Target alignment positioner in the National Ignition Facility's target chamber.

Laser glass for the National Ignition Facility.

Nuclear Weapons

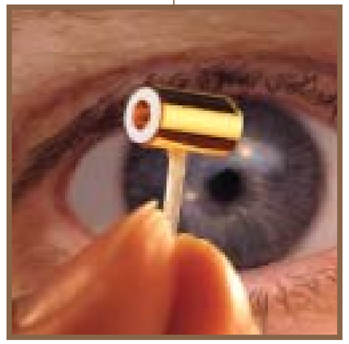
Stockpile Stewardship

Lawrence Livermore National Laboratory was established in 1952 to help ensure national security through the design, development, and stewardship of nuclear weapons. National security continues to be the Laboratory's defining responsibility. Livermore is one of the three national security laboratories that support the National Nuclear Security Administration (NNSA) within the Department of Energy (DOE).

Livermore plays a prominent role in NNSA's demanding Stockpile Stewardship Program for maintaining the safety and reliability of the nation's nuclear weapons. The Stockpile Stewardship Program integrates the activities of the U.S. nuclear weapons complex, which includes Livermore, Los Alamos, and Sandia national laboratories as well as four production sites and the Nevada Test Site. As the nuclear weapons in the stockpile continue to age, Laboratory scientists and engineers must ensure their performance and refurbish them as necessary without conducting nuclear tests.

Working with the other NNSA laboratories, Livermore is attending to the immediate needs of the stockpile through assessments and actions based on a combination of laboratory experiments and computer simulations of nuclear weapon performance. In addition, the Laboratory is acquiring more powerful experimental and computational tools to address the challenging issues that will arise as the nation's nuclear weapons stockpile continues to age. These vastly improved scientific capabilities will also be used by experienced nuclear weapons designers to train and evaluate the skills of the next generation of stockpile stewards.

Rapid-growth, large crystal for National Ignition Facility optics.



Capsule that holds a National Ignition Facility fusion target.

Ambassador Linton Brooks, administrator of the National Nuclear Security Administration, at the Laboratory.

Certifying Stockpile Safety and Reliability

Livermore is a key participant in formal review processes and assessments of weapons safety, security, and reliability. In 2003, the eighth cycle of the Annual Assessment Review was completed. This annual certification of the stockpile was first mandated by the president and is now required by law as a result of congressional legislation enacted in 2002. The formal process is based on the technical evaluations made by the laboratories and on advice from the three laboratory directors, the commander-in-chief of Strategic Command, and the Nuclear Weapons Council. To prepare for this process, Livermore scientists and engineers collect, review, and integrate all available information about each stockpile weapons system, including physics, engineering, chemistry, and materials science data. This work is subjected to rigorous, in-depth intralaboratory review and to expert external review, including formal use of red teams.

For the Annual Assessment Review—and the formal certification of refurbished warheads—weapons experts depend on an extensive range of aboveground testing, vastly improved simulation capabilities, and the existing nuclear test database. Livermore and Los Alamos have developed and are implementing a new methodology, quantification of margins and uncertainties (QMU), that is serving as the basis for formal certification actions. Important decisions at the Laboratory about research and development priorities in support of the Stockpile Stewardship Program are also guided by QMU considerations. The methodology, which entails the development and application of a rigorous set of quantitative standards, is analogous to the use of engineering safety factors in designing and building a bridge. The QMU approach was first applied in Livermore's certification of the design changes to refurbish and extend the life of the W87 ICBM warhead.

Life Extension of the W87 ICBM Warhead and the W80 Cruise Missile Warhead

Livermore's W87 Life Extension Program, begun in late 1994, continues to meet all its major milestones. The program has been a very successful demonstration of stockpile stewardship in the absence of nuclear testing. Refurbishment of the W87 ICBM warhead, the design with the most modern safety features in the stockpile, extends the lifetime of the weapon to beyond 2025. The Laboratory developed and certified the engineering design of the W87 modification through a combination of nonnuclear experiments, flight tests, physics and engineering analyses, and computer simulations.

Refurbished W87 warheads are being delivered to the Air Force after assembly at the Pantex Plant in Texas. The Laboratory is collaborating with the production plants, working to ensure the quality of the W87 refurbishment work while maintaining the targeted production rate. The final unit is scheduled for completion in 2004.

Lawrence Livermore and Sandia national laboratories have also assumed responsibility for the W80 Life Extension Program. In October 2004, the two laboratories will assume responsibility for all currently stockpiled W80 warheads as well. The W80, designed by Los Alamos, is currently deployed in air-launched and sea-launched cruise missiles. An extensive program of experimental and computational activities was performed in 2003 in support of a life extension schedule that calls for completing the first production unit of the refurbished warheads in FY 2008.

Laboratory scientists performed numerous high-resolution, 2D and 3D computer simulations to design and test new components, predict system performance, and prepare for certification of the W80's proposed modifications. The simulations also assisted in the preparation of experiments, and the tests, in turn, provided data to compare with model predictions.

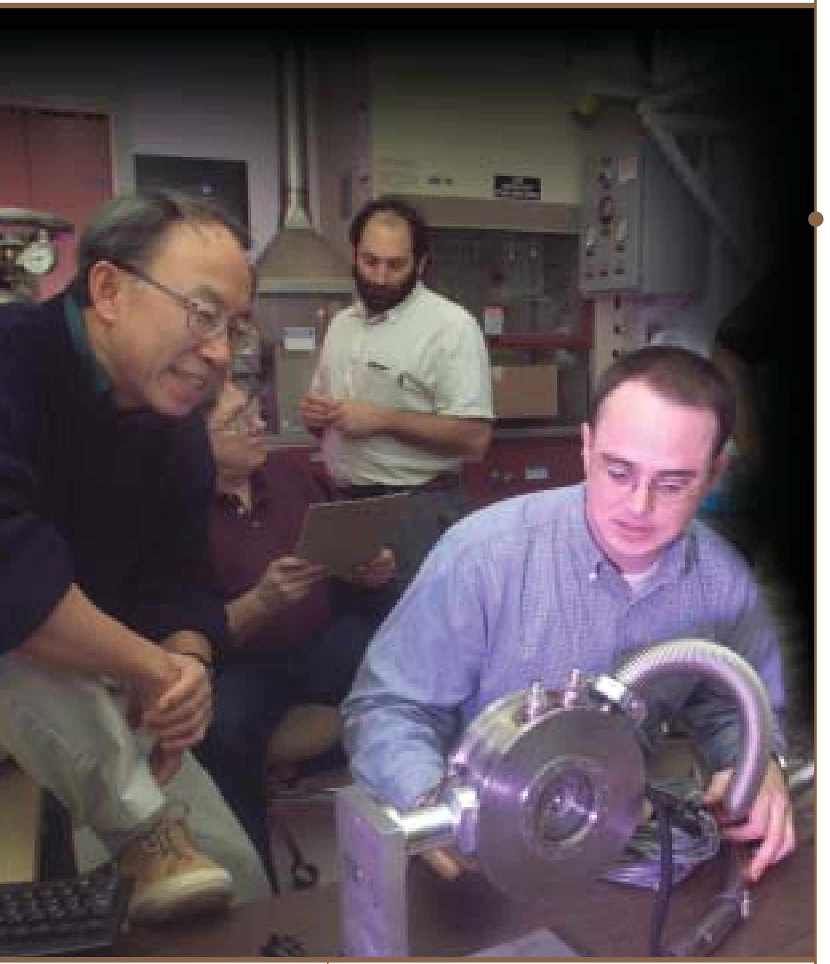
A particularly important part of the W80 Life Extension Program is hydrodynamic testing, in which scientists study the performance of mock weapon primary pits as they are imploded by high explosives. Hydrodynamic experiments are carried out in the Contained Firing Facility at Site 300, the Laboratory's experimental test area 24 kilometers southeast of the main site. The facility's firing chamber is designed to contain the blast (up to 60 kilograms of high explosive) and minimize the environmental consequences in repetitive tests. Hydrodynamic tests performed in 2003 for the W80 program showed impressive agreement with the predictions provided by computer simulations.

Experiments to Better Understand Plutonium

A research team led by Livermore scientists conducted landmark experiments that promise to reveal much about the physics and material properties of plutonium. Plutonium is an extremely complex material, and it is critically important to the functioning of

W80 test unit.

Inside the Contained Firing Facility.



Plutonium phonon research team.

JASPER gas gun.

nuclear weapons. Comprehending the detailed properties of plutonium metal and alloys is one of the major scientific challenges in the Stockpile Stewardship Program. As the plutonium in deployed weapons grows older, the effect of aging-related changes on weapon performance must be thoroughly understood.

As reported in *Science*, the research team fully mapped the phonons in an alloy of plutonium—gallium-stabilized delta plutonium—for the first time. Phonons are lattice vibrations produced by the movement of atoms in a solid. Their variations along different directions in a crystal, called phonon dispersion curves, describe how atoms move within a solid. These data are key to understanding many of plutonium's physical and structural properties.

Plutonium and its alloys have defied phonon measurements for the past 40 years, in part because the conventional method for mapping the data requires the growth of large single crystals. Instead, the team was able to obtain the data by focusing a micro-beam from an extremely bright x-ray synchrotron source on a single grain of plutonium alloy. The work was performed at the European Synchrotron Radiation Facility in Grenoble, France. Researchers at that facility and the University of Illinois at Champaign-Urbana were part of the team.

Livermore scientists are also investigating the properties of plutonium at extreme conditions—high temperatures, pressures, and strain rates. In July 2003, the first experiment with a plutonium target was conducted at the Joint Actinide Shock Physics Experimental Research (JASPER) Facility at the Nevada Test Site. Livermore took the lead for NNSA in constructing JASPER and bringing it into operation. This multi-laboratory user facility is designed to accommodate experiments to study uranium, plutonium, and other hazardous materials.

JASPER is a nearly 30-meter-long, two-stage gas gun that accelerates a projectile to speeds of up to 8 kilometers per second. The impact of the projectile produces an extremely high pressure shock wave in the targeted material. High-speed diagnostics gathered precise data about the equation-of-state of shocked plutonium in the first experiment, which used a tantalum projectile fired at 5 kilometers per second. Three tests were completed in 2003, and about 24 tests per year are planned for the future.

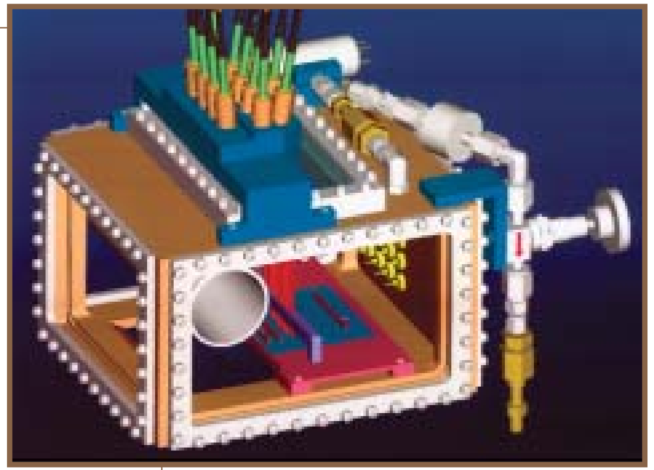
These gas-gun experiments are augmented by high-static-pressure (diamond-anvil) experiments at the new high-pressure beam line at Argonne National Laboratory's Advanced Photon Source as well as subcritical tests conducted in an underground tunnel at the Nevada Test Site. Diamond-anvil cell experiments supplied information about the crystal structure of the high-pressure phase of plutonium and led to the discovery of a new phase of this element. The highly instrumented subcritical tests provide data on the behavior of plutonium when it is strongly shocked with explosives and show how that behavior depends on the plutonium's age. In September 2003, the Laboratory conducted a highly successful subcritical experiment named Piano.

From Construction Project to Experimental Facility

Major progress continues to be made on construction of the National Ignition Facility (NIF). Upon completion in 2008, NIF's 192-beam ultraviolet laser system will be used to compress fusion targets to conditions required for thermonuclear burn, liberating more energy than that required to initiate the fusion reactions. Other NIF experiments will study physical processes at temperatures approaching 100 million degrees and 10 billion atmospheres, conditions that exist naturally only in the interior of stars and planets and in exploding nuclear weapons. These temperatures and pressures are needed to validate weapons-physics computer codes and address important issues of stockpile stewardship. Experiments on NIF will also evaluate the feasibility of inertial fusion energy, a long-standing program goal within DOE. In addition, NIF will allow laboratory studies of astrophysics and materials under conditions similar to those found in stars.

The project continues to meet its cost and schedule milestones. With the September 2003 completion of installation of beam-path infrastructure for all 192 laser beams, the NIF laser system is ready for the installation of the hundreds of precision optical and opto-mechanical assemblies—called line replaceable units (LRUs)—that make up each laser beam. Altogether more than 7,500 large precision optics and more than 26,000 small optical components are being assembled into the LRUs and installed in each beam line. Laboratory scientists and engineers are working in partnership with the optics industry to implement production processes for manufacturing NIF's precision optics.

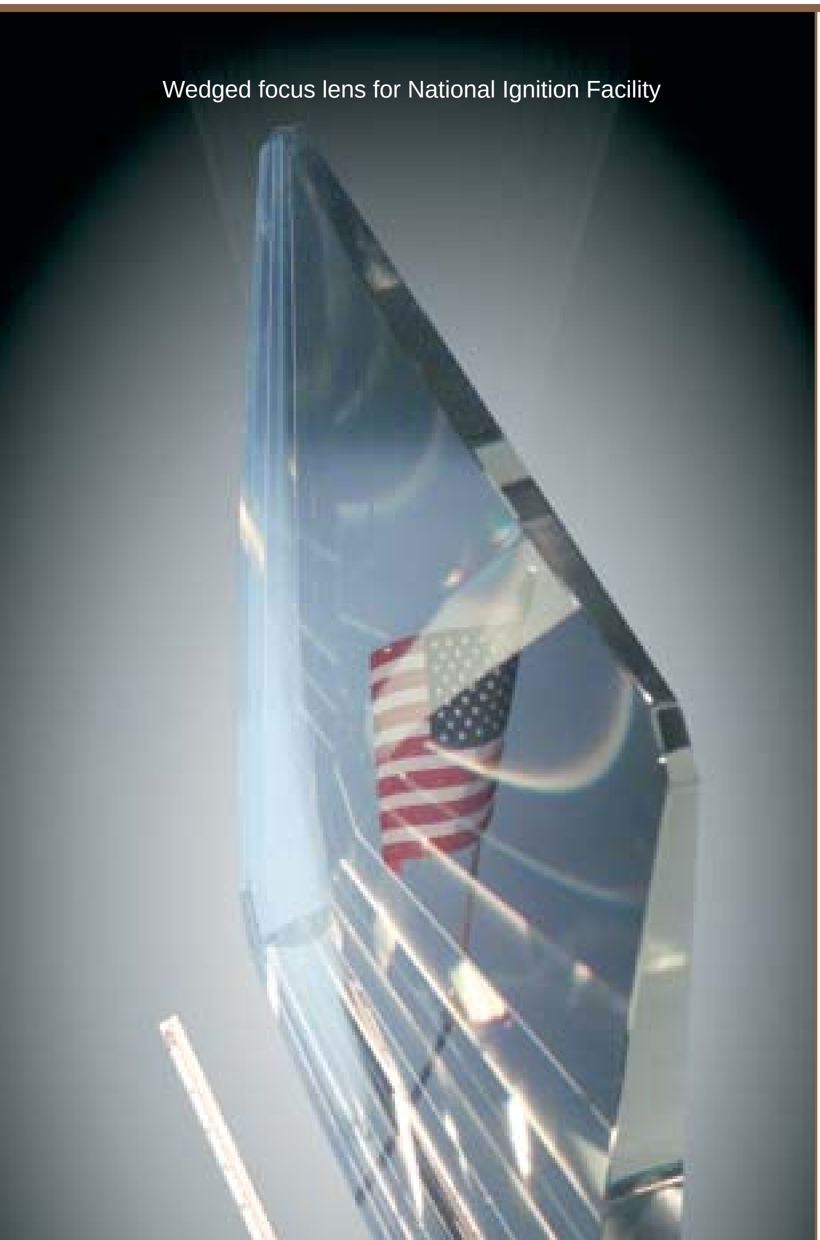
A key event for the transformation of NIF from a construction project to an experimental facility was activation of the first four laser beams, called a quad, in December 2002. This goal—NIF Early Light—was established in 2001 to provide early demonstration that the integrated laser system works and to



Simulation of experimental setup for the Piano test.

Laser beams travel to the target chamber through these enclosures in one of the National Ignition Facility's two laser bays.

National Ignition Facility.

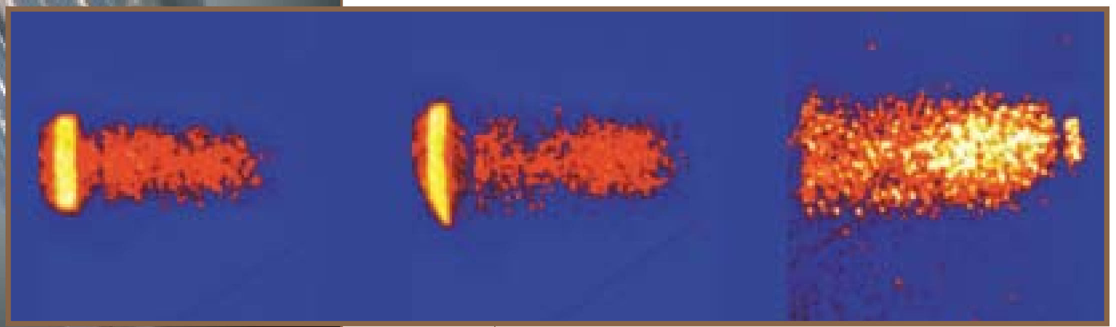

Wedged focus lens for National Ignition Facility

expedite the start of NIF's experimental program. In May 2003, 10.4 kilojoules (kJ) of ultraviolet light were produced in a single laser beam line, setting a world record for laser performance. In subsequent shots, NIF set single-beam-line energy records for infrared and green light (26 kJ and 11 kJ, respectively). With just 4 of its 192 beams in operation, NIF is already the highest energy infrared laser in the world.

Laser beam quality on NIF meets performance criteria for beam energy, beam output, uniformity, beam-to-beam timing, and delivery of shaped pulses. Overall, the NIF laser system has demonstrated ultraviolet laser energy equivalent to 2 million joules (MJ) in all 192 beams, which exceeds the specified design requirement of 1.8 MJ. In addition, the functioning of the first laser quad successfully tested almost all of the critical systems in NIF including laser components and optics, the laser beam path and supporting utilities, the power conditioning system, diagnostics, and computer controls.

After achieving Early Light and demonstrating key aspects of NIF's laser performance, the project team transported the beams to the final optics mounted on NIF's 10-meter-diameter target chamber. The final optics convert the infrared laser light to ultraviolet light and focus it precisely to the center of the chamber, which is kept under vacuum. Laser performance and physics experimental campaigns are now regularly conducted using the first diagnostics mounted on the target chamber. By the end of 2003, more than 200 full-system shots had been fired.

In August 2003, scientists performed the first set of physics experiments at NIF. Ultraviolet light from NIF's first quad of lasers was precisely aimed at millimeter-sized, gas-filled targets in the center of the target chamber. The experiments were fielded to study the interaction of intense laser beams with low-atomic-number gases such as carbon dioxide. The first of NIF's sophisticated experimental diagnostics were used to measure the x rays produced. Preliminary results were presented at the Third International Conference on Inertial Fusion Sciences and Applications, in Monterey, California, in September. The conference was hosted by the University of California and Livermore.

Laser–plasma interaction experiment at the National Ignition Facility. The target used is at the left.

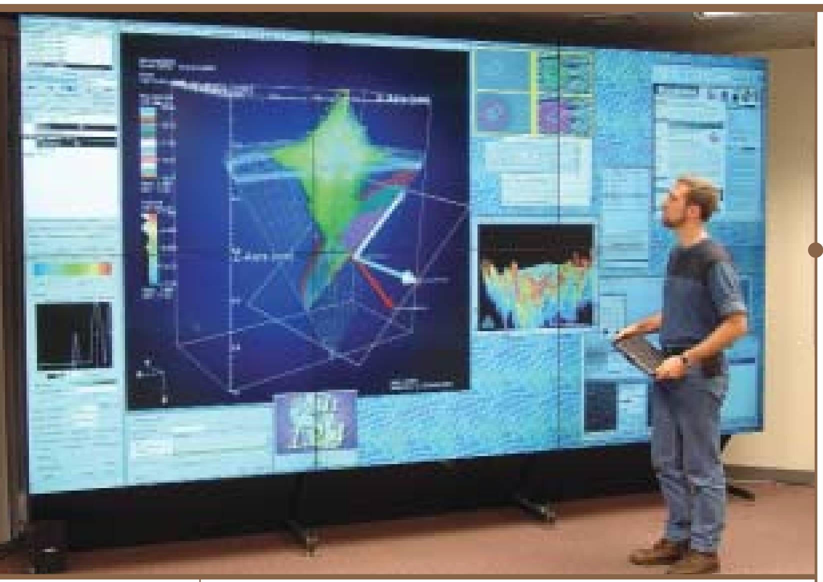

Inside the National Ignition Facility target chamber (photo courtesy of *National Geographic*).

Advances in High-Energy-Density Physics and Future NIF Experiments

Laboratory scientists are making significant advances in high-energy-density physics through computer simulations and experimental research at a number of laser and pulsed-power facilities in the U.S. and around the world. Their work is leading to imaginative ways to use the NIF facility more effectively—beyond what was conceived when the NIF project began. Many exciting proposals are emerging for high-energy-density physics experiments, and researchers are exploring ways to make NIF an even more capable facility. For example, shorter pulses on NIF, using special optical systems to generate picosecond pulses, can provide an enhanced x-radiography capability, which is important for diagnosing high-density and high-atomic-number experiments on NIF.

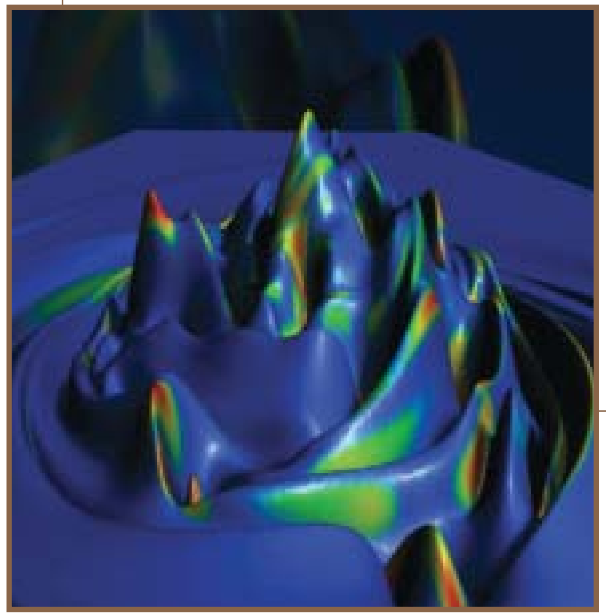
Livermore scientists are performing groundbreaking research using short-pulse, high-power lasers. In 2003, the JanUSP laser at Livermore was used to create a focused beam of high-energy protons that could rapidly heat targets for equation-of-state experiments. Configuring some NIF beam lines to function as ultra-short-pulse lasers would make such experiments possible as well as high-energy (10-kiloelectronvolt to 1-megaelectronvolt) x-radiography and high-energy (50-megaelectronvolt) proton radiography. These capabilities would allow experimentalists to study much denser and higher atomic number targets with NIF.

Computational modeling of ignition in laser fusion capsules has led researchers to suggest operating NIF's lasers in multiple colors (green and ultraviolet) instead of just one color (ultraviolet). This option would allow even higher energies to be directed onto targets, which could be advantageous for higher gain fusion yields and for stockpile stewardship experiments on materials. In 2003, a Laboratory researcher who performed studies on optimizing NIF ignition targets at green and ultraviolet wavelengths was awarded a prestigious Edward Teller Medal for his work (see p. 44).



A power wall visualization of a 3D simulation.

ViSUS view of vortical flow simulation.



Improved Algorithms for and Visualization of 3D Simulations

The 3D physics simulations that Livermore scientists run in support of the Stockpile Stewardship Program require supercomputers performing in the range of teraops (trillions of operations per second). These computers are acquired through the Advanced Simulation and Computing (ASC) Program, previously known as the Accelerated Strategic Computing Initiative, or ASCI. ASC is the NNSA's vehicle for advancing scientific supercomputing so scientists can make much more realistic physics and engineering simulations of the performance of an aging nuclear weapons stockpile. At 12 teraops, ASCI White is the Laboratory's largest classified machine supporting stockpile stewardship, and greater capabilities are coming soon.

More than requiring just large machines, better simulations also depend on the development of computer algorithms that run efficiently on massively parallel computers. Sophisticated data management tools are essential for preparing problems and analyzing the enormous amount of information generated.

The Scalable Linear Solvers (SLS) project at Livermore is developing fast, parallel, multigrid algorithms and software for solving large, sparse linear systems of equations. This work, supported by both the ASC Program and the DOE Office of Science's Mathematical, Information, and Computational Sciences Program, is dramatically improving the capabilities of codes. The objective is to make simulations run faster and at much higher resolution. For example, new algorithms made possible the largest-ever ALE3D calculations in 2003. Used for large 3D structural dynamics simulations, ALE3D solved for 610 million unknowns, using 4,032 processors of the ASCI White supercomputer. This calculation is 100 times larger than the simulations of only three years ago, using just 10 times the number of processors.

To interpret the results of simulations, scientists turn to such software tools as Visualization Streams for Ultimate Scalability (ViSUS), developed at the Laboratory. ViSUS gives researchers full control over visualization parameters so they can explore and interact with their data in ways that are most useful to them. ViSUS supported a study of the mixing of two dissimilar liquids and led to the production of an award-winning video, "Visualizations of the Dynamics of a Vortical Flow," which can be viewed at www.llnl.gov/icc/sdd/img/images/aps02.mov.

The World's Most Powerful Computers

Construction of the $91-million Terascale Simulation Facility (TSF) will be completed in October 2004, on budget and over a year ahead of schedule. The TSF, an ASC facility, encompasses 253,000 square feet, including 48,000 square feet of raised computer floor. The facility also includes visualization theaters and laboratories to study the extremely large data sets produced by ASC scientists. The building will house more than 250 staff, primarily in secure work areas. Computer center staff expect to move into the building in November 2004. Two new computers, Purple and BlueGene/L, will be delivered the following year.

Purple is designed and built by International Business Machines (IBM) Corporation. This machine will be the world's most powerful production computer operating at 100 teraops. ASC Purple will enable 3D simulations with high-fidelity physics models of the performance of a full nuclear weapon system. It will help to meet critical stockpile stewardship deliverables—in particular, for life extension programs. The supercomputer will be powered by 12,288 microprocessors in 1,536 individual nodes, each node consisting of eight processors interconnected via two high-performance Federation switches. The system will also have 50 terabytes (trillion bytes) of memory, over 2 petabytes (quadrillion bytes) of disk storage, and 122 gigabytes per second of delivered input/output bandwidth. This machine is currently planned to run critical benchmarks at IBM in June 2005 and will be delivered in July 2005.

BlueGene/L will be delivered in stages during the first half of 2005. This IBM research computer is an innovative, scalable supercomputer based on low-power-consuming, "system-on-a-chip" technology. With 65,536 nodes, BlueGene/L will have a peak performance of 180 to 360 teraops. This machine will draw significantly less power than Purple (2 MW versus 7.5 MW) even though its peak speed is far higher. BlueGene/L will be used to explore properties of materials from atomic to engineering scales. Such work is expected to increase understanding of weapons physics and accelerate the development of better models of materials in weapons. These models would subsequently be incorporated into and improve the ASC weapons simulation codes that are run on production machines such as Purple. In addition, experience gained working with BlueGene/L could define a path to affordable petaops (quadrillion ops) computing in the 2007 to 2009 timeframe.

Terascale Simulation Facility.

Enrico Fermi Award for Seymour Sack

Seymour Sack, a Livermore physicist, earned an Enrico Fermi Award in 2003 "for his contributions to the national security of the United States." During his 35 years at the Laboratory, Sack emerged as one of the foremost U.S. nuclear weapons designers. His weapon-design programs introduced insensitive high explosives, fire-resistant plutonium pits, and other state-of-the-art nuclear safety elements into the nuclear weapons stockpile. Concepts developed by Sack are found in all U.S. nuclear weapons—designs from both Livermore and Los Alamos. The Fermi Award was presented by DOE Secretary Spencer Abraham on behalf of President Bush. It recognizes scientists of international stature for lifetimes of exceptional achievement in the development, use, or production of energy.