealed a narrow ring around the star (left), which could be dust from asteroids or comets left behind by planet formation. An image of only polarized light (right) more clearly shows starlight scattered by the nearer side of the ring.

Designated OGLE-2005-BLG-290 Lb, the newly found planet is composed of rock and ice, has five times the mass of Earth, and orbits a red dwarf star at about three times the distance between Earth and the Sun. It was discovered through microlensing, which occurs whenever a distant solar system so closely aligns with the nearby star that the two appear as one image in a telescope. The gravity of the nearer star acts as a lens, bending the path of the photons from the solar system; the closer the alignment of the two, the greater the apparent brightness. A small, 12-hour-long fluctuation in brightness provided evidence of the presence of the orbiting planet.

To image and characterize distant planets, Livermore scientists and engineers began in 2005 to develop a next-generation, dedicated planet-hunting, high-contrast "extreme" adaptive-optic (ExAO) system for the Gemini Observatory in Chile. LLNL's

Bruce Macintosh (now at Stanford University) served as principal investigator of the GPI project, an international partnership. First-light experiments occurred in November 2013.

Sensitive enough to see giant (but not Earth-sized) planets, GPI sits on the 8.1-meter-diameter Gemini South telescope, at an altitude of 2,715 meters. The size of a small car, GPI is mounted behind the telescope's primary mirror. LLNL engineers devised a remarkably agile ExAO system that measures 1,000 times per second the light passing through 2,000 control points at the aperture of the telescope. Every thousandth of a second, the system adjusts the shapes of two deformable mirrors to correct for atmospheric distortions. The 2.56 centimeter-square mirror designed for fine focusing employs 4,096 tiny microelectromechanical actuators. GPI produces the fastest and clearest images of extrasolar planets ever recorded.

During its first observations, GPI captured images of a planet four times the size of Jupiter orbiting the star Beta Pictoris, 63 light-years from Earth. Two disks of dense gas and debris were also observed. The Beta Pictoris system and a later discovered Jupiter-like planet orbiting a young star, 51 Eridani, provide clues about the early formation of solar systems. These discoveries are part of an ongoing three-year effort to find and study young Jupiters circling about 600 nearby stars.

Determining that Nuclear Weapon Pits Age Gracefully

Heading into 2006, there was uncertainty about how long aging plutonium pits in the U.S. nuclear deterrent would work. DOE was considering development of a new, multibillion-dollar facility to remanufacture pits, one of the most important components comprising a nuclear weapon.

Many physicists, metallurgists, and chemists have worried that the natural radiation produced by plutonium over many years might sufficiently damage the pit, compromising weapon performance. Although the plutonium isotope used in pits has a half-life of 24,000 years, its decay rate is high enough to produce a significant amount of damage after only a few decades. Weapon scientists needed greater assurance that a pit would retain its size, shape, and strength in the presence of an ever-increasing amount of radiation damage. Many pits are in deployed weapon systems that are far older than their originally planned lifetimes.

In 1997, DOE launched a $100-million effort at Livermore and Los Alamos national laboratories directed at studying this enigmatic material. Livermore scientists used some of the most accurate instruments in the world to measure the microstructural, physical, and chemical properties of plutonium and its alloys. In dynamic experiments such as gas-gun tests and static studies using diamond anvil cells, they examined how radioactive decay affects plutonium's structure, phase stability, and equation of state (EOS). They also measured the element's density and volume with unprecedented accuracy and reviewed data from past nuclear tests.

One of the challenges associated with forecasting aging effects was that the oldest weapons-grade plutonium made in the U.S. and available for detailed analysis was about 45 years old, taken from pits retired from the stockpile. To simulate the properties of pits many decades into the future, researchers accelerated the age of samples by adding isotopes with shorter half-lives. The researchers "spiked" an alloy of weapons-grade plutonium-239 with plutonium-238, which has a half-life of 87 years, so that it accumulates radiation damage 16 times faster than weapons-grade plutonium alone. Artificially aged samples can then be tested against new and naturally aged samples.

Years of research culminated in 2006 with the announcement that plutonium aging would not affect warhead reliability for decades. The laboratories' results indicated that pit lifetimes were much longer than scientists had previously estimated. An independent panel of scientists, who advise the government on science and technology, reviewed their work and concurred that the credible lifetime for most pit types is at least 100 years.

Plutonium continues to age gracefully. Ongoing research since 2006 shows that no unexpected aging issues are appearing in plutonium that has been accelerated to an equivalent of around 150 years of age, lending increased confidence in the reliability and effectiveness of the current stockpile. Production of new weapons pits will be needed for the W87-1 Modification Program, with first production unit scheduled for 2030.
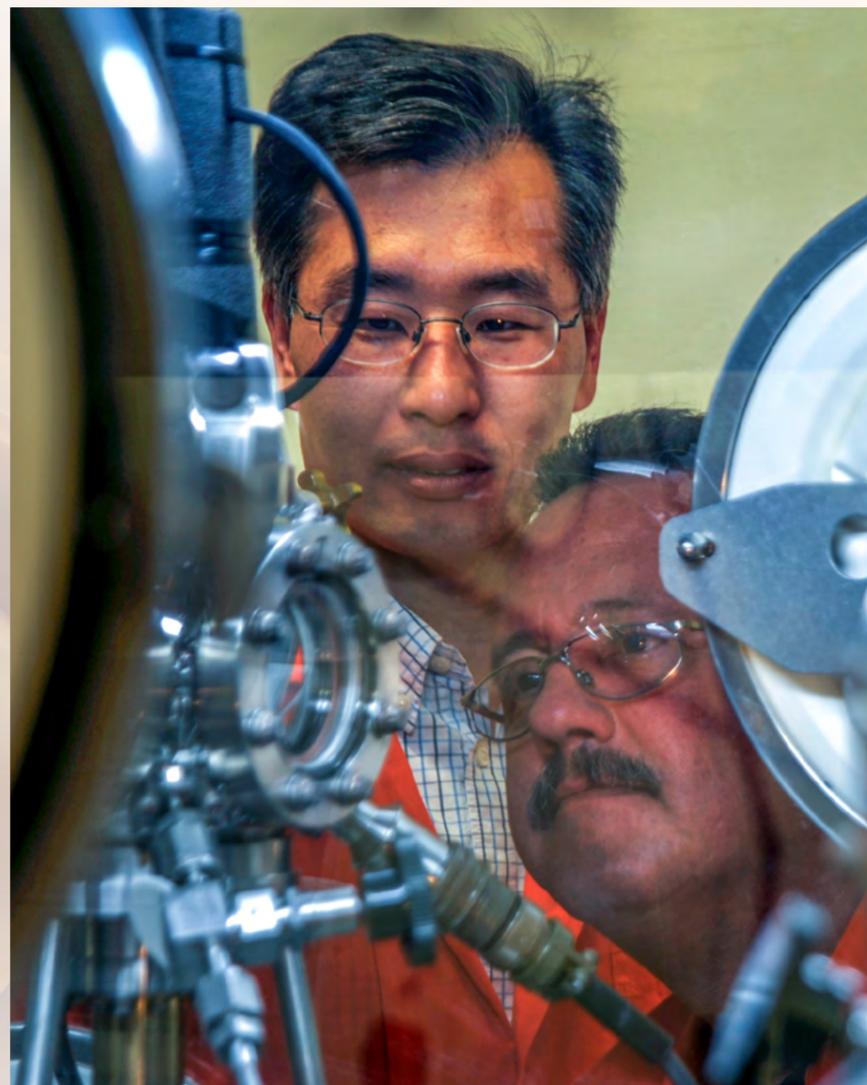

Researchers used the gas gun at the Joint Actinide Shock Physics Experimental Research facility to simultaneously shock samples of aged and new plutonium.

Livermore chemist Brandon Chung (left) and mechanical technologist Kenneth Lema peer through a glovebox to check the setup on the dilatometer that measures the dimensions of plutonium samples.

JASPER Supports Plutonium Aging Studies

On September 25, 2012, JASPER (the Joint Actinide Shock Physics Experimental Research facility) fired its 100th shot. Located at the Nevada National Security Site, the 20-meter-long, two-stage light gas gun is a key scientific tool for the Stockpile Stewardship Program. Experiments at JASPER have enabled LLNL scientists to understand important properties and behaviors of plutonium. The shots make essential contributions to aging studies. The gun can shoot a projectile at up to about 17,000 miles per hour into a chamber containing at a small plutonium target, subjecting it to millions of times atmospheric pressure and temperatures of thousands of degrees. LLNL operates JASPER in conjunction with the Joint Laboratory Office–Nevada.

A Nobel Peace Prize and the Challenge of Climate Change

As principal investigator for the Earth System Grid Federation (ESGF), computer scientist Dean Williams led the development of a large, interactive data and visualization system for researchers from around the world to securely store and share models, analyses, and results along with observational data. ESGF supported the fourth assessment report of the Intergovernmental Panel on Climate Change.

In 2007, the Nobel Peace Prize was shared by the Intergovernmental Panel on Climate Change (IPCC) and former Vice President Al Gore for their efforts to build up and disseminate knowledge about the role human activities play in climate change and to lay the foundations for the measures that are needed to counteract such change. At the Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI), more than 40 LLNL employees were delighted with and honored by the choice (see Year 1992).

That year IPCC issued its Fourth Assessment Report. In the opening acknowledgements of the report, PCMDI is thanked for "the archiving and distribution of an unprecedented amount of climate model output." IPCC presented PCMDI a plaque with the inscription, "in recognition of extraordinary contributions to the Fourth Assessment Report." PCMDI has made major contributions to all five IPCC reports, from the First Assessment Report in 1990 to the Fifth Assessment Report in 2013. Laboratory scientists authored sections of reports and provided comparisons
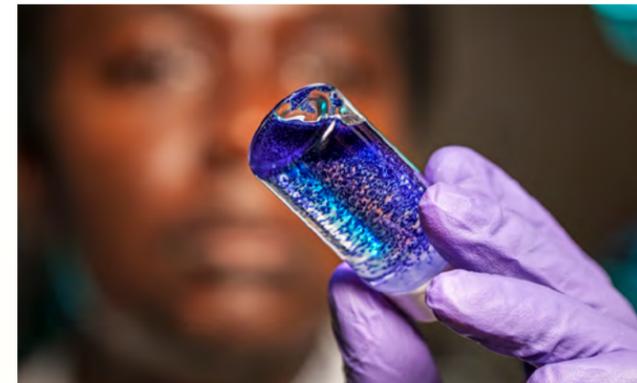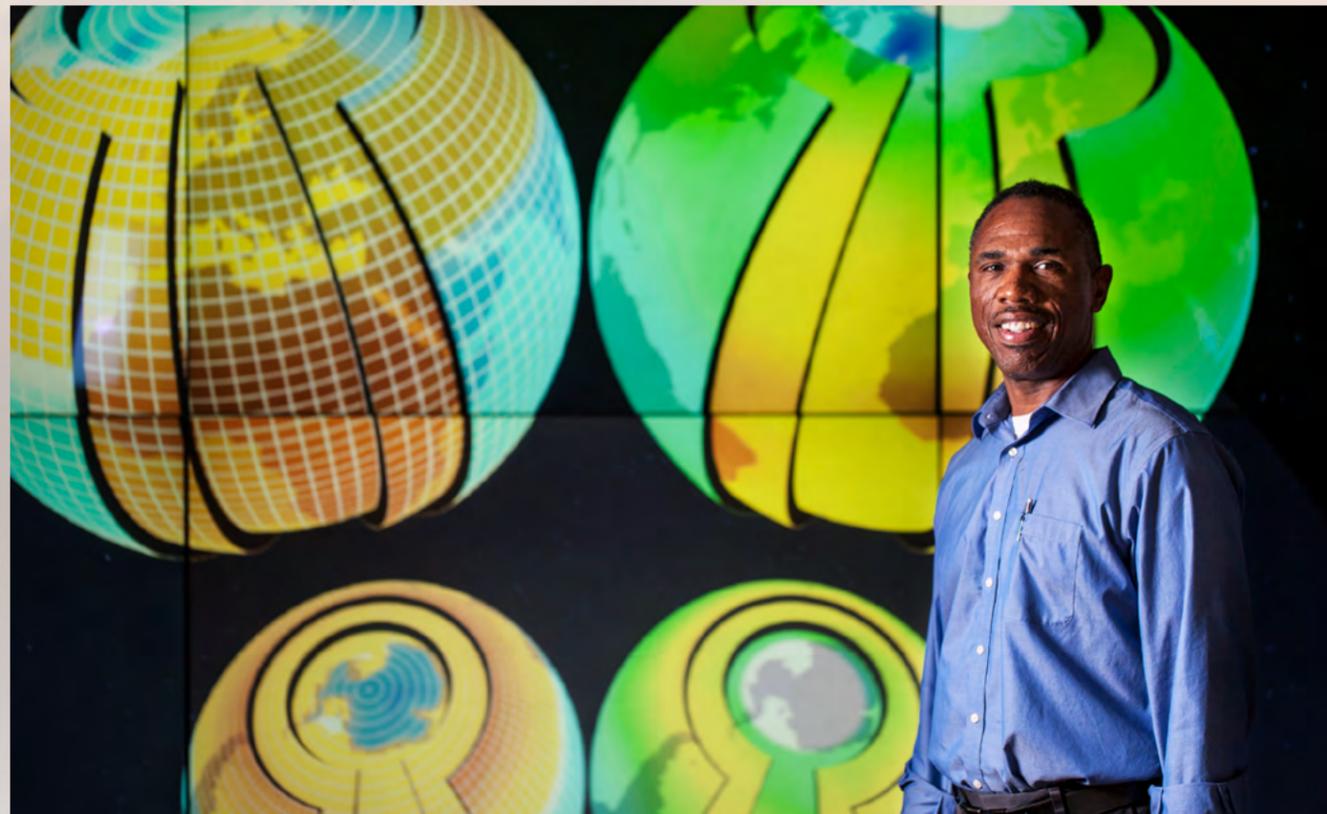
Laboratory researcher Will Smith looks at microcapsules that can be used to capture carbon dioxide from coal or natural gas-fired power plants, as well as in industrial processes like steel and cement production.

LLNL chemist Sarah Baker holds a gas chromatography vial used to measure the amount of methanol produced by a 3D-printed enzyme-embedded polymer. The research could lead to more efficient conversion of methane to energy production and should be useful in a wide range of applications.

and assessments of worldwide climate models that feed into IPCC conclusions and recommendations.

Moreover, PCMDI researchers provide valuable database support to the global climate analysis community; work on key issues such as ocean warming, cloud modeling, and natural climate fluctuations; and conduct studies of human influence on climate. Comparing past data records with the results from climate models and satellite records, they work with colleagues worldwide to better understand contributing factors to climate change and improve predictions of expected variations.

Facing the prospect of significant climate change, Laboratory researchers are devising innovative "negative emissions" technologies—eliminating the emission of greenhouse gases in the atmosphere. Livermore scientists, along with collaborators, developed a new type of carbon-capture media composed of core-shell microcapsules, which consist of a highly permeable polymer shell and a fluid made up of sodium carbonate solution (simple baking soda found in grocery stores). The fluid reacts with and absorbs carbon dioxide (CO_2), confining it within the shell. Once saturated, the microcapsules

are emptied of the CO_2 in an environmentally benign manner and ready for reuse. Another team of LLNL researchers combined biology and 3D printing to create the first chemical reactor that can continuously produce methanol from methane (a potent greenhouse gas) at room temperature and pressure.

More broadly, LLNL is applying expertise in high-performance computing (HPC), additive manufacturing (see Year 2014), and materials science to enhance the nation's energy and resource security. For example, Laboratory scientists are working to make liquid hydrogen practical as a zero-emission fuel for transportation, and they are part of a

Laboratory–industry collaboration that designed a tractor-trailer truck with 104 percent improved fuel efficiency. LLNL is also leading the multilaboratory DOE HPC for Manufacturing Program, which provides HPC expertise to help U.S. industry advance innovative clean energy technologies, reduce energy and resource consumption, and strengthen competitiveness.

As part of a Navistar SuperTruck I team, Livermore helped design a new type of tractor-trailer truck that significantly improves fuel economy. Full-scale wind tunnel tests of the design have been conducted at the NASA Ames Research Center.

Detecting Clandestine Nuclear Explosions

In 2008, Lawrence Livermore, Los Alamos, and Sandia national laboratories were working with the U.S. Air Force Technical Applications Center (AFTAC) to produce the first 3D model of the Earth specifically for monitoring nuclear tests. Led by LLNL's Stephen Myers, the collaborators developed the Regional Seismic Travel Time (RSTT) technology, which dramatically improved international capabilities to detect and locate low-yield nuclear explosions. The four-year-long effort, which began in 2006, earned Myers an Ernest O. Lawrence Award for his leadership of the project.

Before the development of RSTT, detection of small-yield events was problematic. The weak signal challenged the ability to use long-range seismic data. Events were difficult to locate using regional seismic

An improved version of RSTT called LLNL-Global 3D (G3D) is used to simulate the waves generated by a hypothetical seismic event. The seismic waves (the yellow lines) are shown propagating through the Earth's interior. Added to the simulation image are representations of the surface waves.

LLNL engineer Justin Jones inspects the interface at the top of the high-explosives canister in preparation for the Source Physics Experiment-6 test, which was conducted at the Nevada National Security Site in October 2016.

data because the propagation of regional signals depends on local geological details. Because of these geological variations, event location could not be pinpointed by using signal travel times to various regional seismic stations. RSTT includes a worldwide digital 3D model of the seismic properties of Earth's crust and upper mantle, which makes it possible to accurately calculate travel times and incorporate regional seismic data. Small-yield events are detected quickly and with an accuracy once achieved only with large, globally recorded events. To date, the United States has sponsored six workshops to share the RSTT technology with 67 nations.

AFTAC and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty use RSTT to monitor nuclear events around the world, including those in North Korea. The existence of a cluster of events in North Korea enables RSTT to determine event location even more precisely. Seismologists have been able to pinpoint the locations of five North Korean underground nuclear tests—in 2006, 2009, 2013, and two in 2016—within about 100 meters accuracy when the location of one event is known. In addition, LLNL researchers have built upon the RSTT model and extended it to the center of the Earth, an additional depth of more than 6,000 kilometers. The Laboratory is pursuing even-more-accurate 3D models to better detect small clandestine nuclear explosions.

The NNSA laboratories and collaborators continue efforts to improve detection capabilities. Source Physics Experiments (SPEs) are being conducted at the Nevada National Security Site. These highly instrumented underground, high-explosives tests provide data to improve capabilities to detect and identify low-yield nuclear explosions amid the clutter of conventional explosions and small earthquakes. Phase I of the SPE series, which consisted of six experiments, concluded in October 2016.

Lawrence Livermore is also partnering with Los Alamos, Pacific Northwest, and Sandia national laboratories in the Low Yield Nuclear Monitoring Program, a five-year collaborative initiative to address key obstacles that hamper detection of low-yield nuclear tests. The research focuses on signature discovery, understanding, and signature exploitation.
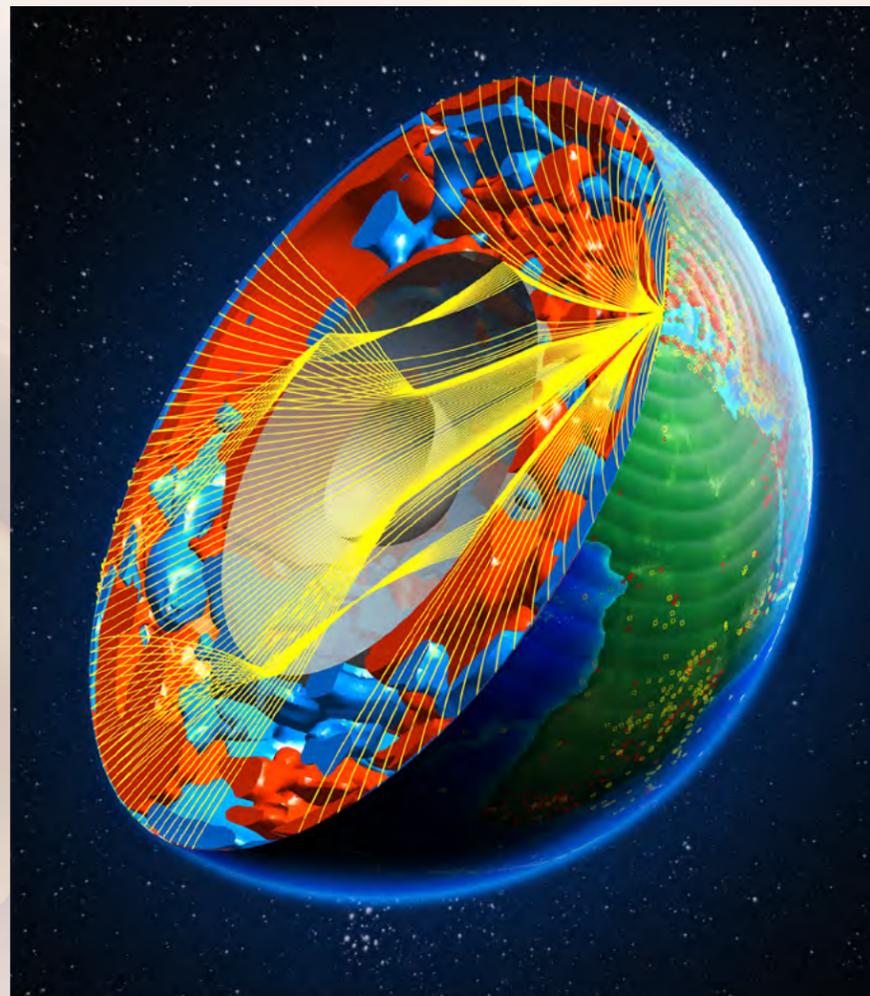
South Napa Earthquake Simulation

Laboratory seismologists used supercomputers to simulate the ground motion of the magnitude 6.0 south Napa earthquake on August 24, 2014. The University of California at Berkeley's Seismology Laboratory provided descriptions of the earthquake source, and high-resolution LLNL simulations determined how the rupture process affected the region's 3D geological structure. The simulations also examined the impact of surface details on local ground motion. Comparison with observed data serves to improve models, making them better tools to study future earthquake scenarios.
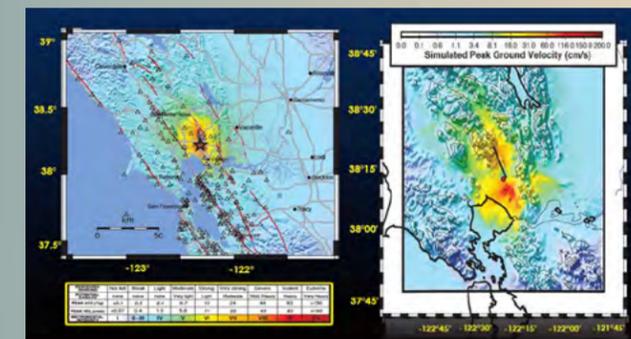
A Mainstay for Stockpile Stewardship and HED Science

The National Ignition Facility (NIF) was formally dedicated on May 29, 2009, exactly 12 years to the day after its groundbreaking. Prominent dignitaries and more than 3,500 guests attended the ceremony, portions of which were aired live on network television. Construction of NIF, the world's largest laser, was honored by the Project Management Institute as a facility "pushing beyond the state of the art," earning the prestigious

Project of the Year for 2010. The award recognizes the year's most innovative and successful project. The effort was completed on budget and on time according to the construction schedule that was rebaselined in 2000 (see Year 1997).

Because NIF is the only facility that can create the conditions that are relevant to understanding the operation of modern nuclear weapons, the 192-beam, 1.8-million joule


NIF experiments require specially-designed, precision-fabricated targets, such as the one shown, which is used to study how to manage instability growth and achieve the fuel density conditions needed to achieve fusion ignition.

laser is a crucial element of NNSA's Stockpile Stewardship Program. NIF creates high-energy-density (HED) conditions—temperatures of 100 million degrees and pressures 100 billion times that of the Earth's atmosphere—similar to those in stars and detonating nuclear weapons.

Campaigns of HED science experiments at NIF explore wide-ranging phenomena central to stockpile stewardship. The experiments provide valuable data about the properties of materials at extreme conditions, the interaction of matter with intense radiation, and hydrodynamic turbulence and mixing. These issues are critical to understanding nuclear weapons performance and improving the predictability and results of fusion-ignition experiments (see Year 2013). Achieving ignition is a vital goal in support of stockpile stewardship and provides an option for long-term energy security.

As the world's premier HED science experimental facility, NIF is also operated as a user facility for the scientific community with an unprecedented capability for studying materials at extreme conditions. While the defining mission of NIF is stockpile stewardship, experiments also support broader national security needs. In addition, a Discovery Science program provides opportunities for researchers to explore conditions that exist in the core of planets and re-create at miniscule scale puzzling energetic phenomena observed by astronomers. The NIF User Group includes researchers from DOE national laboratories, international fusion energy researchers, scientists from academia, and other national and international users.
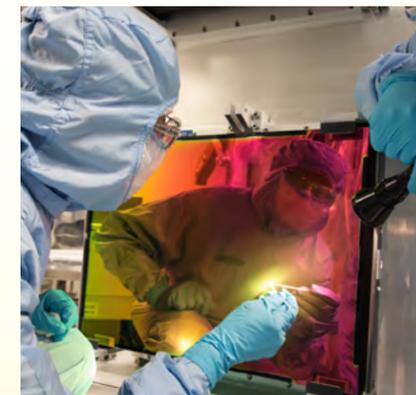
Upgrades to NIF are dramatically improving diagnostic capabilities. Technicians inspect a mirror (left) in the Advanced Radiographic Capability (ARC), which will be used to produce an x-ray "movie" to diagnose NIF target implosions with tens-of-picoseconds resolution. In addition, a new Target and Diagnostic Manipulator (TANDM, shown below) is being used with a newly installed Advanced Tracking Laser Alignment System to further enhance the efficiency of NIF operations.

The demand for experimental time to use NIF's unique capabilities has always exceeded supply. The NIF team took steps to dramatically increase shot opportunities in response to this demand and budget constraints. These efforts benefited from the results of a NIF efficiency improvement study requested by Congress and conducted by the NIF team in partnership with the other NNSA laboratories. The shot rate increased from 191 in FY 2014 to 415 in FY 2016. In addition to

many process improvements, new equipment and technologies are reducing the time between shots. With the combination of enhanced diagnostics, improved capabilities to manufacture complex targets, and the development of new types of experimental platforms, faster progress is possible in HED science for stockpile stewardship. The range of innovative HED experiments that can be performed at NIF is ever expanding.

Laboratory Director George H. Miller introduces dignitaries at the NIF dedication ceremony held in May 2009 (top). The facility required more than 55,000 cubic meters of concrete, 7,600 tons of reinforcing steel rebar, and 5,000 tons of structural steel. The giant laser has nearly 40,000 optics that precisely guide, reflect, amplify, and focus 192 laser beams onto a target about the size of a pencil eraser.

The Teens

New Leadership

Penrose C. Albright
(2011 • 2013)

Bret E. Knapp
(2013 • 2014)
Acting Director

William H. Goldstein
(2014 • 2021)

The 21st century presents an expanding array of challenges and an ever-changing security environment. Nuclear deterrence remains the ultimate security guarantee for the United States; yet, we face tensions with increasingly bold actors in a complex strategic environment with growing threats in multiple security domains. We must be prepared for surprises.

As a "new ideas" laboratory, our mission is to strengthen the nation's security through cutting-edge science, technology, and engineering. Livermore's first priority is to sustain the nation's nuclear arsenal. Responsible for the next two warhead life-extension programs, LLNL is pursuing innovations in materials

A laboratory for the 21st century

and manufacturing to transform the NNSA weapons complex by expediting production, lowering costs, and delivering systems that are safer and more secure.

Research at the frontiers of science and technology underlies our ability to deliver cutting-edge solutions to the nation's most pressing challenges. Leadership in high-performance computing, for example, is enabling predictive simulations and extraction of information from "big data" for applications ranging from bioinformatics to persistent surveillance. Expertise in materials science and engineering, combined with unique experimental capabilities, makes possible development of advanced neurological sensors, discovery of new elements and new planets, and progress toward a clean energy future.

Development of a New Precision Munition—in 18 Months

The U.S. Air Force had an urgent need for a game-changing conventional munition. U.S. troops were on the ground in increasingly crowded battlefields, and air support was limited by the risk of collateral damage. A team of LLNL researchers answered the call. Within nine months, they completed prototype development, a process that typically takes four to six years, and provided the m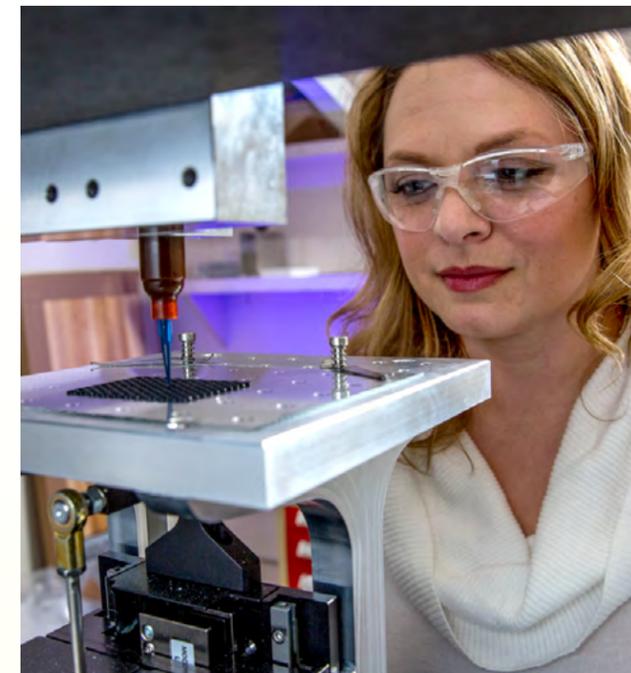anufacturer with most of the tooling needed to assemble the newly designed munition. The first BLU-129/B was delivered to the theater of operations in 2011, 18 months after the effort began. The Air Force had a munition fully capable of being safely deployed near friendly soldiers and noncombatants.

The breakthrough design of a low-collateral-damage munition and its expeditious development was the product of a long-running munitions program with the Department of Defense (DOD) coupled with Livermore's signature capability of pairing high-performance computing (HPC) simulations with focused experiments to accelerate technology development. Ongoing work as part of the Joint DOD/Department of Energy Munitions Technology Development Program provided excellent options— disruptive new technologies—for high explosives and case materials to minimize collateral damage. Scientists and engineers were able to rapidly converge on a production-ready design that optimized performance through iterations of experiments and detailed HPC simulations of material behavior under extreme conditions.

The BLU-129/B uses a new type of explosive charge called multiphase blast explosive (MBX). Experiments conducted by the Air Force Weapons Laboratory had revealed that a target subjected to an MBX detonation experienced a greater impulse of energy than did targets subjected to other explosive compositions. The high-explosive confines damage to a small zone near the target location. The use of MBX also made it possible to replace metal, which is a source of shrapnel, with carbon fiber as the case material. Combined use of MBX and a carbon fiber composite case greatly reduces collateral damage.

Development activities greatly benefited from Livermore's growing expertise in modeling and fabricating composite materials such as carbon fiber. Composites are made from two or more chemically and physically different materials that when combined can be "tailored" to deliver specific effects. The pattern in which the fibers are wound further control the composite's precise characteristics. LLNL's HPC modeling capabilities helped researchers optimize case materials to meet stringent operational and performance requirements. The BLU-129/B's carbon-fiber composite case has the strength to withstand penetration into concrete structures and produces no lethal fragments on detonation. The total system weight is also greatly reduced.

This weapon exemplifies a new class of innovative munitions, integrating disruptive technologies that significantly reduce unnecessary loss of life. The ability to couple sophisticated guidance systems with weapons that have a more accurate lethal footprint has been profound. The BLU-129/B has been in service since 2011, and in 2017, it entered into a third production run.

An experiment team including (from left) Dennis Freeman, Lee Griffith (behind the device), and David Hiromoto positions a munition case prior to structural testing.

This testing was part of LLNL's rapid development of the BLU-129/B munition for the U.S. Air Force, completed in the short span of 18 months. The munition is designed to be more effective against the intended target and reduce collateral damage—both critical concerns for warfighting in urban environments.

The BLU-129/B's carbon-fiber composite case produces no lethal fragments when the munition is detonated. The case also weighs much less than a conventional steel case.
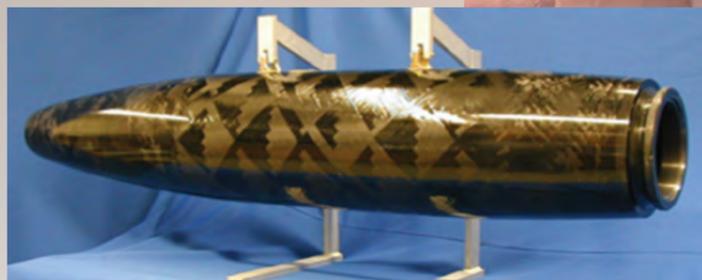

Materials scientist Jennifer Rodriguez examines a high-performance carbon composite part, created using the 3D direct-ink writing process newly developed at LLNL. Carbon fiber structural material has important applications in aerospace, transportation, and defense.

Supporting the Warfighter

In addition to developing advanced conventional munitions, LLNL is providing the DOD Combatant Commands with timely, actionable intelligence to the warfighter to combat the spread of weapons of mass destruction. In the early 1990s after the Gulf War, LLNL developed the concept of combining intelligence with engineering assessments of industrial sites and processes to help in planning military operations potentially involving weapons of mass destruction facilities and other industrial hazards. In 1994, when the U.S. military began extensive counterproliferation planning, LLNL was well-prepared to work closely with military planners to establish the Counterproliferation Analysis and Planning Systems (CAPS) program. LLNL operates CAPS and is often called upon on short notice by the Intelligence Community, DOD, and the Combatant Commands to respond to urgent science and technology queries and taskings in times of crises.

Bioinformatics for Biosecurity and Human Health

In 2011, researchers reported results from an early application of the newly developed Lawrence Livermore Microbial Detection Array (LLMDA), a tool for rapid detection of bacteria, viruses, and other organisms. Working with the San Francisco-based Blood Systems Research Institute, Laboratory scientists used LLMDA to test whether samples of seven live, attenuated viral vaccines used for infants were contaminated with other viruses. The

rapid, low-cost tests successfully confirmed the results found by the institute's laborious DNA sequencing of all the genetic materials in the vaccines.

Since then, LLNL has worked with more than three dozen collaborators from seven nations employing LLMDA in widespread applications: better understanding diseases, advancing health care, detecting animal diseases, improving treatment of U.S. soldiers'

wounds, and studying human archeological remains. Soon it will be in the International Space Station monitoring the presence of microbes that might pose health threats.
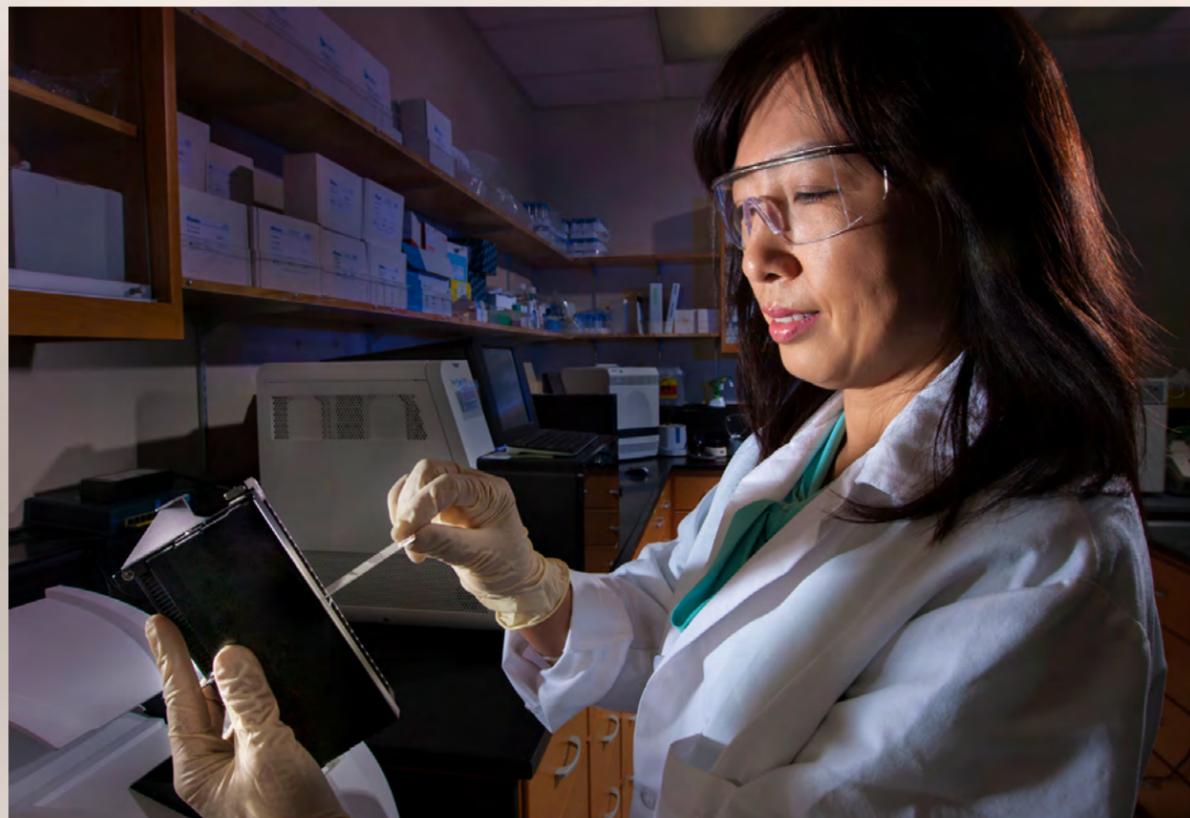
The heart of LLMDA is a microarray (about one inch square) filled with distinct microspots, called probes, where strands of DNA are attached to a surface. The latest version of LLMDA, the Axiom Microbiome array, can handle up to 96 samples in separate microarrays. Each microarray has 1.4 million probes and can detect 12,513 different microorganisms, including 6,901 bacteria, 4,770 viruses, 381 fungi, 370 archaea, and 91 protozoa. And the detection work can be performed within a 24-hour period. LLMDA has been commercialized and is now available in high-throughput format, processing 96 samples at a time.

LLNL's expertise in bioinformatics and high-performance computing, combined with a biotechnology advance, led to the invention of LLMDA. After the anthrax letter scare in 2001 (see Year 2001), the Laboratory's bioinformatics group, focused on biosecurity, began to build computer software that would search for unique "signatures"—spanning 100 to 200 DNA bases—in bacterial and viral pathogens. The application, called KPATH, efficiently tackled the "big data" problem of finding unique signatures among all other already-sequenced human and microbial genes. When a sudden outbreak of severe acute respiratory syndrome (SARS) occurred in 2003, the Centers for Disease Control and Prevention sought help from LLNL, and KPATH produced several candidate signatures in three hours. The team has developed DNA-based signatures for virtually every biothreat pathogen for which adequate genomic

LLNL biologist Crystal Jaing is preparing to insert the LLMDA array into the microarray scanner. Results are then displayed at nearby computer monitor.
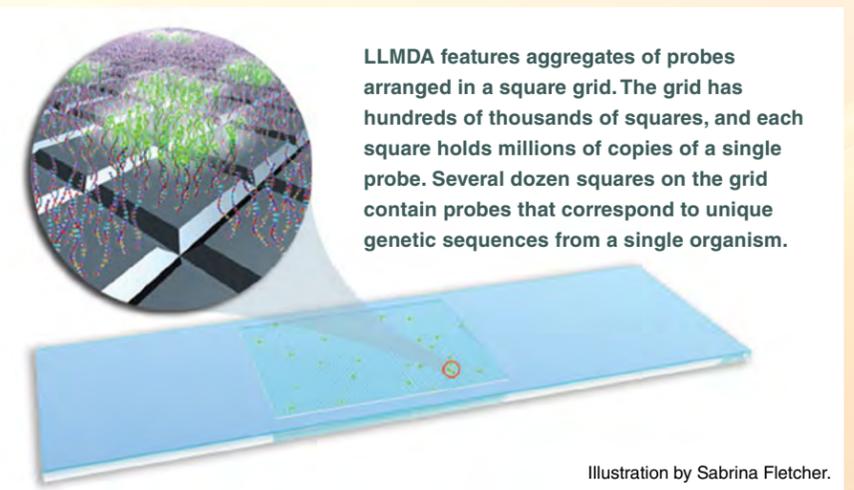
LMAT: Livermore Metagenomics Analysis Toolkit

Today, it is possible to identify microbial pathogens in a sample without any prior knowledge of the organisms present. DNA extracted from the sample can be sequenced to recover short genetic fragments, which can be compared to accumulated genomic data. The huge challenge, addressed by the developers of the Livermore Metagenomics Analysis Toolkit (LMAT), is that genomic data is 115 gigabases in size and constantly growing. LLNL researchers successfully addressed the big-data search problem using one of the Laboratory's most advanced computers and then devised a means to use cloud computing to make LMAT widely available to other researchers.

Laboratory researchers tested the dual use of LLMDA and LMAT in a study on microbial infections and the healing of U.S. soldiers' wounds. The combination of technologies provided an efficient means for associating the presence of certain bacteria with the rate of healing, information that can help clinicians make more informed treatment decisions.

LLMDA features aggregates of probes arranged in a square grid. The grid has hundreds of thousands of squares, and each square holds millions of copies of a single probe. Several dozen squares on the grid contain probes that correspond to unique genetic sequences from a single organism.

Illustration by Sabrina Fletcher.

sequences are available.

The same year as the SARS outbreak, Thomas Slezak, the bioinformatics group leader, conceived of LLMDA when he learned of an important technology breakthrough in microarray technology: DNA probes of 60 or more bases became possible. This advance made it feasible to design a microarray in which the large

number of probes would have different DNA sequences, providing signatures of microorganisms for which there is interest. Complementary advanced software could then determine what microbes are in a tested sample based on sequences that match between a probe and sample DNA that has a fluorescent tag for detection with a laser. The idea worked.

New Superheavy Elements for the Periodic Table

Livermore entered the history books on May 30, 2012, when the International Union of Pure and Applied Chemistry (IUPAC) adopted the name livermorium for element 116, in honor of the discovery team at Lawrence Livermore National Laboratory and the City of Livermore. The city and the Laboratory jointly celebrate the discovery of the element on Livermorium Day, May 30th, each year at Livermorium Plaza (located, coincidentally, at 116 S. Livermore Avenue).

Livermorium and flerovium (element 114) joined the periodic table on the same day. The name flerovium honors

Georgy N. Flerov, the head of the Laboratory of Nuclear Reactions, later named the Flerov Laboratory of Nuclear Reactions, which is part of the Joint Institute for Nuclear Research in Dubna, Russia. Livermore chemist Ken Hulet met Professor Flerov at an international meeting in 1989, and the two agreed to join forces to create new superheavy elements using the U400 cyclotron at Dubna. During 40 days of virtually continuous operations in November–December 1998, an American–Russian team accelerated ten-thousand trillion calcium-48 (a rare isotope of calcium with 48 neutrons) ions per hour to

about 10 percent the speed of light and bombarded plutonium-244. On November 22, 1998, they created the first atom of flerovium-289, which lived for 30.4 seconds before decaying. In 2000 and 2001, the collaborators performed three sets of experiments with curium-284 targets and produced livermorium-292, once in each campaign.

This LLNL–Dubna team has discovered six elements (for some, with additional key collaborators)—113, 114, 115, 116, 117, and 118. All six elements have been officially named: 113-nihonium; 114-flerovium; 115-moscovium; 116-livermorium; 117-tennessine; and 118-oganesson. (IUPAC recognized Japanese scientists at RIKEN as the official discoverers of element 113, though Russian and U.S. teams found the element a few years earlier.)
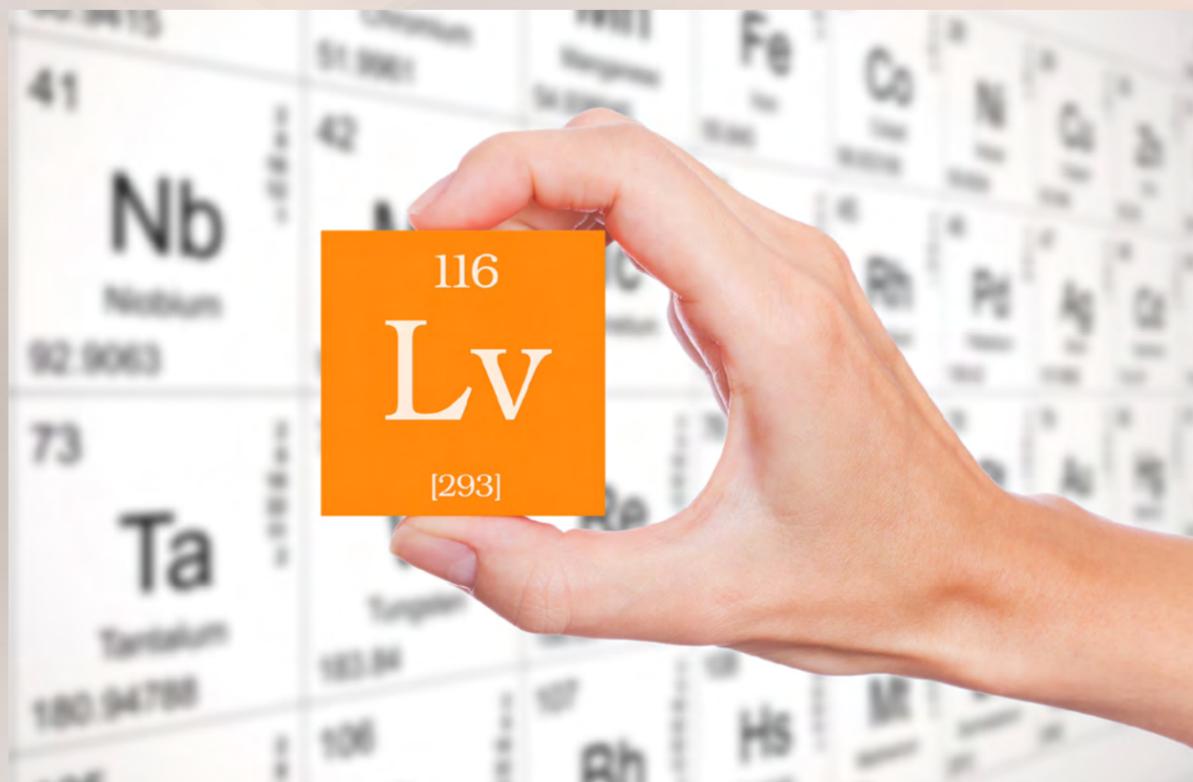
These discoveries are important steps in the quest for the "island of stability," a predicted region of superheavy elements on the chart of nuclides with half-lives that are longer by several orders of magnitude than the half-lives of other superheavy

elements, typically measured in micro- or nanoseconds. Superheavy elements on the island have more spherical shape and should be more stable. The discovery of livermorium and flerovium—on the edge of the island of stability—demonstrated its existence. Researchers are probing the new elements' chemical properties and exploring ways to create more of their isotopes. The Livermore–Dubna team is also awaiting construction of an additional dedicated accelerator at Dubna, which should greatly increase the production rate of superheavy

elements. Many fundamental questions remain about the limitations of matter and its chemical behavior at the far end of the periodic table.

Discovery and exploration of the properties of superheavy elements is just one facet of Laboratory core capabilities in radiochemistry. Expertise in radiochemistry provided essential support to the nuclear test program, and interest in the field is expanding again with applications in national and global security, energy security, environmental stewardship, and human health.

LLNL Director Parney Albright (left) accepts a proclamation from Livermore Mayor John Marchand during the naming of 116 S. Livermore Avenue as Livermorium Plaza. With the discovery of Livermorium, the city of Livermore is one of only six cities to have an element named after it on the periodic table.

Livermore nuclear chemist John Despotopulos (below) works with the Laboratory's automated ion chromatography fraction collection system, which can chemically separate up to 12 samples simultaneously. The capability supports many LLNL missions, including studies of the properties of the newly discovered elements.

2013 Self-Heating

Progress on the Path to Fusion and Energy Gain

LLNL researchers prepare for an experiment at NIF. Every aspect of a shot is checked and monitored in NIF's NASA-inspired Control Room, where operators access data through a hierarchy of on-screen graphics menus.

On August 13, 2013, researchers conducted the first of a series of experiments at the National Ignition Facility (NIF) that clearly demonstrated self-heating, a mechanism needed to achieve fusion ignition and sustained fusion burn. The shot imploded a tiny cryogenically cooled deuterium–tritium capsule and produced a record number of neutrons (3×10^{15}). In March 2014, a subsequent experiment increased the neutron yield to 9.3×10^{15}. Alpha particles (helium nuclei) from fusion reactions further heated the plasma in a central spot and produced more than half of the total fusion yield (27 kilojoules). The fusion yield was considerably more than the energy imparted to the imploding deuterium–tritium fuel.

These successful shots were part of a "high-foot" campaign. The high-foot laser pulse is shaped in a way that reduces hydrodynamic instabilities and breakup of the imploding capsule shell; however, overall compression in the implosion is insufficient for ignition. Experimental results were remarkably close to simulations that modeled asymmetries and some engineering details. Seeing how these higher velocity implosions behaved was important for understanding and identifying other issues that affect performance.

Achieving fusion ignition and energy gain at NIF is a grand scientific challenge. Experimental campaigns, such as the high-foot shots, are making progress in identifying impediments to success and exploring ways to overcome them. One impediment is associated with poor control of the overall symmetry of the x-ray pulse created by the laser beam impinging on the walls of the hohlraum, the open-ended cylinder containing the target capsule. Drive symmetry is needed to implode the target uniformly to about 30 times smaller diameter, create a central hot spot, and ignite the fuel.

To improve target performance, researchers have been investigating a complex set of trade-offs among hohlraum designs and gas fills, and they experimented with high-density carbon (diamond) target capsules with a low-level fill of helium in the hohlraum. With less helium, the interaction between the laser light and the helium plasma is reduced so that 20 to 25 percent more x rays radiate the capsule. However, the laser pulse must be shorter so as not to be partially blocked by the faster ingress of the expanding hohlraum walls that are less restrained by helium. Because of diamond's high density compared to other capsule materials, the capsules work with the shorter pulse length and produce higher efficiency, more symmetric implosions. The experiments are enabling a closer look at engineering features that impact the implosion, such as the fill tube and the capsule support.

Hydrodynamic instabilities in the imploding capsule present another set of issues—they can perforate the confining shell and they can contaminate the hot spot through the mixing of materials into the fuel. Experiments demonstrated that the "tent"—an ultrathin membrane that supports the target capsule inside the hohlraum— and the tube that fills the target with deuterium–tritium fuel

Photo credit: Don Jedlovec.
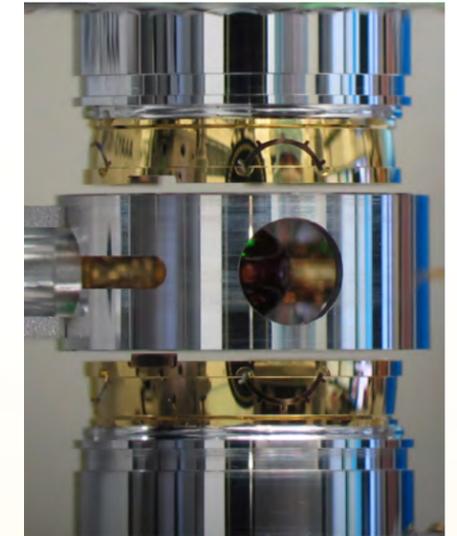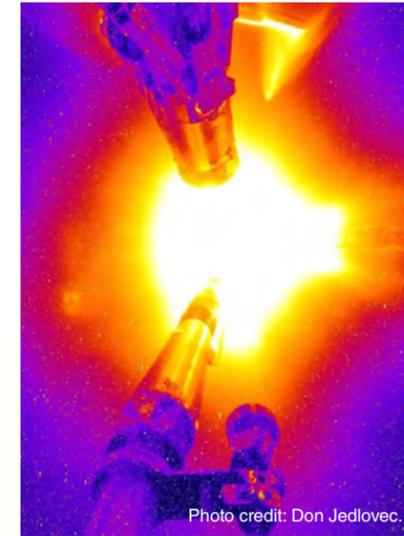
A colorized image shows a NIF "big foot" deuterium–tritium (DT) implosion (left) conducted on February 7, 2016. The shot used a shortened three-shock pulse, a thinner DT ice layer, and a subscale diamond ablator. Other experiments are testing whether rugby-ball-shaped hohlraums (right) can better control the drive symmetry on the target capsule.

Finding a Balance and Understanding Boost

As the Stockpile Stewardship Program began, weapon designers faced two key scientific challenges: energy balance and boost. Energy balance pertains to "missing energy" in the sophisticated simulation codes used to design weapons. Nuclear tests had gathered data used to adjust for this missing energy. One of the most notable accomplishments of science-based stockpile stewardship was a theoretical explanation, modeled with high-performance computing (HPC) and validated by experiments, including shots at NIF.

Livermore physicist Omar Hurricane won the Ernest O. Lawrence Award for creating the energy balance model and leading a team over a 10-year effort that solved the mystery of missing energy. Subsequently, he led the "high-foot" campaign. Boost, the use of thermonuclear reactions to enhance the yield of a weapon's primary, also needs to be better understood. That will require continued advances in HPC and future experiments at NIF including progress toward ignition, which will provide the energies necessary to conduct experiments relevant to understanding boost process details.
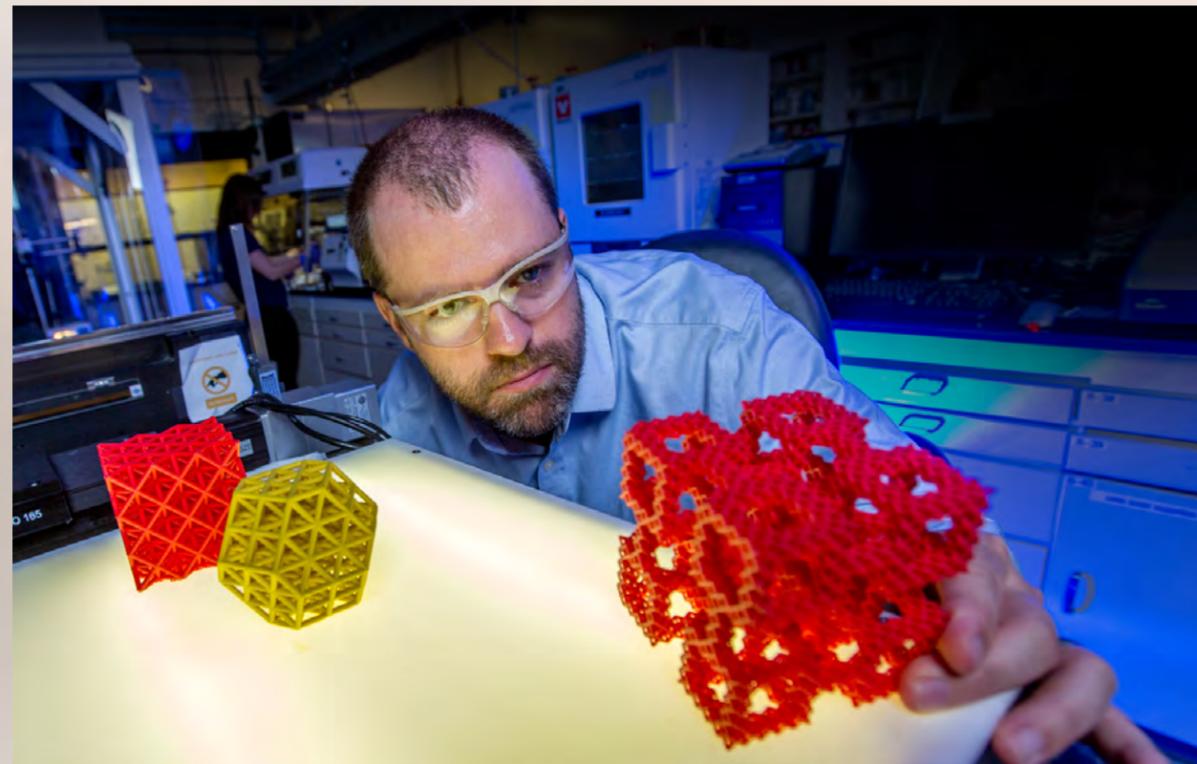
are significant sources of material mixing that reduce neutron yield. Researchers are considering design options to reduce these effects.

2014 Additive Manufacturing

21st-Century Production of Tailor-Made Materials and Components

LLNL's Laboratory Directed Research and Development Program investments in the early 2010s launched an explosion of interest and remarkable advances in additive manufacturing (AM). Often in the form of 3D printing, AM typically adds successive layers of materials to precisely fabricate objects that may be designed to have very complex geometries. The focus has been to advance those technologies—together with "ink" and "dry powder" starting materials—that are important for mission applications and not commercially available.

By integrating manufacturing expertise, precision engineering, materials science, and high-performance computing, LLNL's AM research has led to innovative multifunctional materials for stockpile stewardship, global security, and energy security. Materials of interest have ranged from aerogels with special structural properties

Illustratiion by Ryan Chen.

to actinides; from carbon fiber composites to precision optical glass; from blood vessels to high explosives; and from polymers to metals and ceramics of all sorts.

A principal driver behind the focus on AM was Livermore's responsibility to lead for NNSA the next two warhead life-extension programs (LEPs, see Year 2016). The combination of thorough integration of simulation and experiments (see Year 2010) and AM promises to accelerate design and development, assist in production certification, reduce manufacturing costs, and improve quality and performance of components. An example is the advance of direct ink writing (DIW) to manufacture cushions and pads, which are used in nuclear weapons to absorb shocks and fill gaps between components.

At first, LLNL researchers collaborated with the inventor of DIW to adapt the technology for printing

LLNL researchers have made graphene aerogel microlattices with an engineered architecture using direct ink writing. The material's exceptional properties will make for better energy storage and nanoelectronics.

the polymer-based cushions and pads. The Laboratory then partnered with Kansas City National Security Campus to bring the technology into the NNSA manufacturing enterprise. The team received an NNSA Award of Excellence in 2015 for exceptional creativity in developing the AM process for cushions and pads. LLNL researchers have also made DIW-printed engineered graphene aerogel microlattices—strong, lightweight, and compressible materials for use in high-performance supercapacitors.

The combination of well-diagnosed experiments and high-performance computing simulations of material behavior is critical to many advances. For example, Laboratory scientists have made key discoveries about defect formation in the 3D printing of metals and ways to prevent it. Researchers have also succeeded in printing aerospace-grade carbon fiber composites. They mastered the flow of carbon fiber filaments through the DIW nozzle and the chemistry for curing the material quickly.

LLNL researchers have gained international recognition for their capabilities in developing AM methods for producing materials with never-before-realized properties and their increasingly deep understanding of the complex physics underlying AM. In January 2019, the 14,000-square-foot Advanced Manufacturing Laboratory opened at the Livermore Valley Open Campus to further expand partnerships. Many academic collaborations, Cooperative Research and Development Agreements (CRADAs), and industry-related projects are under way.

Engineer Eric Duoss examines models of new ultralight structures Laboratory researchers have fabricated by AM. The team has developed, for example, micro-architected metamaterials—artificial materials with properties not found in nature—that can withstand a load of at least 160,000 times their own weight.
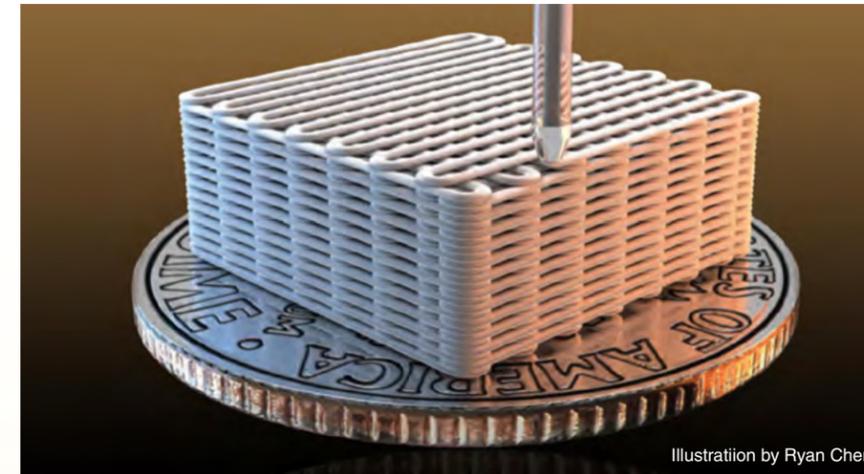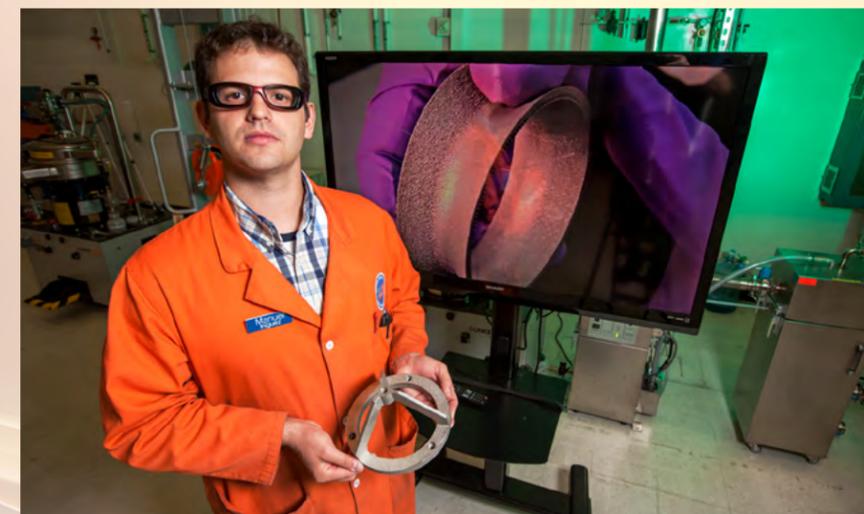

Livermore AM technician Manuel Iniguez holds a metal part produced in partnership with the Y-12 National Security Complex. This match drill fixture is the first additively manufactured part to be qualified for NNSA production and takes one-fifth the labor hours to produce as compared with previous manufacturing methods.

Neural Implants, Plus a Human-on-a-Chip

In 2014–2015, LLNL's Neural Technologies Group launched several flagship projects under the White House BRAIN initiative. The initiative aims to build the next-generation brain interfaces for human therapeutic use and for advancing fundamental understanding of the brain. Supported by the Defense Advanced Research Projects Agency and the National Institutes of Health, LLNL engineers and researchers from the University of California at San Francisco (UCSF) began to design and build an advanced, human-implantable neuromodulation system to treat neuropsychiatric conditions, such as anxiety, depression, and post-traumatic stress disorder. The system will be capable of autonomous, closed loop sense-and-stimulate therapy.

In collaboration with Case Western Reserve University, Laboratory engineers also began building a prototype neural system to enable naturalistic feeling and dexterous control of prosthetic limbs for wounded warfighters. Additionally, an LLNL–UCSF team started work on an electrode array system for studying brain activity at unprecedented resolution. They are designing and building electrode arrays that can record from hundreds to thousands
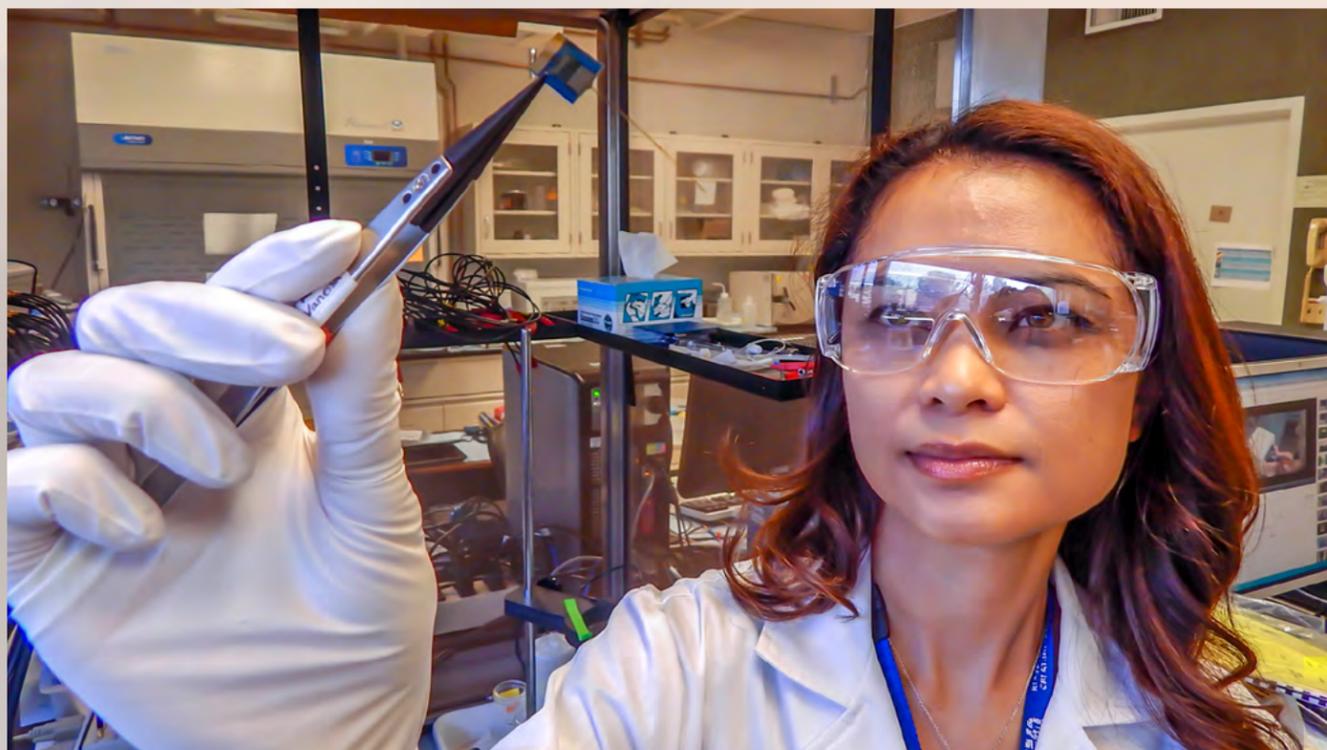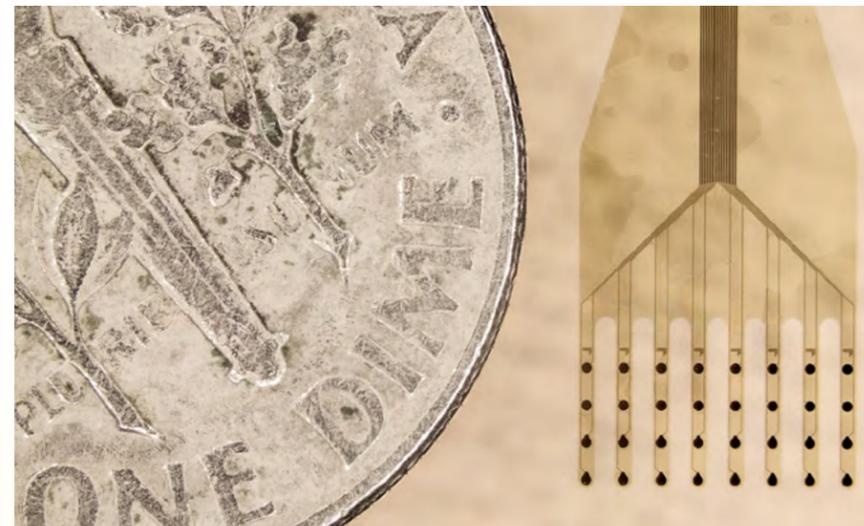
LLNL's tiny thin-film electrode array, compared to the size of a dime, uses complex electronics connections to stimulate and record neural signals. The implantable device offers a wide range of treatment applications, from Parkinson's disease to seizures or depression.

of brain cells simultaneously. The ultimate goal is to develop arrays with 1,000-plus channels that can be expanded to 10,000 channels.

The keys to success in these projects are LLNL's expertise in nano- and microtechnologies and their development of novel materials that make devices biocompatible and fully implantable for long-term use, supported by a dedicated Medical Device Fabrication Facility. Laboratory researchers have continued to improve key technologies since their first major success in 2009: LLNL led a multi-institutional team in the design and fabrication of an artificial retina—a fully implantable neural prosthetic that restores a sense of vision to people who have lost their sight because of ocular disease. LLNL engineers were responsible for systems integration and contributed three major components to the artificial retina program.

In addition to the development of neural implants, LLNL researchers applied their expertise and unique capabilities to create a "human-on-a-chip." The in vitro chip-based human investigational platform (iCHIP) combines living primary human cells, tissue engineering, and microfluidics to reproduce the body's physiological response under an array of conditions. The iCHIP serves as a testing platform for exposure to agents whose effects

are unknown to humans. Its use in testing new pharmaceuticals could dramatically accelerate the drug development process.

In 2014, LLNL scientists used the iCHIP platform to expose isolated human dorsal root ganglia nerve cells, which form part of the peripheral nervous system, to capsaicin (responsible for the burning sensation in chili peppers) and quantified cell response. By 2017, researchers reproduced on iCHIP four major biological systems vital to life: the central nervous system (up to four different types of brain cells), peripheral nervous system, the blood–brain barrier (which keeps potential toxins outside the brain), and the heart. More recently, LLNL researchers created a 3D "brain-on-a-chip" and recorded the neural activity of living brain cell cultures for up to 45 days. Future work includes the integration of these systems—and other organs—to create a complete testing platform.

Illustration by Ryan Chen.

Through "heart-on-a-chip" technology—modeling a human heart on an engineered chip and measuring the effects of compound exposure using microelectrodes—Laboratory researchers hope to ensure potentially lifesaving new drugs are safe and effective while reducing the need for human and animal testing.

Laboratory engineer Vanessa Tolosa holds up an implantable flexible electrode array. Capable of monitoring and stimulating thousands of neurons for years, the technology leverages LLNL work on the groundbreaking artificial retina project (top), which developed and applied biologically compatible micro-technologies to restore eyesight.

Extending the Stockpile Life of a Legacy Warhead

Hydrodynamic experiments performed at Livermore's Contained Firing Facility (CFF) and at Los Alamos provide essential support to the W80-4 LEP. A recent upgrade for the Flash X-Ray machine (below) in the CFF provides the capability to take two images during a single experiment, enabling researchers to follow the time evolution of implosions.

The W80 thermonuclear warhead entered service in 1982 with a 20-year design life. Its delivery system, a long-range cruise missile developed by the U.S. Air Force, had a 10-year design life. After more than three decades in service, researchers are now working in earnest to extend the life of the warhead and replace the missile.

LLNL is partnered with Sandia National Laboratories to develop and certify the refurbished W80 warhead, which is designed for the new Long-Range Standoff Missile being developed in parallel by the U.S. Air Force. Designated the W80-4, this will be the first warhead designed for use with a new missile or delivery system since nuclear testing ended in 1992. The design options being considered for the W80-4 are cost-conscious and offer improvements to weapon safety, security, and effectiveness. First production of the W80-4 is planned for 2025.

In 2016, the W80-4 life-extension program (LEP) was in the midst of Phase 6.2, during which the project

A critical need for the W80-4 LEP is to qualify and remanufacture additional insensitive high explosives to be used in the refurbished warheads. Work on the processing (e.g., shaping and machining) of batches of high-explosive materials for testing purposes is conducted in facilities at the Laboratory's remote Site 300.
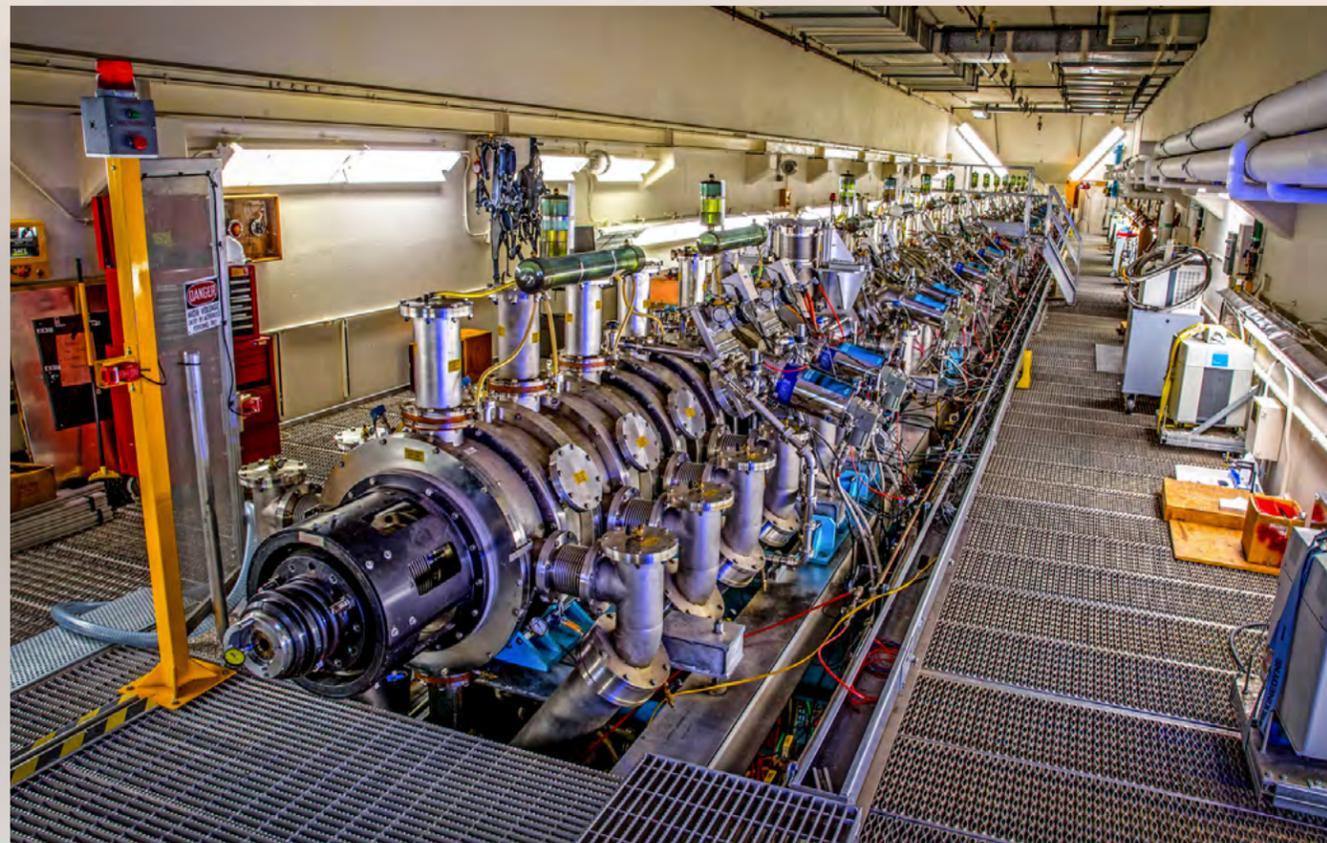
team must down-select among options generated in Phase 6.1. A mature set of requirements has been defined, business systems put in place to track schedule and budget, and NNSA made significant investments to recapitalize critical infrastructure at the Laboratory. In support of the LEP, researchers have initiated the first sets of major non-nuclear experiments, and LLNL's exceptional high-performance computing capabilities are being heavily used to study and refine design options.

A major challenge of extending the life of the W80 is refurbishing materials and components that cannot be produced exactly as originally manufactured. For instance, the main explosive charge needs replacing; however, the original producers of the high-explosive constituents are either no longer in business or have made production process changes. Accordingly, LLNL has been working with the current material manufacturers to reconstitute the facilities and modify processes necessary for production, and researchers have started the process of reformulating the material (see Year 1976).

The design and certification process will require innovations and extensive use of world-class computational

LLNL engineers and materials scientists developed a method to additively manufacture cushions and pads that protect and position components within a nuclear weapon. Use of AM lowers production costs and allows for precise control of the material properties, which improves the predictability of performance.

and experimental resources. An area of significant innovation at LLNL is the use of additive manufacturing (AM) to improve the quality and reduce the cost of parts for weapons undergoing LEPs (see Year 2014). Major achievements in 2016 included producing AM parts for testing and developing refined capabilities to control the microstructure and physical properties of these parts. Two major hydrodynamic tests conducted during the fiscal year provided important data

in support of an option for the W80-4 using AM.

As efforts on the W80-4 LEP continue, LLNL scientists and engineers resumed work in 2019 on the W87-1 Modification Program, which will replace the aging W78 warhead and be fielded on the Air Force Sentinel ICBM. These two programs offer opportunities to introduce modern, efficient processes and technologies into the NNSA nuclear weapons complex to lower costs (see 2019).

2017 Sierra

Sierra, the Future of Supercomputing, and the Laboratory

The history and the future of Lawrence Livermore National Laboratory and supercomputing are deeply intertwined. Before the doors opened for business on September 2, 1952, the Laboratory's founders ordered delivery of a Univac-1, the world's most powerful computer at the time. After taking a crash course in the new art of computer programming, Livermore scientists used the machine while it was at the vendor in Philadelphia, Pennsylvania, untill the Univac's

delivery to Livermore in April 1953. On the 65th anniversary of LLNL, computer scientists are busy adapting their simulation codes so that they run proficiently on Sierra, which is being delivered to Livermore and will be one of the world's most capable supercomputers when fully operational in 2018.

The remarkable advances the Laboratory has made in nuclear weapons design and engineering stem from a continuing unchanged

Sierra (left), built by IBM and delivered in 2017–2018, was the next in a long line of supercomputers at LLNL. The Laboratory and IBM Research are exploring another approach to supercomputing with the 16-chip TrueNorth platform (right), delivered in 2016. It is a first-of-a-kind brain-inspired platform for deep learning for complex cognitive tasks such as pattern recognition.

practice: work hand-in-hand with U.S. industry to push the state of the art in high-performance computing (HPC) and then effectively integrate scientific and engineering simulations with more expensive, time-consuming testing to move innovative ideas to final products. This approach to problem solving permeates all mission areas at LLNL. It is particularly essential for stockpile stewardship. In the absence of explosive nuclear testing, experiments test aspects of nuclear weapons performance. They also provide data to validate simulation models used to support integrated assessments of the condition of aging nuclear weapons and extend their stockpile life.

Sierra, the next-generation supercomputer built by IBM, is a result of DOE's Collaboration of Oak Ridge, Argonne, and Livermore (CORAL) initiative, a three-laboratory partnership of NNSA's Advanced Simulation and Computing (ASC) Program and the Office of Science's Advanced Scientific Computing Research Program. In 2018, with support from ASC and institutional funding, LLNL will also take delivery of a smaller, unclassified companion to Sierra to provide the most advanced computing capabilities to all program and mission areas at the Laboratory.

Computer scientists Adam Bertsch (left) and Pythagoras Watson examine components of the Sierra early-access machine, which was used to help prepare codes to run on the full version of Sierra as soon as it came online.

Sierra is expected to provide four to six times the sustained performance and handle five to seven times the workload of Sequoia. Sited at Livermore and serving the needs of the three NNSA laboratories, Sequoia is NNSA's fastest supercomputer at 20 quadrillion (1015) floating-point operations per second. With its advanced architecture that includes graphics processing units, the new machine is five times more energy efficient than Sequoia; however, restructuring existing and designing new software to run efficiently on Sierra—and anticipated future supercomputers—is a challenge.

Sierra is an important next step toward exascale computing, an essential goal for long-term success in stockpile stewardship. LLNL is one of six laboratories helping to execute the Exascale Computing Project (ECP), a collaborative effort between DOE's Office of Science and NNSA, that is performing the necessary research and development for efficient exascale-class systems. Benefiting from the results of ECP, current plans are for NNSA to fund the delivery of an exascale computer to LLNL in 2023. It is an exciting prospect for the future of HPC and the Laboratory.

LLNL scientists (from left), Vladimir Tomov, Tzanio Kolev, and Veselin Dobrev examine a simulation that is representative of the type of computing methods that will be needed on future supercomputers. As part of the DOE's Exascale Computing Project, Livermore is leading a co-design center, the Center for Efficient Exascale Discretizations. Co-development of the software ecosystem, the hardware technology, and a new generation of applications is necessary to ensure all the components work together as a system.

Understanding Climate Change and Managing Carbon

E3SM combines models of global atmosphere and land surface with ocean, sea ice, and river models. Simulations can be run at 100-kilometer resolution over the globe with a finer 25-kilometer resolution over North America or at much higher resolution to study regional conditions.

Early in 2018, the DOE Office of Science launched version 1 of the Energy Exascale Earth System Model (E3SM), which simulates the fully-coupled climate system at high resolution. Designed to run on exascale computers, E3SM was developed by a large multilaboratory team with an LLNL scientist serving as the Principal Investigator. Since its debut, a faster, more capable E3SM version 2 has been released to the broader scientific community, which eagerly awaits arrival of DOE's first exascale computers, enabling even more realistic simulations to be performed.

Laboratory researchers continue to make important advances in climate research, including key contributions to a multi-year international study that narrowed the bounds of uncertainty regarding the effect of increased atmospheric carbon dioxide (CO_2) would have on the Earth's climate. LLNL focused on processes that amplify or diminish warming trends and feedback from clouds, which are a key source of uncertainty. This study supported the Working Group 1 portion of the Sixth Assessment Report, issued by the Intergovernmental Panel on Climate Change (IPCC) in August 2021. Other projects examined regional effects of climate change, helped to reconcile model simulations with collected satellite data, and improved climate "fingerprinting" techniques to investigate anthropomorphic influences on climate. An LLNL-led multi-institutional research team clearly identified that human activities have led to the observed different rates of warming between the northern and southern hemispheres.

LLNL is also at the forefront of devising technical means to reduce atmospheric CO_2. Launched in 2018, the Laboratory Director's Engineering the Carbon Economy initiative fosters investments in science and technology innovations and partnerships aimed at creating a new carbon economy based on global-scale CO_2 removal solutions. The initiative ties together efforts in carbon capture, beneficial use of captured CO_2, soil carbon, and carbon storage that were started before 2018. It supports faster development of concepts and analysis of the benefit of innovations.

Removing excess atmospheric CO_2 is difficult but uses the same concepts as earlier work on carbon capture, such as the LLNL-developed permeable microcapsules containing sodium carbonate to capture CO_2 from fossil-fuel power plants (see Year 2007). By combining expertise in advanced manufacturing with computer simulations, Laboratory researchers are also making breakthrough progress on inventing new electro-, thermal-, and biochemical approaches for converting harvested atmospheric CO_2 into hydrocarbons that are valuable industrial feedstocks. Other LLNL scientists are studying how plants, microbes, and soil interact to store carbon—two-thirds of the carbon in the terrestrial biosphere is stored underground as soil organic matter. High-resolution imaging and isotopic studies enable a better understanding of this living, changing system. Investigations into much deeper engineered underground storage of

CO_2, such as in oil fields, are benefiting from GEOSX, a simulation tool for predicting the behavior of subsurface storage options.

Laboratory systems analysts are seeking win–win solutions for investments that must be made to achieve established goals for limiting atmospheric CO_2. In a groundbreaking study completed in 2020, LLNL scientists and collaborators identified a robust suite of technologies to help the State of California become carbon neutral by 2045. *Getting to Neutral: Options for Negative Carbon Emissions in California* is serving as a valuable resource for policymakers, government, academia, and industry.
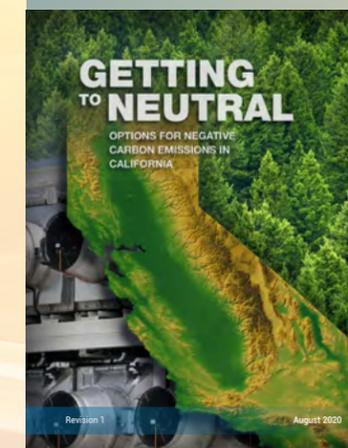

Combining additive manufacturing with multiscale computer modeling, Livermore researchers are rapidly cycling the design and testing of modular electrochemical reactors to covert CO_2 into hydrocarbons. Precise 3D printing makes it possible to tailor reactors to specific operating environments.

Getting to Carbon Neutral

Getting to Neutral: Options for Negative Carbon Emissions in California thoroughly assesses existing advanced carbon reduction technologies and their costs, as well as the tradeoffs necessary to reach the state's decarbonization goal. The study team identified a portfolio of approaches for achieving greater than 125 million tons per year of negative emissions for California by 2045. They also evaluated the scope of state and private investment to best achieve the goal. The report was funded by the Livermore Lab Foundation with grant support from the ClimateWorks Foundation.

2019 Polymer Production Enclave

# Weapons Modernization on the Fast Track with Enclaves

The fabrication room in the Polymer Production Enclave features new machines and tools equivalent to those in use on the Kansas City National Security Campus's production floor. A dedicated LLNL team completed the repurposing of the facility and installation of equipment in just over a year.

In 2019, LLNL and the Kansas City National Security Campus (KCNSC) embarked on the creation of the Polymer Production Enclave (PPE). The enclave is an important visible step toward realizing much closer partnerships between the nuclear weapons laboratories and the NNSA production facilities to improve the responsiveness and resilience of nuclear weapons development and modernization programs. Such partnerships are vital to the success of the W80-4 life-extension and W87-1 modification programs. The Laboratory's initiatives to establish enclaves—as well as other means for tighter integration of design-to-production processes—support NNSA's goal to increase the agility and efficiency of its Nuclear Security Enterprise (NSE) through modernization.

PPE is located within LLNL's newly established Applied Materials and Engineering (AME) campus, which synergistically consolidates capabilities that support the weapons

modernization programs into renovated and newly constructed facilities. Groundbreaking for AME occurred in June 2019 and PPE was one of the first facilities opened for operation. The state-of-the-art polymer design and production facility, dedicated in September 2020 and fully operational in January 2022, houses machines, tools, and other production equipment that are equivalent to resources at KCNSC. The Livermore facility also features a materials-mixing laboratory, a post-manufacturing evaluation space, and offices and conference rooms for KCNSC and other partners and stakeholders, including Sandia, Los Alamos, and the United Kingdom's Atomic Weapons Establishment.

Collaborators can simultaneously complete multiple additive manufacturing (AM) production phases—such as ink processing, printing, materials characterization, and quality control—and immediately incorporate their findings into development and testing. The envisioned collaborative approach to
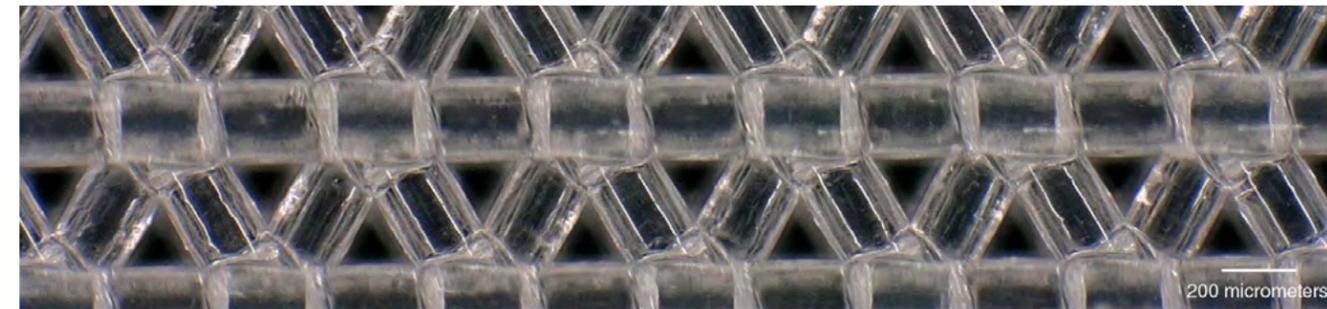
co-development of new technologies within the enclave will accelerate transition to production. The PPE team has already realized several important early wins, including the ability to tailor an ink's response to different loading conditions and print dynamically responsive foams that can accommodate multidimensional stress and strain. For complex parts, the printing nozzle needs to align within tens of micrometers rather than the more typical plus or minus 50 micrometers. To improve the yield on such parts, the team has also developed customized methods to measure and correct the tool path in real time.

With the success of PPE, LLNL and the Pantex Plant are in the process of establishing the Energetic Materials Development Enclave at Site 300. This enclave will drive a new approach to accelerate the adoption of new explosive materials and production capabilities within the NSE. In addition, Livermore and the Y-12 National Security Complex have teamed up to rapidly modernize technology and production methods for crucial weapons components. Utilizing manufacturing space in Oak Ridge, Tennessee, and its unique capabilities to handle hazardous materials, the joint LLNL and Y-12 materials team successfully installed and tested the electron beam cold hearth melting (EBCHM) technology—a machine that can melt and cast various metals including uranium alloys. When compared with legacy production methods, EBCHM has the potential to improve material utilization, drastically reduce waste, and shorten the cycle time for producing metal ingots.

Direct ink writing techniques used for additive manufacturing (AM) within the Polymer Production Enclave allow researchers to produce highly intricate and precise lattice structures, including helicoidal or flat spiral structures. The newly developed abilities to mix materials across parts provide a range of characteristics and features not previously available for weapons components using legacy foams.
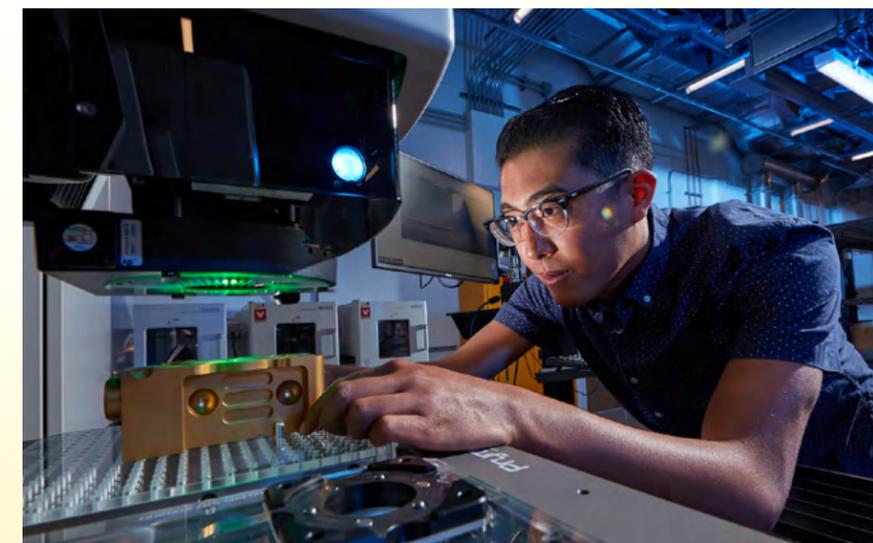
An additive-manufacturing engineer assesses the quality of parts using a highly sensitive and accurate coordinate measurement system to assess the quality of parts.

New Materials require new design tools

Computer scientists and engineers at the Laboratory's Center for Design Optimization are working to fundamentally transform how engineers design complex additively-manufactured parts and systems. Design has become a bottleneck that is sometimes more difficult than actual fabrication. Conventional design methods and computer algorithms do not take advantage of advances in modeling and simulation capabilities, data analytics, and algorithms that are common in high-performance computing (HPC). The research team is leveraging LLNL's extensive HPC capabilities to develop an efficient design optimization software package called Livermore Design Optimization (LiDO). LiDO will provide a cohesive design environment to seamlessly combine LLNL's rapidly growing AM capabilities with HPC resources.

The Twenties

New Leadership

Kimberly S. Budil
(2021 • Present)

From the first Polaris warhead to the record-breaking 1.3 megajoules of fusion energy produced at the National Ignition Facility in 2021, Livermore has made the impossible possible. Since the Laboratory's inception, the world has changed dramatically—and rapidly in the 2020s. The COVID-19 pandemic and the Russian invasion of the Ukraine have challenged international order and national security. At the Laboratory, a new generation of scientists and engineers, most with less than five years of service, are being called upon to continue LLNL's tradition of science and technology

Making the impossible possible

excellence and deliver game-changing transformational solutions to the biggest national security challenges.

Livermore is striving to transform nuclear weapons production processes through two warhead modernization programs. Laboratory researchers are contributing to improve understanding of climate change and fostering a new carbon economy based on CO_2 removal. They are also pursuing faster ways to develop new drugs and respond to future pandemics. In support of all mission areas, LLNL is at the forefront of applying high-performance computing and artificial intelligence to accelerate scientific discovery, invention of new materials, and the concept-to-product development process.

Coping with COVID-19 and Responding to Bioresilience Needs

A Livermore-designed machine-learning platform was used to model the 3D structures of the SARS-CoV-2 spike protein (blue) and an antibody candidate (green and red) shown alongside.

The Laboratory responded quickly and effectively to the COVID-19 pandemic. At the end of January, when the global threat was emerging, LLNL stood up its Pandemic Response Team, which enabled a rapid shift to a safe standby operational posture when Alameda County issued a shelter-in-place order on March 16th. Overnight, LLNL reduced from nearly 8,000 persons on site to a few hundred. Within a week, an extraordinary effort by LLNL information technology (IT) teams provided thousands of employees the ability to telecommute and work remotely. Researchers were able to maintain productivity, and major programmatic delays were mitigated.

The health and safety of LLNL personnel dictated management decisions about the pace of increasing onsite activity. On March 24th, Livermore received NNSA concurrence to resume additional onsite work. The initial activities focused on core national security missions and progressed with gradual, deliberate resumptions of other work consistent with programmatic priorities and local conditions. In July, the Laboratory was operating effectively with the daily onsite population reaching approximately 2,700 (roughly one-third full staff). To address virus-related risks, new work controls were established together with work guidelines on personal protective equipment and social distancing requirements.

Laboratory scientists and engineers also rapidly refocused on study of the SARS-CoV-2 virus and countermeasures. In early February, they developed a preliminary set of predicted 3D protein structures based on a previously peer-reviewed modeling process, the genetic sequence of SARS-CoV-2, and the known structure of a protein found in the virus that causes SARS. The predictions closely matched the later experimentally determined structure of the key protein. LLNL researchers also used artificial-intelligence to virtually screen an enormous set of possibilities to find potential candidate antibodies capable of binding and neutralizing SARS-CoV-2. High-performance computing (HPC) simulations then tested the efficacy of the selected candidates' molecular interactions.

Many of LLNL's intensive HPC efforts, including time provided to external users, were conducted as part of DOE's National Virtual Biotechnology Laboratory (NVBL), which was created in response to the pandemic. As another NVBL activity, a Laboratory

Experiments at the Laboratory showed that thermal inactivation is a potential widely deployable method for reuse of N95 respirators.

To minimize virus related risks, on-site workers followed new work control procedures that included use of personal protective equipment and specific rules when social distancing requirements could not be met (left), while teleworkers managed to work productively and participate in meetings while at home (right).

team updated the Lawrence Livermore Microbial Detection Array (see Year 2011) to identify unique sequences of the COVID genome for detecting virus mutations over time. In addition, two companies, Bio-Rad Laboratories, Inc. and Cepheid, Inc. developed diagnostic tests for the SARS-CoV-2 virus using diagnostic technologies that they had previously licensed from Livermore. Both technologies provided the foundation for products used for years to identify other pathogens. Finally, LLNL teamed up with an industrial partner to quickly develop a simple, easy to assemble mechanical ventilator in anticipation of nation-wide equipment shortages.

Throughout the year, the Laboratory worked closely with NNSA's Livermore Field Office to ensure that resources were allocated to maximum benefit for meeting program objectives. The necessary work adjustments and newly added IT capabilities have led to substantial advances in the efficiency of operations, safety, security, and environmental management and state-of-the-art business practices and processes. LLNL has adjusted to a new standard for "normal operations" that takes full advantage of a robust, secure virtual private network for telecommuting to greatly enhance work environment options for employees.

Vaccines against biothreats

The Laboratory brings more than a decade of experience exploring the use of nanolipoproteins (NPLs) as particle platforms to deliver vaccines and drugs inside the human body. NLPs can self-assemble in a relatively simple manner and provide a structure or platform for connecting other molecules. The NLP platform makes it possible to develop customized vaccines to target a range of pathogens. Rather than serving as a single-pathogen solution, the NLP platform can work more broadly, providing the foundation to fabricate potent vaccines targeted at biothreats.

LLNL researchers characterize nanolipoprotein particle vaccine formulations using a dynamic light-scattering instrument.

At the Threshold of Fusion Ignition
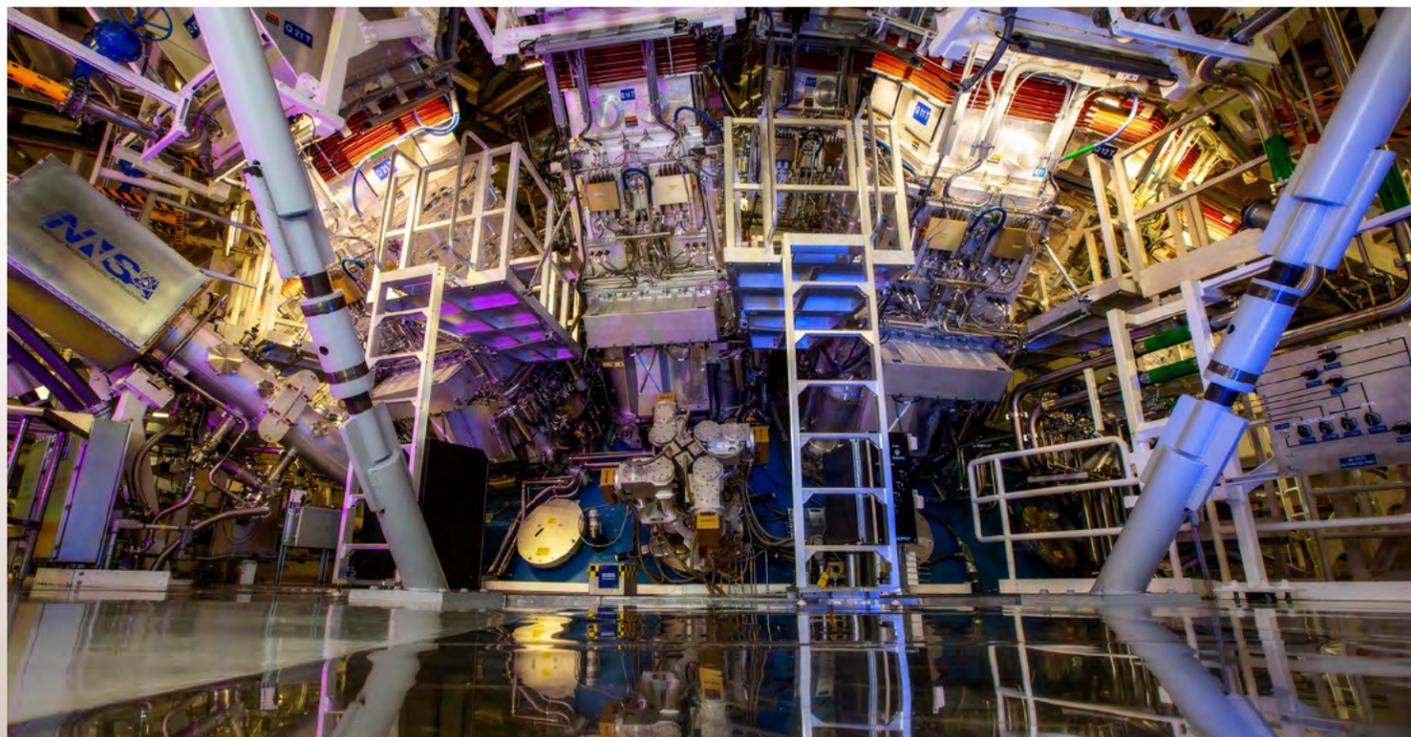
Within the confines of the target chamber (shown), the NIF experiment on August 8, 2021, brought researchers to the threshold of ignition, creating a hot spot at the center of the target capsule and triggering a self-sustaining burn wave of fusion reactions.

Laboratory director Kim Budil (far left) served as moderator for the opening panel of the White House Fusion Summit in March 2022, where experts from DOE national laboratories, academia and industry discussed the status and benefits of fusion technology. The event was co-sponsored by the White House Office of Science and Technology Policy and DOE.

On August 8, 2021, researchers conducted a shot at the National Ignition Facility (NIF) that produced a record-breaking 1.3 megajoules (MJ) of fusion energy by imploding a deuterium–tritium (DT) fuel capsule with 1.9 MJ of laser energy. The capsule, located within a hohlraum that converted the laser light into x rays, produced about six times as much fusion energy as the x-ray energy it absorbed. The x rays imploded the DT fuel within the capsule to eight times the density of lead and generated more than 10 quadrillion watts of fusion power for 100 trillionths of a second.

The fusion yield was 25 times higher than the record set in 2018 and eight times higher than results achieved earlier in FY 2021. The experiment benefited from extensive efforts during the year to improve the target design (called Hybrid-E), which includes a large high-density carbon (diamond) capsule Hybrid-E couples more energy to the fuel capsule than the earlier baseline design, compresses the fuel faster, and increases hot-spot pressure and temperature. In addition, changes in target fabrication processes led to a significant decrease in the diameter of the DT fill tube—from 10 to 2 micrometers—and improved shell quality, reducing capsule defects by two orders of magnitude.

The August 2021 shot was the first time in a laboratory that scientists have observed signs of a self-sustaining wave of nuclear reactions—thermonuclear burn—in the DT fuel. The hotspot experienced rapid self-heating and began to propagate burn into the surrounding dense shell, which increase in fusion yield, temperature, hotspot mass, and energy. The experiment's fusion yield was about 70 percent of that defined as achieving ignition, which occurs when the fusion energy produced exceeds the amount of laser energy delivered.

The Hybrid-E target was used in the milestone shot. During the experiment, laser beams enter the hohlraum through laser entrance holes and strike the hohlraum's inside walls. The resulting x rays blow off the surface of the tiny capsule containing DT fuel, causing a high-velocity implosion that fuses hydrogen atoms and releases large amounts of energy.
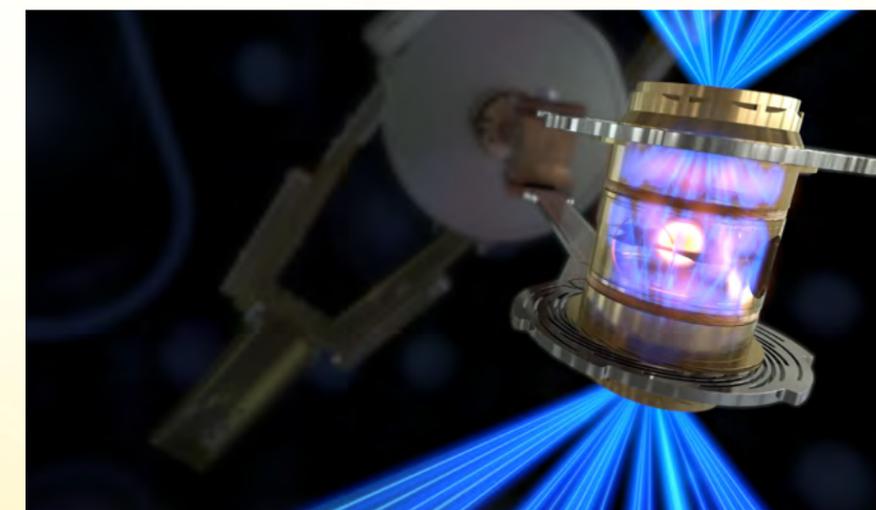
This experimental result is a huge step forward for internal confinement fusion (ICF) research. It opens a fundamentally new regime to explore and advance our critical national security missions. Gaining access to thermonuclear burn in a laboratory setting will enable experiments that more rigorously check theory and validate simulation of high-energy-density physics pertinent to weapons performance. Fusion ignition is also an important gateway toward pursuit of high fusion yields, which would be necessary for fusion energy applications.

The highly successful shot was the culmination of painstaking efforts undertaken by a team of multidisciplinary experts over multiple decades. Since the inception of LLNL's Laser Program in July 1972—now 50 years ago—scientists and engineers from across the Laboratory have been at the forefront of scientific and technological innovations that have paved the way to the milestone achievement. These advancements were a concerted effort of Livermore and collaborators including industrial and academic partners, Los Alamos and Sandia national laboratories, the University of Rochester's Laboratory for Laser Energetics, General Atomics, and the Massachusetts Institute of Technology. Being at the threshold of ignition builds on the work of the entire team, including the people who pioneered ICF research since the Laboratory's earliest days.

Using Artificial Intelligence to Improve Scientific Prediction

LLNL and Cerebras Systems have installed the company's CS-1 AI computer into the Laboratory's Lassen system, making LLNL the first institution to integrate the cutting-edge AI platform with a large-scale supercomputer. The integration creates a radically new type of computing solution, cognitive simulation, enabling researchers to investigate novel, AI-driven approaches to predictive modeling.

To study cancer-causing mutations of RAS proteins, researchers simulate a system with hundreds of proteins and a cell membrane is simulated at low resolution and then use ML to determine which regions require investigation in a microscale simulation at much higher resolution. Analysis from this microscale simulation is fed back into the macroscale model to improve its fidelity.

In December 2021, the Laboratory established a collaborative hub for experts in artificial intelligence (AI) from LLNL, industry, and academia to advance AI and machine learning (ML) for large-scale scientific and commercial applications. Called the AI Innovation Incubator (AI3), it provides a place where experts with diverse backgrounds and approaches can come together, nurture ideas, and grow projects that push the frontiers of the technology. AI is a "tool of the future" that is already providing breakthrough advances in many mission areas at the Laboratory.

Livermore is especially focused on cognitive simulation—combining AI and ML, high-performance computing (HPC) simulations, and 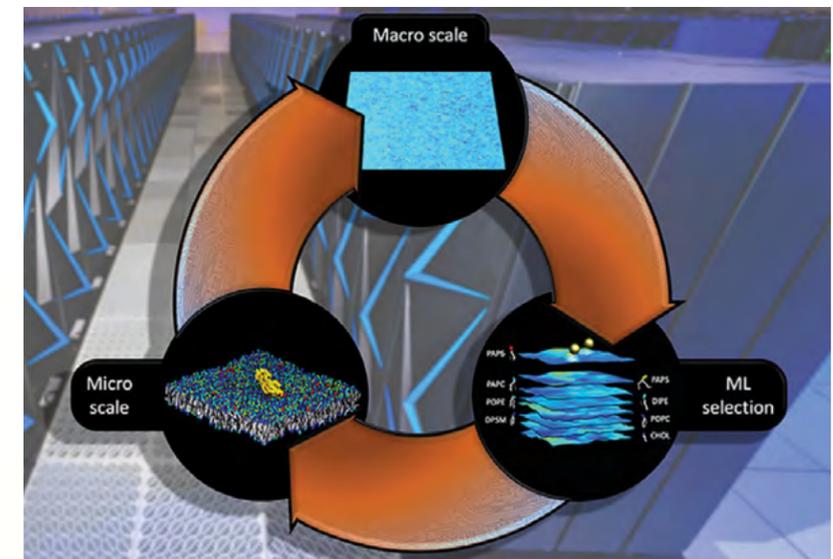empirical data to dramatically improve predictive analysis for complex data-driven problems. Rapidly expanding simulation capabilities are combined with experimental data sets through ML to create "CogSim" models that improve predictability and quantification of uncertainties. Applications range from nuclear security to health care.

An important pioneering application of ML is supporting inertial confinement fusion (ICF) research. Since 2018, LLNL has been developing, testing, and improving ML tools to better predict experimental results. A promising technique, called transfer training, teaches the machine the basics of ICF physics with a very large number of 1D simulations, further trains the model with more costly 2D simulations, and then "corrects" the model through further training with prior experimental results. In support of LLNL's nuclear deterrence mission, ML is also enhancing additive manufacturing capabilities to produce and certify tailor-designed parts. More broadly, the combination of AI and ML promises to accelerate both experimental discovery and concept-to-prototype development.

Health care is prominent among the many other mission areas finding breakthrough applications. As part of the Accelerating Therapeutic Opportunities in Medicine (ATOM) consortium, LLNL leads in applying ML to predict properties of proposed drug molecules, screen them virtually for desired attributes, identify optimal designs, and use experimental feedback to improve the model. In another collaboration, an AI/ML-backed multiscale model simulates the behavior of proteins linked to cancer-causing mutations.

CogSim challenges the Laboratory's supercomputers, which are designed for scientific simulations. The workflow associated with ML training is inefficient. The solution is to integrate an AI accelerator, specifically designed to run an ML model, with the HPC machine. In 2020, LLNL integrated AI accelerators designed by SambaNova Systems and Cerebras Systems with Laboratory supercomputers performing complex scientific simulations. LLNL's cutting-edge work with industry partners tests teaching methods and learning algorithms, explores applications, and improves designs to optimize performance and manage workflow.

The AI3 hub is building on existing industrial collaborations and fostering new ones. Livermore has entered into memoranda of understanding with Google, IBM, and NVIDIA to use the incubator for future collaborations around hardware, software tools, and utilities to accelerate AI for applied science. Other companies, universities, and AI research leaders are being encouraged to join AI3, where early research areas are expected to include advanced material design, 3D printing, predictive biology, energy systems, "self-driving" lasers, and fusion energy research.
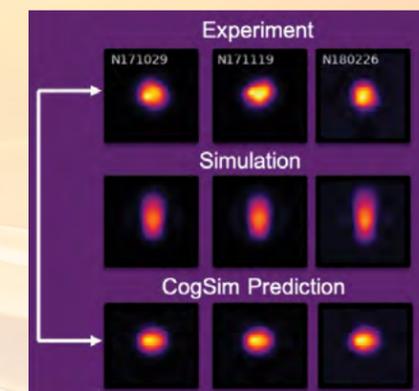
Cognitive simulation models use experimental data to correct simulation predictions. Here, a CogSim model ingests image data from past NIF experiments to make predictions of real experiments.

ACKNOWLEDGMENTS