April/May 2009

Science & Technology Review

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Powering the Future with LIFE

Also in this issue:

- National Ignition Campaign Begins
- Simulating Conflict Scenarios
- Neutron Detection in the Field
- Building a Better Catalyst

About the Cover

A fusion-based engine called LIFE (Laser Inertial Fusion Energy) has the potential to revolutionize our energy future. As the article on p. 6 describes, LIFE offers a pathway toward a fusion-based energy economy and sustainable, safe, carbon-free electrical power. LIFE's engine design will build on the success of ignition at the National Ignition Facility (NIF), which will be dedicated on May 29, 2009. On the cover, an artist's composite image depicts the relationship between NIF and LIFE. The composite consists of a NIF target holder (bottom center), a target capsule (lower left), the NIF target chamber (lower right), and global energy (upper right and center).

Cover design: George A. Kitrinos. Cover illustration: Brian A. Chavez.

About the Review

At Lawrence Livermore National Laboratory, we focus science and technology on ensuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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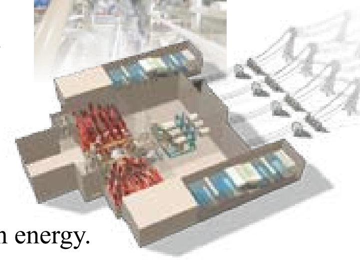

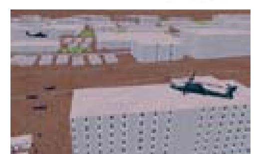

Research Highlights

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Long-Standing Astronomy Mystery Solved

Scientists from Lawrence Livermore and the University of California (UC) at Santa Cruz and UC Berkeley may have solved a long-standing mystery concerning the growth of massive stars—those with mass up to 120 times that of the Sun. Massive stars produce so much light that the radiation pressure they exert on the gas and dust around them is stronger than their gravitational attraction. Previous theoretical studies have indicated that accretion—growth by gravitationally attracting more matter—should limit star mass to about 20 times that of the Sun, but astronomers have discovered stars well above that size. The three-dimensional radiation hydrodynamics simulations developed by the Livermore–UC collaboration are helping explain this discrepancy.

Using the ORION code, the team simulated the collapse of an enormous interstellar gas cloud over a virtual period of 57,000 years. Results showed that gravitational instabilities channeled gas onto the disk-shaped star system through filaments, allowing the radiation to escape through optically thin bubbles. As the simulated system evolved, a secondary star became large enough to break away and acquire its own accretion disk, growing into a massive companion star. Another small star formed and was ejected into a wide orbit before falling back and merging with the primary star. These two stars, which had masses of 41.5 and 29.2 times that of the Sun, circled each other in a fairly wide orbit.

The Livermore–UC collaboration received funding from the National Science Foundation, the National Aeronautics and Space Administration, and the Department of Energy. The team's research results appeared in the February 6, 2009, issue of *Science*.

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Comprehensive Review of Actinide Research

Laboratory researcher Kevin Moore and his collaborator Gerrit van der Laan at the Diamond Light Source in the United Kingdom have refined decades of actinide science research in the February 6, 2009, issue of *Reviews of Modern Physics*. Their paper, "Nature of the 5*f* States in Actinide Metals," describes the electronic, magnetic, and crystal structure of these radioactive metals.

Actinides encompass the 15 chemical elements that lie between actinium and lawrencium on the periodic table. Atomic numbers for this series range from 89 to 103. The 5*f* states refer to electrons in the thin outer shell called 5*f*. The complicated wave functions exhibited by electrons in the 5*f* shell produce unusual physical behaviors in the actinide series.

Theoretical work on the actinides is substantial. However, few experiments have been performed because the toxic materials are difficult to handle and thus expensive to work with. As a result, researchers do not have the experimental data needed to validate theoretical calculations. "The actinide series as a whole is modestly understood," says Moore, "and the level of comprehension decreases as atomic number increases."

Moore and van der Laan sifted through decades of theoretical and experimental research and condensed the data. Their definitive article explains the progress scientists have made in understanding the electronic structure of actinides in the 5*f* states and demonstrates the importance of actinide science to a broad range of researchers in such fields as stockpile stewardship, nuclear nonproliferation, and nuclear fuel sources.

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Collaboration to Improve Wind-Energy Forecasting

Lawrence Livermore has signed a two-year, $2 million cooperative research and development agreement with Siemens Energy, Inc., to use the Laboratory's high-resolution atmospheric modeling capabilities for improving wind-energy forecasts. Under this agreement, Livermore researchers will develop numerical weather-prediction models that combine atmospheric turbulence calculations with complex databases of topography and sea-surface temperature. The resulting simulations will predict how wind conditions will affect power generation and in turn allow operators to increase wind-farm production.

Many U.S. wind farms are yielding up to 20 percent less energy than predicted because of uncertain forecasts. This loss of energy can have complicated financial consequences. For example, operators may be penalized when their farms produce less energy than estimated and may receive no payment for power generated above an estimate. More accurate wind predictions hours or even days ahead of time would significantly increase the efficiency of wind-farm operations.

Atmospheric scientist Julie Lundquist leads the wind-forecasting project, which began with funding from Livermore's Laboratory Directed Research and Development Program. "Our improved methods for simulating the turbulent properties of the lower atmosphere should translate into a significant predictive advantage for wind-energy applications," says Lundquist. More accurate predictions could also reduce the investment risks in wind-powered projects, improve the design of tall wind turbines so they can withstand the increased turbulence higher in the atmosphere, and enable optimal bids on wind-farm production.

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Leveraging the National Ignition Facility to Meet the Climate–Energy Challenge

On May 28 and 29, Lawrence Livermore National Laboratory will be hosting distinguished visitors from around the world for the dedication of the National Ignition Facility (NIF). Completion of the facility and commissioning of NIF's 192 laser beams is a pivotal event in the long march from the invention of the laser 50 years ago to the use of lasers to produce energy through a process called inertial confinement fusion (ICF).

Experiments are about to begin in which NIF's 192 laser beams will implode a peppercorn-size capsule filled with deuterium and tritium, two isotopes of hydrogen. Compressed to a density greater than that of lead and heated to a temperature of 100 million kelvins, the deuterium and tritium will fuse, releasing more energy than was used to implode the fuel. Fusion ignition and energy gain will be an unprecedented technical accomplishment with far-reaching societal ramifications.

The article beginning on p. 6 discusses Laser Inertial Fusion Energy, or LIFE, which ignition on NIF will make possible. LIFE is a concept to help solve an enormous 21st-century problem: the combination of global warming and the increasing demands for clean energy worldwide. Carbon-emission-free sources of energy are urgently needed to replace current carbon-emitting sources and to support economic growth around the globe—in emerging nations, states with a burgeoning middle class, and fully modernized countries such as our own. Currently, no clear-cut solution exists. Investments in carbon-free energy technologies, such as LIFE, are needed to develop workable, affordable medium- and long-term options.

Advances in laser and fusion technologies—realized in NIF—make technically possible the concept of using high-energy neutrons from fusion reactions to generate electricity from fusion and to burn fissile material, such as spent nuclear fuel from fission reactors, natural uranium, and depleted uranium, to also create energy. Since the 1950s, eminent scientists have discussed a fusion–fission hybrid. Today, NIF researchers are close to ignition and poised to demonstrate key technologies required to make LIFE a reality.

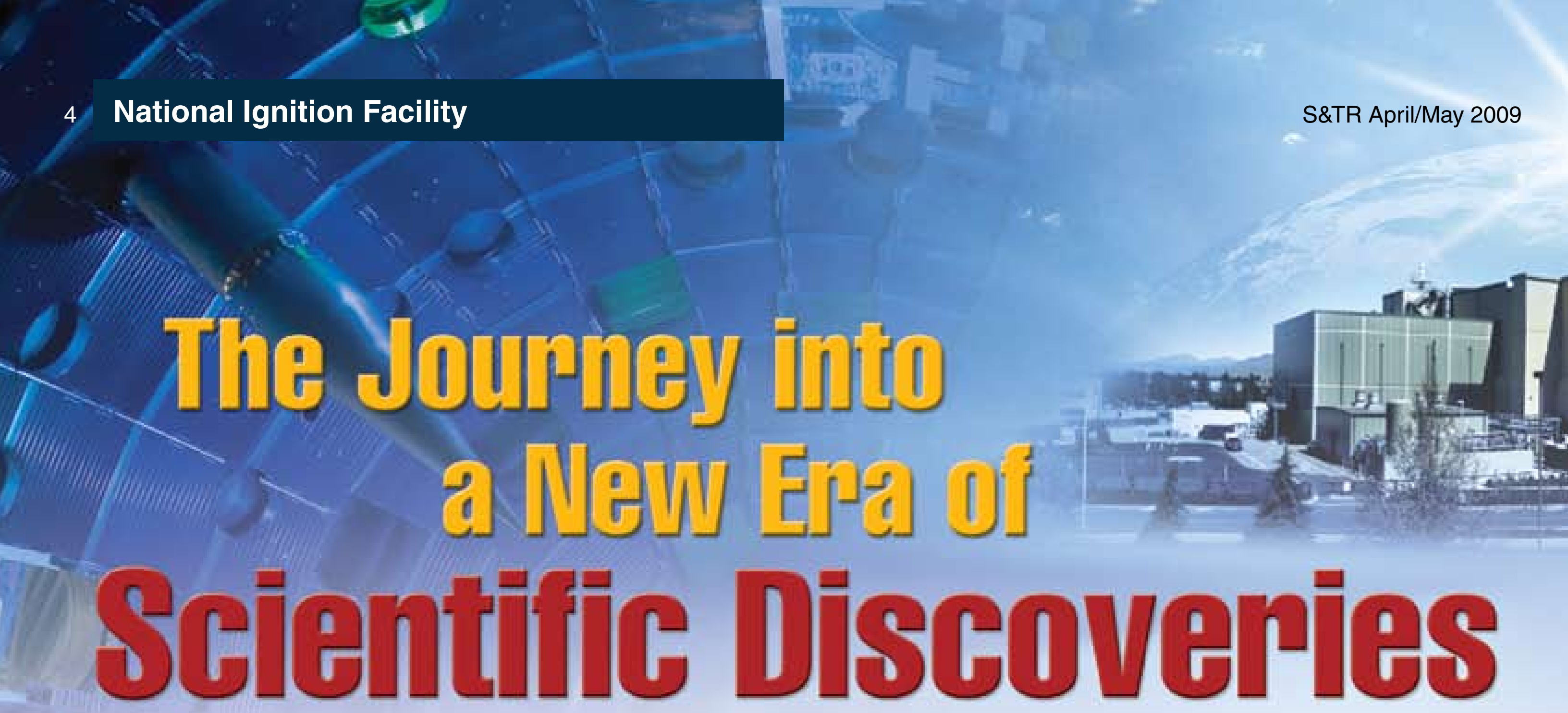
By 2100, LIFE engines could be powering a substantial part of the U.S. and worldwide energy grid and supplying hydrogen fuel for transportation, while generating far less radioactive waste than current nuclear plants. The laser in a LIFE power plant would fire many times per second and generate gigawatts of power for 40 years or longer without refueling. These LIFE engines could significantly reduce the amount of spent nuclear fuel awaiting long-term storage. Spent reactor fuel and depleted uranium, now considered waste, would be fuel for the LIFE engine. LIFE could supply U.S. electricity needs for more than 1,000 years by burning these two waste materials.

The design of a LIFE engine is passively safe because no "critical mass" of nuclear materials would be present. It also would produce no carbon dioxide emissions. Furthermore, LIFE eases nuclear proliferation concerns by eliminating the need for uranium enrichment and disposing of long-term nuclear waste as it produces power.

After fusion ignition and gain are demonstrated on NIF, several critical technological advances—judged by Laboratory scientists to be achievable in the relatively near term—are needed for the first LIFE pilot plant.

The pursuit of LIFE to address one of this century's most pressing issues poses technical challenges, which are discussed in the article, yet offers huge benefits from success. It is the type of challenge that is appropriate for a multidisciplinary national laboratory, in cooperation with other national laboratories and U.S. industry, and which, over the years, has brought out the best from the staff at Lawrence Livermore. Our innovative advances in science and technology began with the design of a compact thermonuclear warhead for the Polaris submarine in the 1950s and have continued through today with incredible breakthroughs. Many were thought not possible, and yet we have succeeded—in supercomputing, for example, and in the construction of NIF, which produces a factor-of-60 higher energy than any other laser. LIFE continues Lawrence Livermore's long-standing tradition of scientific innovation, technological creativity, and bold thinking.

■ George H. Miller is director of Lawrence Livermore National Laboratory.



The Journey into a New Era of Scientific Discoveries

THE National Ignition Facility (NIF), the world's largest laser, will be dedicated on May 29, 2009. The facility was designed and built to achieve fusion ignition and energy gain in a laboratory setting—a major scientific achievement with far-reaching benefits for humankind. NIF will serve as a unique national resource for sustaining confidence in the U.S. nuclear weapons arsenal, pursuing options for nearly limitless sources of clean energy, and exploring the science of most of the known matter in the universe.

NIF has been the largest scientific-facility construction project in the U.S. With about 7,500 meter-scale and 26,000 small optical components, the stadium-size laser facility required Laboratory scientists and engineers to make many enormous leaps in technology. The result is a laser system capable of producing 1.8 million joules of ultraviolet light—60 times more energy than any previous laser.

The energy will be delivered to the center of a 10-meter-diameter, 1-million-pound target chamber. NIF's 192 beams produce a 10-nanosecond pulse aimed with 50-micrometer accuracy and precisely shaped in time. In inertial confinement fusion (ICF) experiments, the target is a peppercorn-size capsule filled with deuterium and tritium (DT) fuel inside a small can, called a hohlraum, with openings at the ends to admit laser light. In an instant, the fuel will be imploded and compressed to nearly 100 times the density of lead and a temperature of 100 million kelvins. Fusion of the DT will release more energy than delivered by the laser.

Ground was broken for NIF 12 years ago. Design and development of the laser systems and components, construction of the facility, assembly and installation of equipment, and commissioning of the lasers have been a massive effort. Success would not have been possible without the dedication and enormous effort of people from virtually every directorate within the Laboratory, the work of more than 1,000 industrial partners, and the many contributions from other research institutions in this multilaboratory project. Leaders in the executive branch and Congress recognized the importance of NIF, and have provided strong support for NIF construction and now the National Ignition Campaign.

The journey to NIF's dedication began about 50 years ago with two nearly coincidental events. At Livermore, scientists were interested in the peaceful use of nuclear explosions and the possibility of using a series of explosions as a source of electric power. John Nuckolls, later to become Laboratory director, focused on the question, "How small a nuclear explosion is possible?" In June 1960, he calculated that ignition and efficient burn of about 1 milligram of DT might be possible, yielding about 50 megajoules of energy. But what was needed was a precise, extremely powerful nonnuclear driver to power the tiny implosion. In July 1960, the Hughes Research Laboratory in Malibu, California, announced that Theodore Maiman had won the race to build the first laser. The idea of the laser—then called an optical maser—had been proposed by Arthur L. Schawlow and Charles Townes in a 1958 paper.

In 1962, the Laboratory launched a laser-fusion project. Within a few years, work begun to focus on the use of neodymium-doped glass lasers. In the early 1970s, the effort rapidly expanded,


(a)

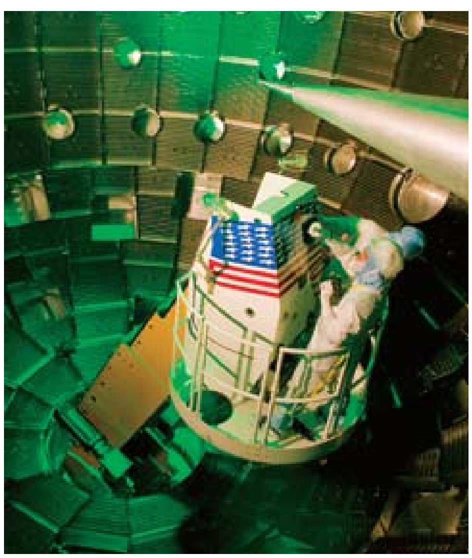

(b)

and Livermore moved to "front stage" in ICF research. The concept of ICF became much more widespread within the technical community with publication in 1972 of the groundbreaking paper in *Nature* by John Nuckolls and collaborators on fusion ignition of a bare sphere of DT. In 1971, Carl Haussmann convinced the Atomic Energy Commission to build a 10-kilojoule laser for ICF research (the future Shiva), and he recruited outstanding young laser scientists to be part of the effort.

Laboratory researchers built the Janus, Argus, and Cyclops sequence of lasers, which led to the 20-beam Shiva, Livermore's first large ICF research laser. The rapid learning process benefited from two factors that have been behind the Laboratory's many successes in ICF research. First, research on ICF targets and lasers has always integrated theory, thoroughly diagnosed experiments, simulations using the most advanced computers of the day, and precision and systems engineering. Second, industries were included as partners in technology development to ensure that laser components, especially precision optics, could be manufactured with high quality and at affordable costs.

One of the lessons learned from these 1970s laser systems is that use of light at higher (ultraviolet) frequencies was necessary to succeed at ignition. Constructed in the 1980s, the 10-beam Nova laser was the first high-energy glass laser that included optical elements to convert infrared light to ultraviolet. Nova experiments performed in the early 1990s using 40 to 50 kilojoules of ultraviolet light provided confidence that a 1- to 2-megajoule ultraviolet laser would be able to achieve ignition and energy gain. Conceptual planning for NIF began.

The NIF dedication is the culmination of a long and exciting journey. A new, even more exciting one is about to begin. As a unique resource for exploring high-energy-density physics, NIF offers the promise of helping to resolve key issues about nuclear weapons performance, providing a pathway to clean energy (see p. 6), and creating opportunities for exciting scientific discoveries about the universe.



(a) Then Energy Secretary Federico Peña joined Laboratory Director Bruce Tarter and Congresswoman Ellen Tauscher on May 29, 1997, to break ground for the National Ignition Facility (NIF). (b) California Governor Arnold Schwarzenegger (left) is briefed by Ed Moses, principal associate director of NIF, while on a tour of the laser facility in November 2008. (c) In the 1970s, fusion fuel was compressed to about the density of lead in the Shiva target chamber. (d) In the NIF target chamber, fuel will be imploded and compressed to nearly 100 times the density of lead and a temperature of 100 million kelvins.

Safe and Sustainable Energy with LIFE

A laser-based fusion system could supply a considerable fraction of the nation's—and the world's—carbon-free electricity needs.

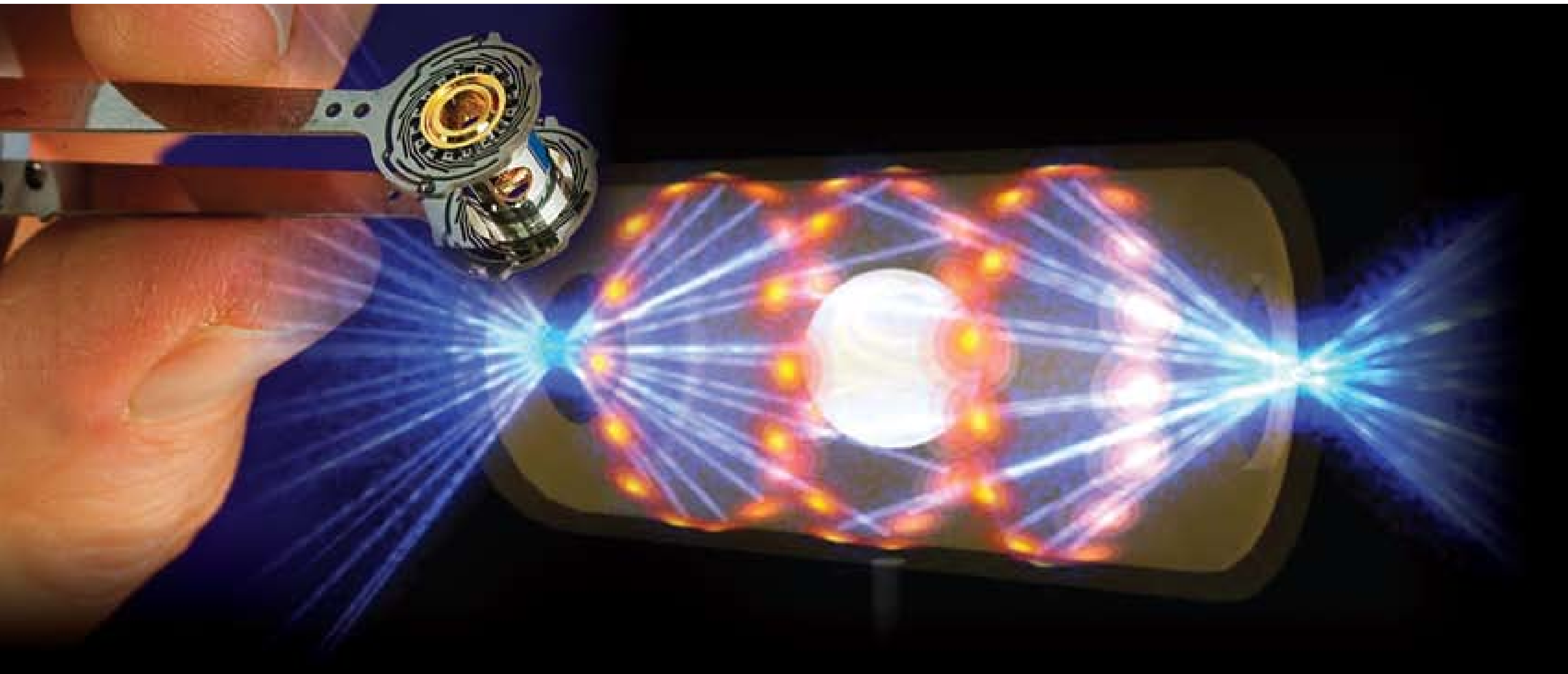
THE planet faces a tremendous challenge this century to close the gap between projected energy demand and the supply of sustainable, carbon-free, affordable energy. Today, 80 percent of the world's total primary energy demand is met with fossil fuels, which emit significant quantities of carbon dioxide (CO_2), a greenhouse gas, into the atmosphere. This situation has implications both for our geopolitical energy security as well as for the global climate and ecosystem.

Energy experts say the global energy system cannot be "de-carbonized" and the climate cannot be stabilized without an energy technology revolution and breakthrough concepts. For their part, Livermore researchers are exploring the idea of a fusion-based system known as Laser Inertial Fusion Energy, or LIFE.

LIFE builds on technology developed for the National Ignition Facility (NIF) and promises safe, carbon-free, and sustainable energy. LIFE offers many compelling advantages, either as a pure fusion energy source or as one that combines the best aspects of fusion and fission energy systems.

According to Ed Moses, principal associate director of NIF and Photon Science, a LIFE power plant is a logical evolution of NIF, which is now operational, and will be dedicated on May 29, 2009. It is the world's largest and highest energy laser

Ignition experiments with the National Ignition Facility (NIF) will culminate decades of inertial confinement fusion research and development, opening the door to previously inaccessible physical regimes and making possible a fusion-based power plant called LIFE (Laser Inertial Fusion Energy).



Above left, a fully assembled ignition target incorporates a capsule assembly, hohlraum, and a surrounding thermal-mechanical package with silicon cooling arms. An artist's rendering shows a 9-millimeter-long hohlraum with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. NIF's computer control system (below) precisely synchronizes thousands of components. On the next page is the main NIF facility.

and the cornerstone experimental facility for stockpile stewardship, the National Nuclear Security Administration's program to assure the safety and reliability of the U.S. nuclear weapons stockpile. The largest single scientific project ever successfully completed by the Department of Energy (DOE), NIF culminates nearly 50 years of research in inertial confinement fusion and high-energy-density science.

In the next few years, experiments on NIF are expected to demonstrate, for the first time, inertial confinement fusion and energy gain, in which more energy is released from a 2-millimeter-diameter target filled with deuterium–tritium fuel than is deposited by NIF's 192 laser beams. With preparations for the first laser fusion experiments well under way, Livermore researchers have been exploring the revolutionary concept of an electrical power plant that is a logical extension of NIF and the knowledge it will generate from planned ignition experiments.

The LIFE design starts with a 10- to 20-megawatt (MW) high-average-power laser system that produces fusion reactions at 10 to 15 times per second. As in NIF, multiple LIFE laser beams will precisely converge on deuterium–tritium fusion targets, producing 350 to 500 MW of fusion energy. The pulsed fusion reactions will produce high-energy neutrons, which then bombard a spherical blanket containing a high-heat-capacity lithium-based molten salt that can convert the energy of the neutrons into heat to produce either steam or another hot gas that will be used to generate electricity.

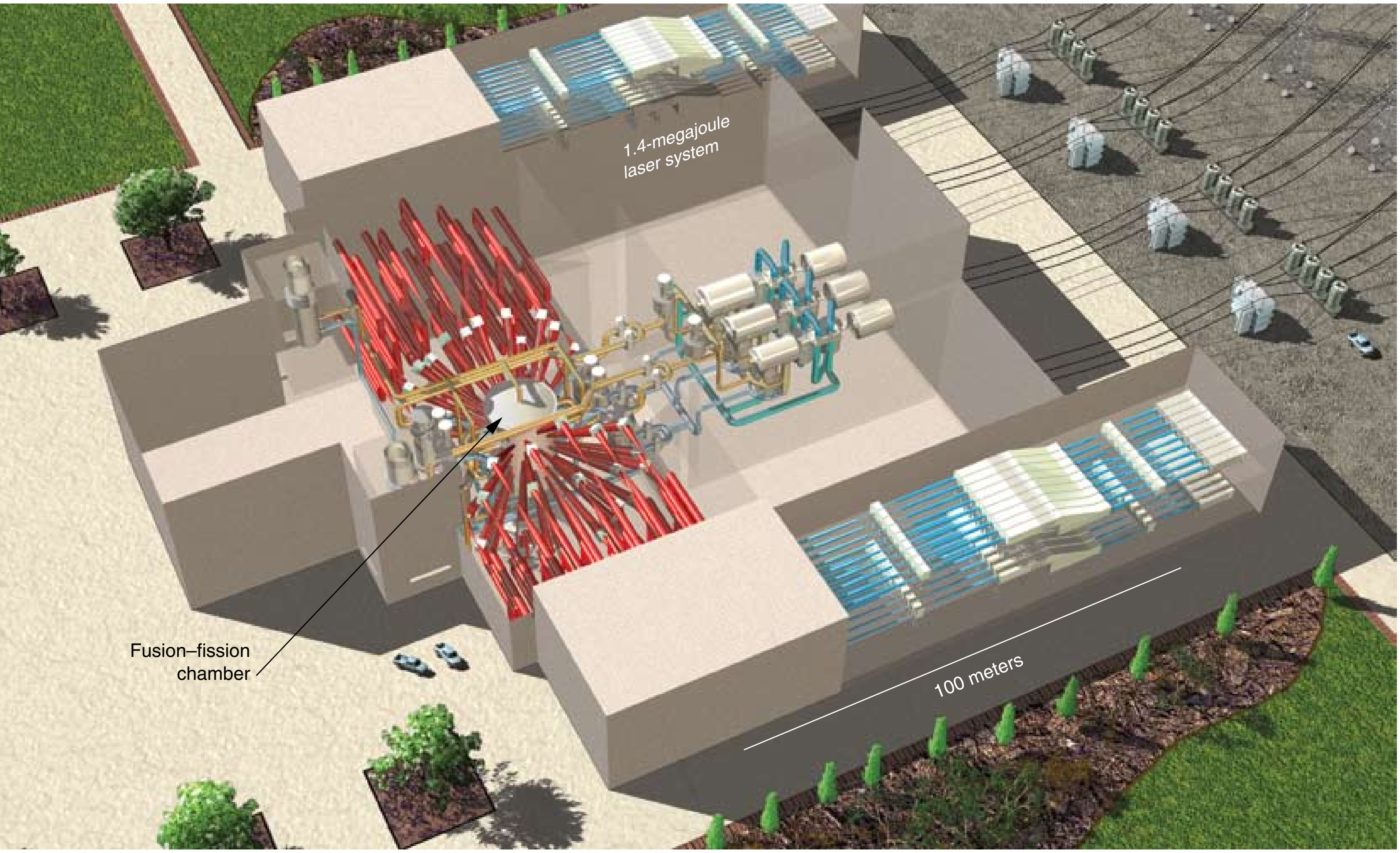
In addition, the LIFE engine design can be "charged" with fission fuel. The resulting fission reactions will produce additional energy that can be harvested for electricity production. Moreover, by using depleted uranium or spent nuclear fuel from existing nuclear power plants in the blanket, a LIFE engine will be capable of burning the by-products of the current nuclear fuel cycle. Because the fusion neutrons are produced independently of the fission process, the fission fuel could be used without reprocessing. In this way, LIFE may be able to consume nuclear waste as fuel, mitigate against further nuclear proliferation, and provide long-term sustainability of carbon-free energy. A LIFE engine, via pure fusion or through the combination of fusion and fission, will generate the steady heat required to drive turbines for generating from 1,000 to 2,500 MW of safe, environmentally attractive electric power 24 hours a day for decades. (See the box on p. 11.)

On the Path to Pure Fusion Energy

Livermore expects to achieve scientific demonstration of fusion ignition and energy gain (output fusion energy/input laser energy) in the laboratory in the next few years. Moses says that successful demonstration of ignition and net energy gain will be a "transforming event" and is certain to focus attention on fusion as a significant energy option. The fusion yields needed for commercial fusion energy (approximately 200 megajoules at 10 hertz) will require continuing research and development that will be pursued at NIF and with the Laboratory's scientific and industrial partners around the world.

In addition, Livermore scientists believe that by combining the best aspects of fusion and fission, a LIFE-based fusion–fission solution could provide safe, carbon-free sustainable power while minimizing concerns and drawbacks associated with the current nuclear energy fuel cycle.

LIFE chief engineer, Jeff Latkowski, points out that current nuclear power plants supply about 16 percent of the world's electricity needs. However, questions remain regarding the potential diversion of nuclear technologies and materials for weapons applications and the long-term sustainability of the uranium fuel supply. Furthermore, today's nuclear power plants generate large volumes of long-lived nuclear waste that must be either reprocessed or stored in repositories designed to remain intact for many thousands of years. "A LIFE engine could be designed to burn spent



This conceptual design shows a LIFE engine and power plant with a 1.4-megajoule laser system. At the facility's center is a fusion or fusion–fission target chamber. For efficiency sake, the balance of the plant (for turning heat into electrical power, as in all electrical power plants) would be sited as close as possible to the LIFE chamber, where the heat is produced. (Rendering by Kwei-Yu Chu.)

nuclear fuel and generate electricity while virtually eliminating all actinides," says Latkowski.

LIFE engines would have enormous fuel flexibility. The fission blanket could consist of natural uranium, spent nuclear fuel (fuel no longer useful in a nuclear power plant and destined for a DOE waste repository), depleted uranium (mostly uranium-238, left over from the process used to enrich uranium for nuclear power plants), highly enriched uranium (rich in uranium-235), natural thorium, excess weapons plutonium, and other actinides. Using these materials, LIFE could supply U.S. electricity needs for more than 1,000 years.

Extracting Nearly 100 Percent Energy

Depending on how it is configured a LIFE engine would require a ramp-up time of days to about 2 years before reaching full electrical power. If configured as a fusion–fission hybrid, the continuous power phase lasts for 5 to more than 40 years, followed by an incineration or burn-down phase in which nearly all actinides are converted to fission by-products. Because a LIFE engine can extract virtually 100 percent of the energy content of its fuel (compared to about 1 percent of a typical nuclear power plant), the nuclear waste it does produce has significantly reduced concentrations of long-lived actinides.

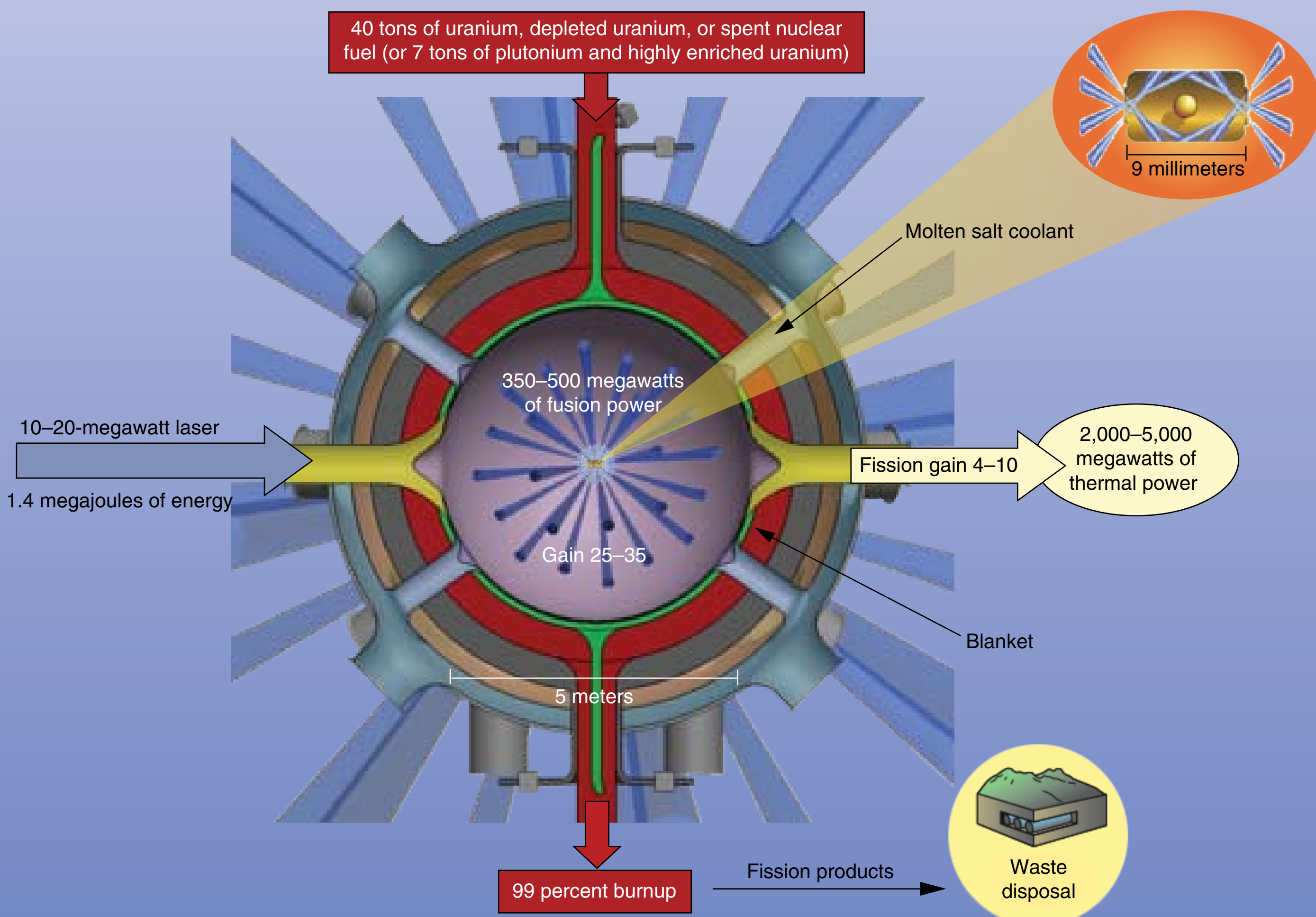
How LIFE Works

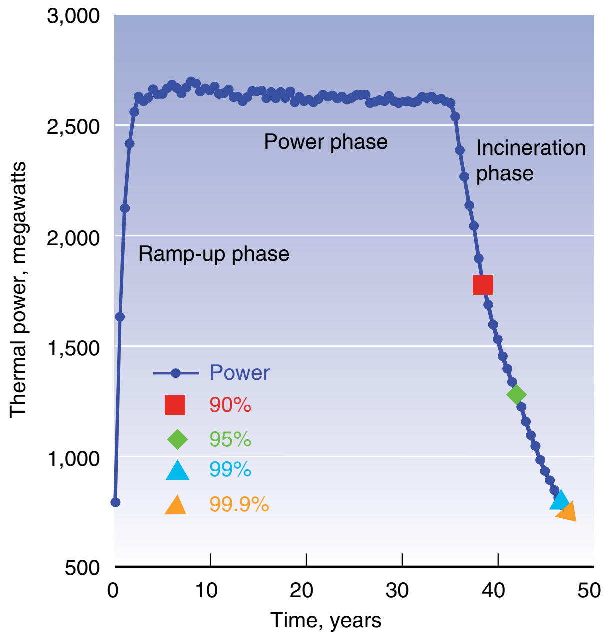
LIFE (Laser Inertial Fusion Energy) is an approach to pure fusion energy as well as a once-through, closed nuclear fuel cycle. A LIFE power plant comprises a solid-state laser system and a fusion target chamber that can be surrounded by a subcritical fission blanket. The balance of the plant includes a fusion target factory, a heat exchanger, and other systems.

The LIFE engine starts with a 10- to 20-megawatt diode-pumped solid-state laser system to provide about 1.4 megajoules of energy. Deuterium–tritium fusion targets are injected at 10 to 15 times a second into the center of a 2.5-meter-radius fusion chamber. The laser beams ignite the fusion targets to obtain energy gains of 25 to 35 and fusion yields of 35 to 50 megajoules of energy, thereby creating 350 to 500 megawatts of fusion power (about 80 percent in the form of fusion neutrons, with the rest of the energy in x rays and ions). Each fusion target generates about 10^{19} neutrons.

The fusion neutrons can also drive fission reactions in a surrounding subcritical fission blanket. The target chamber's structural steel wall is made of low-activation oxide-dispersion-strengthened ferritic steel coated with 250 to 500 micrometers of tungsten to provide resistance to damage by high-energy fusion neutrons and the high temperatures resulting from absorption of the x rays emitted from the LIFE targets. The fusion neutrons pass through the first structural steel wall to a layer of metallic pebbles, which moderate the energy of the fusion neutrons and generate 1.8 neutrons for each neutron they absorb.

The moderated neutrons have a much lower energy spectrum than the fusion neutrons and are ideal for generating fission energy. These neutrons strike the 1-meter-thick subcritical fission blanket containing radiation-damage-resistant fission-fuel pebbles made from materials such as spent nuclear fuel and depleted uranium. The fuel pebbles absorb the neutrons to produce fissile material and drive fission reactions, which release heat to drive turbines. The pebbles are immersed in a molten salt that carries away heat and produces tritium. The tritium can then be harvested to manufacture new fusion targets.





The power curve for a typical LIFE power plant fueled by 40 metric tons of depleted uranium shows a ramp-up time of 1 to 2 years followed by decades of steady power and an incineration phase. Percentages show the fraction of initial fuel burned up.

Overall, a LIFE power plant would produce 20 times less nuclear waste per unit of electricity than existing light-water reactors, thereby drastically minimizing requirements for geologic waste repositories. The size of a repository needed to accommodate waste from an entire fleet of LIFE engines with the same generating capacity as the nation's light-water reactor fleet is about 5 percent of that required for disposal of spent nuclear fuel and would not be needed until the beginning of the 22nd century. Advanced ideas could reduce this need even further.

In addition, LIFE power plants would minimize nuclear proliferation concerns because of their closed, self-contained once-through fuel systems. LIFE engines do not require fuel enrichment before use, refueling during use, or fuel reprocessing after use. If solid fission fuel were used in LIFE power plants, it would be in the form of millions of fuel pebbles, each containing very small amounts of material. Each pebble would be tagged as an accountable item, making it difficult to divert.

LIFE power plants also would avoid the criticality safety concerns associated with conventional nuclear reactors. LIFE's design requires firing the laser to generate neutrons that drive the fission reactions. The fission fuel is deeply subcritical; that is, it is incapable of spontaneously starting or sustaining a chain reaction. The fusion reaction lasts only for trillionths of a second and the fission reactions only for millionths of a second. When the laser stops firing, both fusion and fission reactions "instantly" cease. Residual heat is removed passively, so there is no possibility of a "meltdown" event.

Team Taps Livermore's Strengths

Livermore's LIFE development team includes physicists, materials scientists, chemists, engineers, and energy and national security experts. Led by Moses and Tomás Díaz de la Rubia, chief research and development officer for the Laboratory, the team has prepared a detailed cost and schedule road map, from system demonstrations of scaled pilot and prototype plants to final construction of the first commercial power plant. The first phase would include a combined physics performance, technology development, systems integration, and economic analysis program designed to assess the optimum configuration for commercial use of LIFE systems. Díaz de la Rubia notes that Livermore, teamed with sister DOE laboratories and academic and industrial partners, is uniquely qualified to meet such challenges with extensive experience in optics, photonics, and large laser projects; supercomputing and modeling; nuclear reactor physics; nuclear materials processing; high-energy-density physics; and materials science and engineering.

After fusion ignition and energy gain are demonstrated on NIF, several critical technological steps must be taken to achieve the first commercial LIFE engine by 2030. "Each of these steps seems likely to be achievable," says Díaz de la Rubia, "because the science and technology building blocks for a NIF-based LIFE system are logical and credible extensions of NIF technology as well as of ongoing developments in the worldwide laser and nuclear power industries."

Because the fusion and fission parts of LIFE are technologically and scientifically separable, progress can be achieved at the modular level in separate facilities. "The ability to separate LIFE subsystems makes a rapid demonstration path possible," says Moses. Demonstrating the required fusion performance can be achieved independently of each of the fusion technology systems, such as building a high-average-power laser or high-repetition-rate target capability.

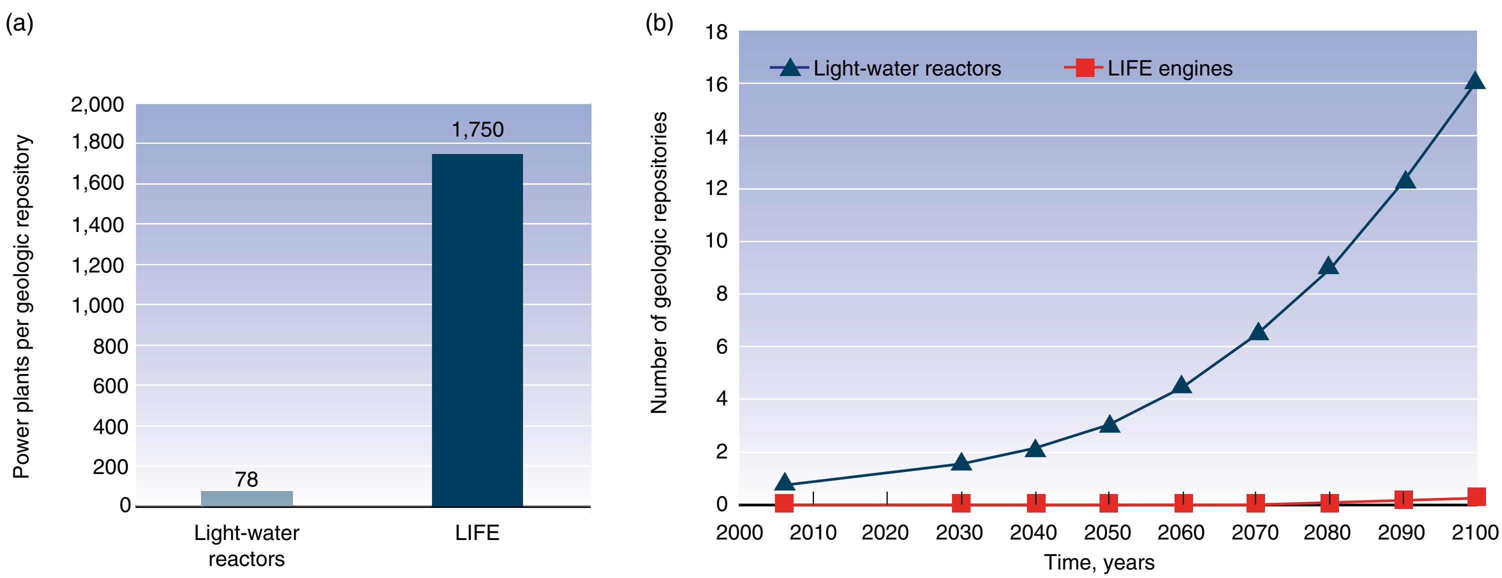
To achieve a high shot rate, LIFE will use diode-pumped solid-state lasers (DPSSLs, invented at Livermore) cooled with flowing helium instead of the uncooled flashlamp-driven lasers used in NIF. Experts predict the cost of diodes will continue to decrease significantly, and many associated technologies have been demonstrated with the Laboratory's Mercury laser. In fact, over the past 12 months, the cost of laser diodes has come down by over an order of magnitude, driven by the increasing demand in the commercial sector for solid-state lasers and other applications of laser diodes. DPSSL technology, along with laser performance and reliability, can be demonstrated with a single beamline laser called a LIFElet. Scientists have begun exploring the requirements for designing a LIFElet laser.

A key technical challenge is developing the process for manufacturing and injecting fusion targets into the center of the target chamber at 10 times per second, and then tracking them in flight for precise engagement by multiple laser beams. Livermore materials science experts, working with General Atomics in San Diego, California, have shown it feasible that fully automated, low-cost, large-volume target manufacturing can be adapted from the food and beverage and other mass-production industries. Researchers have begun using existing modeling codes for NIF fusion targets to design low-cost fusion targets for LIFE that would be scalable to mass production.

Target injection, steering, tracking, and engagement can be demonstrated with surrogate targets and low-power lasers in separate facilities. In this effort, Livermore partners are expected to play an important role. General Atomics has already demonstrated injecting targets at 6 times per second. LIFE's target tracking system will likely take advantage of technologies, originally developed for other missions, to locate targets shot into the fusion–fission chamber with greater than 50-micrometer positional accuracy.

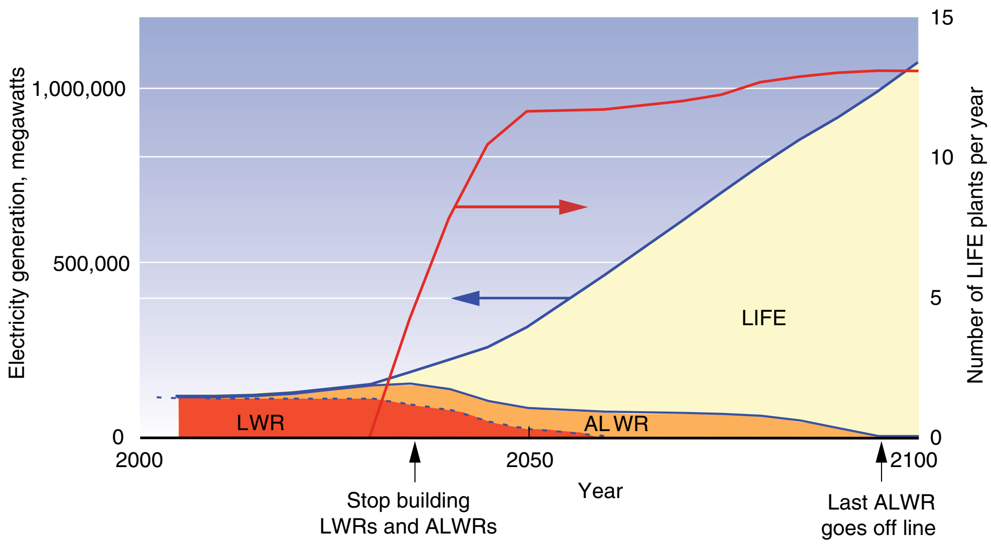
Hot-Spot Ignition to Start

LIFE chief scientist Erik Storm, a preeminent member of the international inertial confinement fusion community, says the first experiments to demonstrate LIFE ignition and gain will use hot-spot ignition targets, the same as now planned for use in initial NIF experiments. In this design, a metallic shell about the size of a pencil eraser—called a hohlraum—surrounds a target capsule containing deuterium and tritium fuel. When irradiated by lasers, the hohlraum emits x rays that vaporize the outer layer of the peppercorn-size target capsule,



(a) LIFE extends the effective capacity of a deep geologic repository assumed to hold 70,000 metric tons of waste by as much as 20 times. (b) This graph shows the number of repositories required over the next century, assuming that the growing demand for electricity is supplied by a conventional fleet of light-water reactors or a fleet of LIFE engines.

Beginning in 2030, construction of 5 to 12 commercial LIFE plants annually could provide 1,000,000 megawatts of electricity (up to half of U.S. electricity demand) by 2100. Light-water reactors (LWRs) and proposed advanced light-water reactors (ALWRs) would be slowly phased out of commission. The red line signifies the number of LIFE plants to be constructed each year. The rate of construction steadily climbs until leveling off at a rate of about 13 new plants per year. During the construction peak of light-water reactor plants, about 10 to 15 were built per year.



causing it to rapidly implode. The resulting temperature and pressure forces the hydrogen nuclei to fuse and ignite in a controlled fusion reaction.

A different approach to ignition, called fast ignition, could reduce both the energy and the compression symmetry required to achieve ignition and would simplify the path toward pure fusion energy. In fast ignition, a standard laser pulse first compresses the target capsule's fuel. The fuel's plasma core is then ignited by an extremely short 10-picosecond high-intensity pulse from a second laser, much like an internal combustion engine. Plans are to demonstrate the physics basis of fast-ignition targets on NIF in conjunction with partners including the Laboratory for Laser Energetics at the University of Rochester. "Fast ignition may give us twice the gain for one-half the laser energy," says Storm. "It is not a requirement for a successful LIFE power plant, but if it works it will make pure fusion and compact fusion–fission systems even more economical and compelling."

Other development efforts will focus on issues associated with the operation of the fission blanket. Díaz de la Rubia says an important goal is to combine theory, experiment, and simulation to develop new materials to achieve significant improvements in properties and performance.

The first wall of the fission blanket must be capable of withstanding high doses of fusion neutrons and temperatures up to 700°C. Accelerated testing with ion beams, coupled with multiscale modeling, will be used to design materials and simulate their property changes expected from the conditions within the target chamber.

Another challenge is designing, modeling, and testing high-temperature candidate fission fuels, which can be either in solid or liquid forms. Most analyses have focused on a solid fuel in the form of 2-centimeter-diameter fuel pebbles immersed in a liquid fluoride salt that carries away heat to drive electrical generators.

The 2020 Vision

Demonstrating individual technologies would validate the subsystems required for LIFE, making possible an integrated prototype plant by 2020. This plant would be configured to test LIFE's energy-production systems operating 10 to 15 times a second. This plant could feature several aspects of various pure fusion and hybrid blankets operating at plant-performance specifications.

Beginning in 2030, annual construction of 5, rising eventually to 12, commercial plants could provide 1,000 gigawatts of electricity (about one-third to one-half of U.S. electricity demand) by 2100. A more ambitious option would supply about two-thirds of the nation's electricity demand by 2100. This option would require construction of 15 to 20 new LIFE plants per year beginning in 2030.

The Livermore team has held discussions with subject matter experts, utilities managers, energy experts, and senior members of the nonproliferation and diplomatic communities. Livermore scientists have addressed major technical symposia around the world.

A number of key officials have visited Livermore for briefings on LIFE. California Governor Arnold Schwarzenegger received a briefing when he toured NIF last November. The governor said LIFE could help meet the state's future energy needs while simultaneously decreasing dependence on fossil fuels. He added that fusion energy would contribute to reducing

Governor Arnold Schwarzenegger (above left, with LLNL director George Miller) was briefed on LIFE while touring NIF in November 2008. At NIF's target chamber are (from the left) Ed Moses, principal associate director for NIF and Photon Science; the governor; and Susan Kennedy, the governor's chief of staff.

greenhouse gas emissions. "This laser technology has the potential to revolutionize our energy future," said Schwarzenegger.

Thanks to advanced Livermore laser and fusion technologies and materials, an idea conceived more than 50 years ago now appears technically possible. By 2050, LIFE engines could be powering a substantial part of the U.S. and worldwide energy grid and supplying hydrogen fuel for transportation. At the same time, LIFE engines could significantly reduce the amount of spent nuclear fuel awaiting long-term geologic storage. Livermore researchers are confident that LIFE may offer a pathway toward sustainable, safe, and carbon-free electric power.

—Arnie Heller

Key Words: diode-pumped solid-state lasers (DPSSLs), fast ignition, fission, fusion, hohlraum, hot-spot ignition, inertial confinement fusion, Laser Inertial Fusion Energy (LIFE), National Ignition Facility (NIF), nuclear power, stockpile stewardship.

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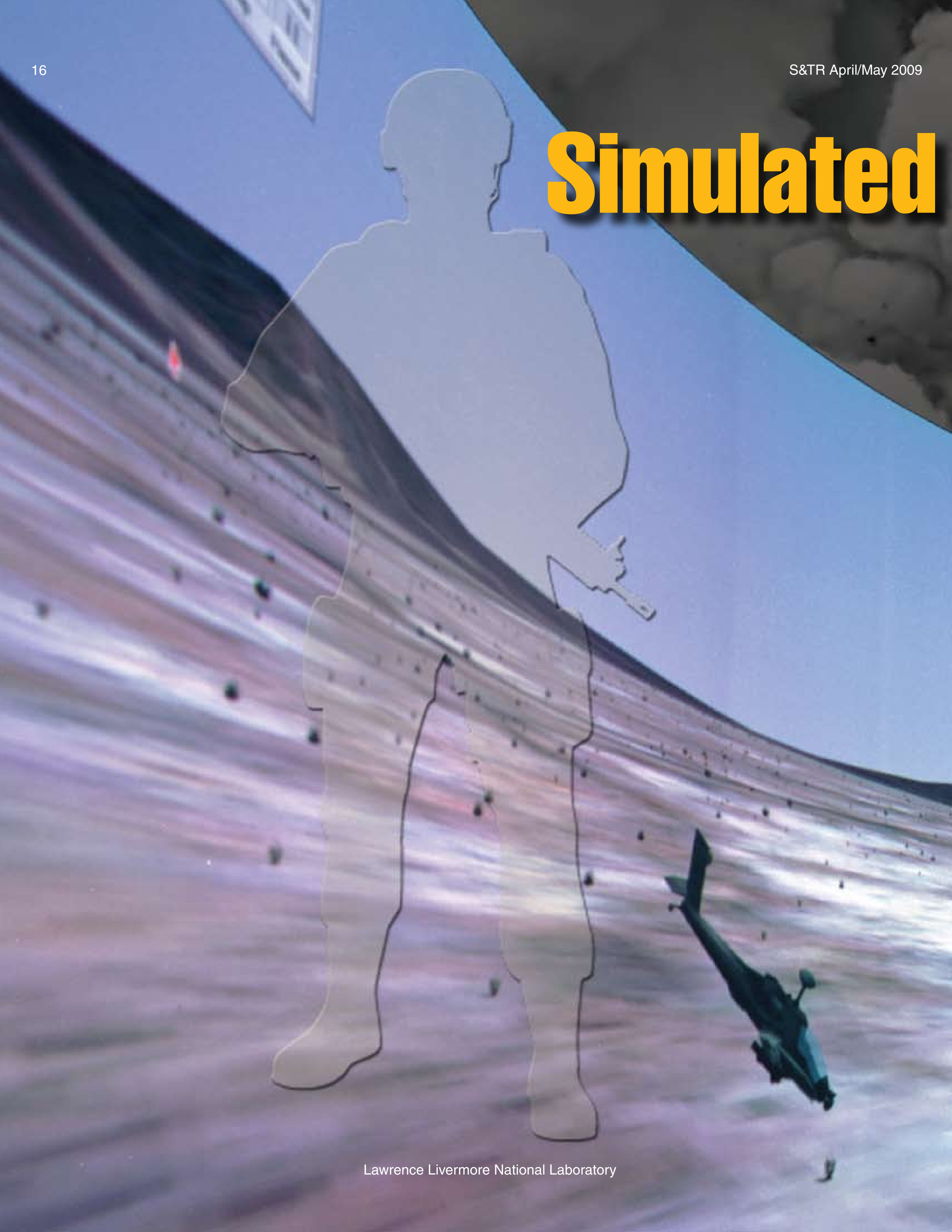
Simulated

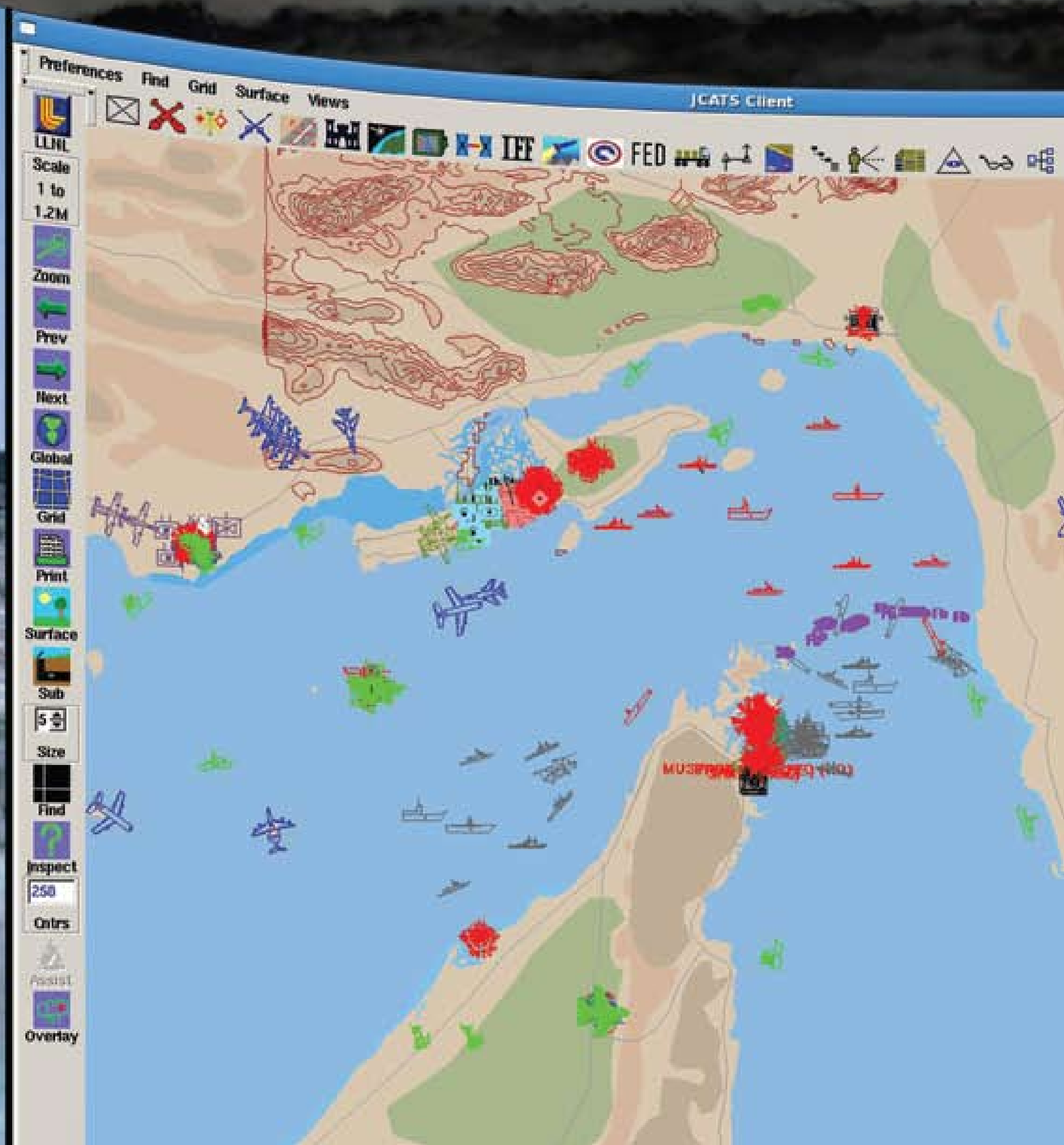


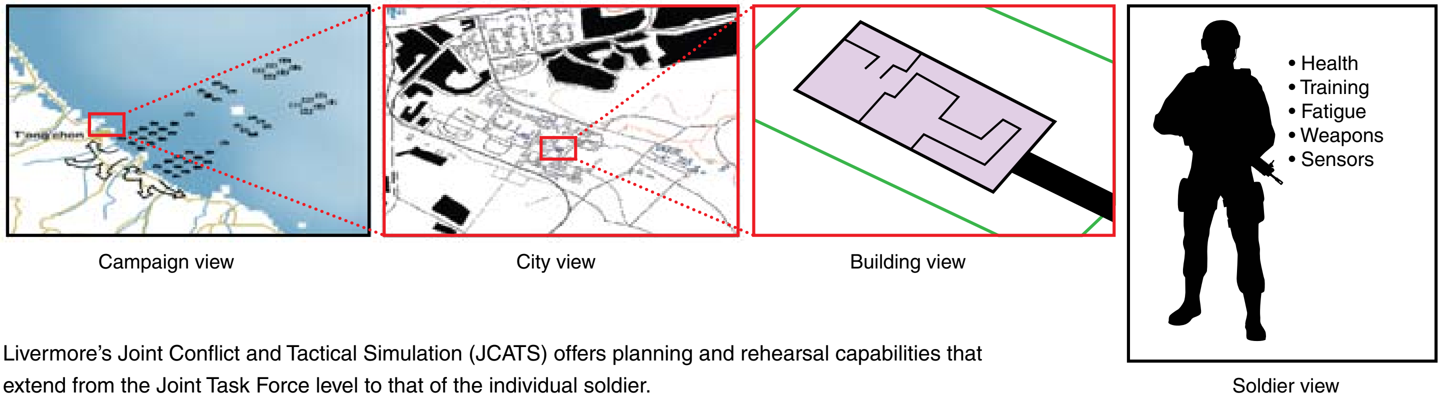
Rehearsal for Battle

A conflict simulation developed at Livermore is used around the world for warfare training, planning, and rehearsal.

MANY military officers headed for deployment in Iraq and Afghanistan get to know Livermore's Joint Conflict and Tactical Simulation (JCATS) whether they realize it or not. JCATS is the most widely used tactical model in the world. It simulates soldier-on-soldier combat with opponents that replicate known enemy tactics and responses.

Leaders of Army and Marine brigades and battalions receive training on laptop and desktop computers where they react to incoming digital information while executing a commander's tactical plan. JCATS's capability for modeling ground maneuvers is supplemented by other models that simulate fire from friendly and enemy artillery, air defense, logistics, intelligence data, and so on.





Livermore's Joint Conflict and Tactical Simulation (JCATS) offers planning and rehearsal capabilities that extend from the Joint Task Force level to that of the individual soldier.

This "federation" of networked modeling tools—which may also include links to live forces on the ground—creates a remarkably accurate picture of battlefield operations.

A recent example of JCATS at work was the October 2008 final phase of the Unified Endeavor 09-01 Mission Rehearsal Exercise, the last training exercise for units slated to deploy in early 2009 as the core element of Multinational Corps in Iraq. Exercise participants were networked from locations throughout the U.S., including Fort Lewis, Washington; Fort Hood, Texas; Fort Leavenworth, Kansas; Camp Lejeune, North Carolina; Hurlburt Field, Florida; and the U.S. Joint Warfighting Center in Suffolk, Virginia. Allied partners in the United Kingdom also participated.

The exercise focused on training joint task forces and major subordinate leaders to meet the expected requirements during their deployment. Data was pulled from the theater of battle to replicate a two-week period in Iraq. The goal for these leaders was to understand—before they arrived in Iraq—the various cells and working groups on the ground, the feel of combat, and the rhythm of battle.

JCATS is sponsored by U.S. Joint Forces Command (USJFCOM) and managed from the command's Joint Warfighting Center. The center uses JCATS and other modeling programs to ensure that all branches of U.S. armed forces work together effectively and that U.S. services can operate with those of other nations as a joint team. (See the box on p. 19.)

The military uses JCATS for training, analysis, and mission planning and rehearsal. The model integrates ground, air, and sea operations as well as real-world command, control, communications, computers, and intelligence—known as C4I. It simulates operations in urban terrain, supports nonlethal as well as conventional weapons, and allows users to quickly assemble and disband units.

JCATS can control more than 100,000 entities, which may be individual soldiers, planes, or mob participants, at more than 150 player stations. The model provides a wide range of operations in a variety of dynamic simulated environments. Modeling the dynamics of individual soldiers, vehicles, and weapons, rather than groups, increases the realism of the simulation and allows more direct participation. JCATS has been integrated into numerous federations in support of U.S. Joint Forces, U.S. Army and Marine Corps, and the North Atlantic Treaty Organization.

"JCATS is totally data driven," says Lauri Dobbs, program leader for Livermore's Conflict Simulation Laboratory, which first delivered JCATS in 1997 and continues to improve it. "Any input will work for any scenario, either military or civilian. JCATS is extremely versatile."

The Department of Energy uses JCATS to assess the security of its nuclear sites. The Naval Postgraduate School (Monterey, California) and the U.S. Military Academy at West Point (West Point, New York) use JCATS for training military leaders in tactical decision-making processes and analyses. In addition, the model is used by numerous Department of Defense (DoD) contractors to develop and analyze new technologies and equipment. DoD has sold JCATS to 20 allied countries who apply it to military and civilian scenarios. The program is in use at more than 350 sites worldwide. Since 2003, the Livermore simulation tool has provided support for operations in Afghanistan and Iraq.

JCATS is also an effective tool for emergency response planning, drug interdiction, and border patrol operations. "Simulations such as JCATS are a huge cost saver for both the military and other users," notes Dobbs. "They can explore various options, see what happens in each, and then make an informed choice. Exercises with actual soldiers or first responders are very expensive.” Over 2,000 exercises with JCATS occur every year across the user community.

JCATS is the latest incarnation of Livermore’s combat simulation tools, which first appeared on computer screens 35 years ago. The landmark Janus program in the late 1970s was the first conflict simulation to use a graphic user interface. Succeeding generations have exploited the latest advances in computer hardware and software. Livermore’s close working relationship with DoD has been instrumental in understanding and meeting their simulation needs. Over the years, JCATS has evolved from a training tool into an operational planning and rehearsal tool.

“Clutter” Enhances Capabilities

Livermore recently enhanced JCATS’s capabilities considerably with the addition of the JCATS Low Overhead Driver (JLOD). According to Tom Kelleher, JLOD’s primary designer, this program fills the gaps for U.S. Joint Forces Command exercises. “JLOD very inexpensively ‘puts a wrapper’ around an area of interest,” he says. “Now a JCATS play area does not have a knife edge around it. We can add civilian activity, merchant ships, or vehicle traffic.” JLOD’s specialty is adding the “clutter” that makes simulations more realistic.

“JLOD is Tom’s brainchild,” says Dobbs. “He saw the gaps in simulation capabilities and came up with a solution for filling them.” The beta version of JLOD has been tested for several years. Version 1.0 will be issued in June 2009.

JLOD first appeared in an exercise covering the area from San Francisco, California, to Seattle, Washington. JLOD was programmed to display civilian vehicle traffic such as tractor-trailers and cars during the day in the inner city. After the simulation was set up, no additional human intervention was required for the duration of the exercise. A similar exercise needed to include boat traffic, and JLOD was able to accommodate that requirement at minimal expense. “JLOD can replace one or two other simulations that require computer hardware and people to operate them,” says Kelleher. “Our goal for the program is to reduce computational requirements while training the same number of soldiers.”

With JLOD, last-minute changes in the design of the exercise are easy to make, even midstream during an exercise. “For example, we had a problem with ship entities during an exercise,” notes Kelleher, “and we shut off JLOD to fix the problem without the trainees being aware of it.”

NATO Forces Train with JCATS

During the first two weeks of November 2008, Livermore conflict simulation experts were on hand in Stavanger, Norway, and Grafenwoehr, Germany, to provide technical assistance to officials of the North Atlantic Treaty Organization (NATO) and U.S. Joint Forces Command with Exercise Steadfast Joiner. Steadfast Joiner is a computer-assisted, command-post exercise to train and evaluate NATO’s Response Force 12. The 2008 exercise showcased the first use of the Joint Multi-Resolution Model Federation, which consists of the Joint Theater-Level Simulation (JTLS) and Livermore’s Joint Combat and Tactical Simulation (JCATS). This federation allows an organization to train from the operational level of war down to the tactical level. Lauri Dobbs, program leader for Livermore’s Conflict Simulation Laboratory, says, “By combining the two simulations, units could be passed into JCATS and dealt with at the individual level and then moved back to JTLS.”

The mission involved training forces to plan and conduct a NATO Crisis Response Operation that would restore peace and security, prevent further destabilization in the designated region, and support post-conflict reconstruction and humanitarian assistance. Training audiences were in Rome, Naples, Valencia, Corsica, and Madrid. Two experiments were embedded in the exercise. One was to divide control between two locations. Some of the interagency role players and tactical units were in Norway with the remainder in Germany. The goal was to achieve a capability that will allow NATO to distribute training and education across various alliance locations and enable nations to train together from home locations using the same decision points. The other experiment was to conduct civil emergency planning and improve processes for military coordination with civilian agencies regarding requests for assistance and support of peaceful operations.

With a split-based control group and training audiences in multiple dispersed locations, the communications support challenges made this the most extensive and robust exercise ever conducted by NATO.

The U.S. government has sold JCATS to 20 countries (shown) for civilian and military use.

Not a Video Game

The analogy of JCATS to a warfighting video game may seem obvious, particularly because the terminology is so similar. In setting up an exercise, users define a gaming area, and participants are players. But this analogy is highly inaccurate. In a video game, a soldier may jump off a 10-meter cliff without a scratch. In JCATS, however, the soldier who makes the same leap will be seriously injured. Commercial games do not take into account basic physics concepts (such as acceleration of a falling body) or variables such as fatigue, inclement weather, low food supplies, and poor visibility. These crucial factors affect how an individual soldier or platoon behaves.

"Video games automate much of the activity you see on screen," says deputy program leader Will Belue. "The game does most of the thinking for you. In JCATS, there is very little automated action. Moving just one soldier from point A to point B requires consideration of a lot of factors: his or her posture and fatigue level, how he or she is armed, and so on." Belue, who has been at the Laboratory for just three years, is a valuable asset to the Conflict Simulation Laboratory team. He is retired from the U.S. Army where he had many years of experience using JCATS and its predecessors as well as training others in their use. Kelleher refers to Belue as their resident "graybeard" on all things military.

Upcoming enhancements to JLOD distance JCATS even more from video games. Work is under way to incorporate some of the "nonkinetic" effects of military and civilian operations. Nonkinetic effects include population moods, such as public perception, willingness to fight, and sense of security. For example, if food is given to this village, will its inhabitants help us? Or, what will happen if we bomb a mosque? Epidemics and their ramifications will also be included, adding yet another layer of complexity to the simulation.

Inside JCATS

JCATS Version 8.0, issued in April 2008, includes a number of new features. One is an interactive three-dimensional (3D) view so users can control entities in either 2D or 3D. Another is a missile fly-out model to simulate tactical ballistic missiles, cruise missiles, and tomahawks—a critical requirement for current wartime efforts. Artillery improvements allow simulated entities in JCATS to request fire support from the Army's real-world fire control computers. Traffic checkpoints also have been added.

They slow movement through controlled areas and allow for the addition of search-and-arrest systems. Graphic images of real people and places can be linked to a simulation, replacing stick-figure images. In addition, building damage can be restored if necessary. According to Dobbs, “When the U.S. Joint Forces Command asked for 45 enhancements in Version 8.0, we gave them 90.”

JCATS describes environments such as terrain, buildings, bridges, and minefields. It incorporates data sets that have been verified by the military for construction of both large gaming areas and detailed urban areas. Terrain data include properties such as height, mobility, and line of sight, all of which are critical for determining how a soldier or vehicle might move, where the enemy will appear, and what weapons are appropriate for use.

Terrain significantly affects movement of troops, aircraft, tanks, and maritime operations. For example, a rescue helicopter cannot safely land in a forest, amphibious landing craft must negotiate rocky shores, vehicles move slowly through swamps, and soldiers slow considerably when marching uphill. Environmental factors such as adverse weather, nightfall, dust from sandstorms, and smoke from combat also affect mobility.

Players can import blueprints of specific buildings for urban warfare and site security exercises. Alternatively, users can create their own town or building, as is often done for drug interdiction training. In these cases, JCATS offers a palette of menus to create everything from windows and doors to streets and parks.

An enormous range of vehicles and weapons can be simulated, from tanks, helicopters, and Humvees to mortars, rocks, pepper spray, and fists. Details on all vehicles and munitions come from validated military data and algorithms. Nonlethal weapons are increasingly important as the military engages in peacekeeping duties around the world.

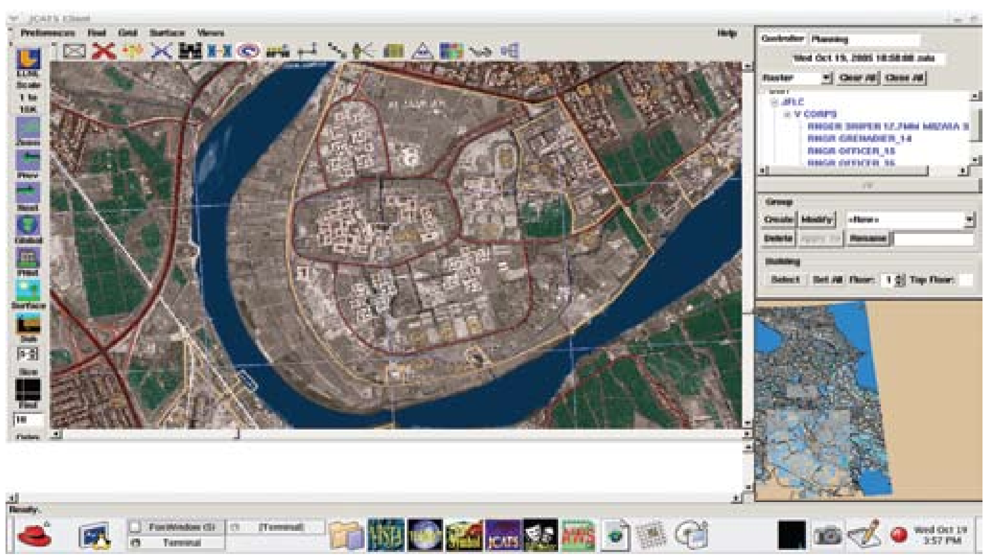
Spanning the Globe

JLOD expands the area that can be played to the entire world. For example, the model offers a view of global operations while players can focus on individual soldiers in such locations as the coliseum in Oakland, California, and the airport in Baghdad, Iraq.

Broad-scope exercises may incorporate three kinds of environments. In a live environment, real people use real equipment in a real training area to simulate their real actions. In a virtual environment, real people use a mock-up of a piece of equipment, such as a flight simulator, to determine if the operator is properly using the equipment. In a constructive environment, real people use simulated people and equipment in a simulated environment. JCATS is an example of a constructive environment. These three environments were first integrated into a single exercise in 1997, and their combined use has grown more sophisticated ever since.

December 2006 saw the rollout of the Joint Live-Virtual-Constructive (JLVC) Federation for the annual Terminal Fury exercise. Terminal Fury is a two-week exercise for the Pacific Command. Personnel from all military services in Japan and Hawaii test their ability to come together as a joint task force to manage emergencies in the region. The task force was designed to be deployable aboard a ship and capable of command and control of Pacific and stateside assets in a war or natural disaster.

“JCATS and JLOD were two of the four constructive simulations used during the 2006 Terminal Fury,” says Dobbs. “They accounted for more than 90 percent of the simulated forces on less than 25 percent of the workstations. Livermore is pushing the technology and driving the development of federations.”



Modeling terrain in JCATS is based on actual maps of the area of interest, in this case the “International Zone” in Baghdad, Iraq.

The JCATS Low Overhead Driver (JLOD) supplements JCATS and other conflict simulations by expanding a game's scope to the entire world with little added computer time or human intervention required. A single war game can include (a) a worldview and detailed information of sites as far apart as (b) the coliseum in Oakland, California, and (c) the airport in Baghdad, Iraq.

Version 9.0 of JCATS (April 2009) includes an improved three-dimensional viewer.

JLOD was used for the first time in a homeland security exercise in May 2007. Ardent Sentry–Northern Edge was a Northern Command training event for U.S. and Canadian civil authorities. This exercise stretched from Japan in the west to Bermuda in the east to Central America in the south. JCATS and JLOD together modeled about 95 percent of the 80,000 simulated entities. JLOD alone modeled more than half of all forces, including merchant ships, National Guard, Coast Guard, and Air National Guard. According to exercise planner Dave Hall, "This was the most integrated Northern Command exercise to date."

"JCATS keeps getting better and better, bigger and bigger," says Belue. "The program is now a huge step beyond its capabilities as a stand-alone simulation." The model is seeing increased use for evaluating readiness of National Guard units. JCATS is also expected to replace other long-used programs that simulate artillery and missile fly out. New features in Version 9.0 of JCATS, rolled out in April 2009, include a further improved 3D viewer, more information for planning amphibious and air assault landings, and dynamic reports that inform players of tardy transports and missing cargo during an assault. "JCATS 9.0 also addresses the bandwidth problem that occurs at big exercises, when users need to push a lot of data quickly," says Dobbs.

The U.S. military is clearly happy with JCATS. Says Brian Gregg, chief of joint modeling and simulation at the Joint Warfighting Center, "We give the hard problems to Livermore."

—Katie Walter

Key Words: conflict simulation, Joint Combat and Tactical Simulation (JCATS), JCATS Low Overhead Driver (JLOD), Joint Warfighting Center, North Atlantic Treaty Organization.

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Improving Catalysis with a "Noble" Material

Carbon aerogels are produced in a variety of shapes and sizes. The carbon gives the aerogel its color and makes it electrically conductive.

AEROGELS are an impressive feat of science and technology. These highly porous, low-density, lighter-than-air structures have become exceedingly useful at the Laboratory in laser target fabrication, energetic composites, sensors, ceramics, and coatings. Over the last decade, researchers have tailored the properties of aerogels in an effort to optimize them for different applications. Using a process referred to as doping, they incorporate additional chemical elements into the material. However, this doping process can be challenging because of aerogel's complex pore structure. Recently, a team of Livermore researchers helped develop an efficient method to dope carbon aerogel—an electrically conductive material—with the noble metal platinum. This method could lead to the development of new designer materials for fuel cells, hydrogen storage, and pollution-control technologies.

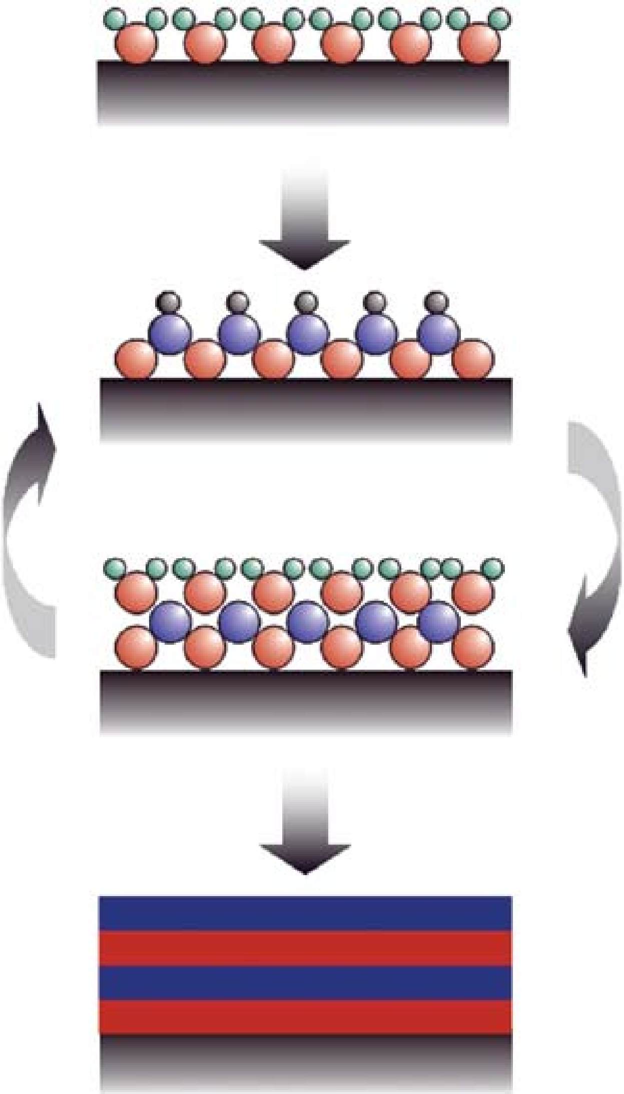
Platinum is an effective catalyst because it can accelerate chemical reactions without being consumed or altered. As an example, catalytic converters on gas-powered vehicles use platinum to convert poisonous carbon monoxide into carbon dioxide through oxidation. In hydrogen fuel cells, platinum is used to catalyze the electrochemical reactions that produce electrical energy. For technologies such as these, more platinum means higher conversion rates. Unfortunately, platinum is expensive, making technologies that require large amounts of the material too costly for everyday applications. However, by incorporating platinum into carbon aerogels, scientists from the Laboratory, Stanford University, and the University of Bremen in Germany have shown that when it comes to platinum, less can do more.

Using atomic layer deposition (ALD)—a gas deposition process that provides atomic-level control of thin films—the team added minute amounts of platinum to uniform discs of carbon aerogel. These platinum-loaded carbon aerogels were then tested for how well they converted carbon monoxide to carbon dioxide. "The catalytic oxidation of carbon monoxide using platinum is fairly well understood and is an easy way to benchmark the material," says Ted Baumann, a chemist in Livermore's Advanced Materials Synthesis Group. The results showed that platinum-loaded carbon aerogels achieved nearly 100 percent conversion efficiency with minimal amounts of platinum, as little as 0.05 milligrams of platinum per square centimeter.

A Complex Kind of Jell-O

Aerogels' internal structure consists of a network of interconnected nanometer-size particles. Because of their structure, aerogels exhibit interesting properties such as low mass densities and large internal surface areas. These properties are a direct result of the methods used to prepare the materials. In a process known as sol-gel chemistry, a solution of reactants is treated to induce the formation of nanometer-size particles, which connect to one another to create a three-dimensional solid network. According to Baumann, who fabricated the carbon aerogels for the experiments, "Making aerogels is a little like making Jell-O." When making Jell-O, gelatin is heated with water and then cooled to create an extremely dilute gelatin network that is responsible for Jell-O's solidlike properties. When making aerogel, the fluid is removed from the pores of the three-dimensional network while the structure remains intact. "The process is equivalent to removing all the water from a Jell-O mold without it collapsing," says Baumann. This transformation requires special drying techniques that typically involve supercritical fluids.

Carbon aerogels, despite their high porosity, can be very strong and are capable of supporting hundreds of times their own weight. Because they are so porous, they also have very high surface areas. For example, the aerogels used in the platinum catalysis experiments have surface areas of approximately 480 square meters per gram. This high surface area allows more of the catalyst to be exposed



In atomic layer deposition (ALD), conformal films are deposited sequentially exposing a substrate surface to two different precursor species whereby surface termination between two states (gray and green circles) is switched. These different surface functionalizations are responsible for the self-limiting character of the ALD process. The process is repeated until the desired thickness is obtained.

when reacting with external chemicals. As a result, less catalyst is needed to produce efficient results.

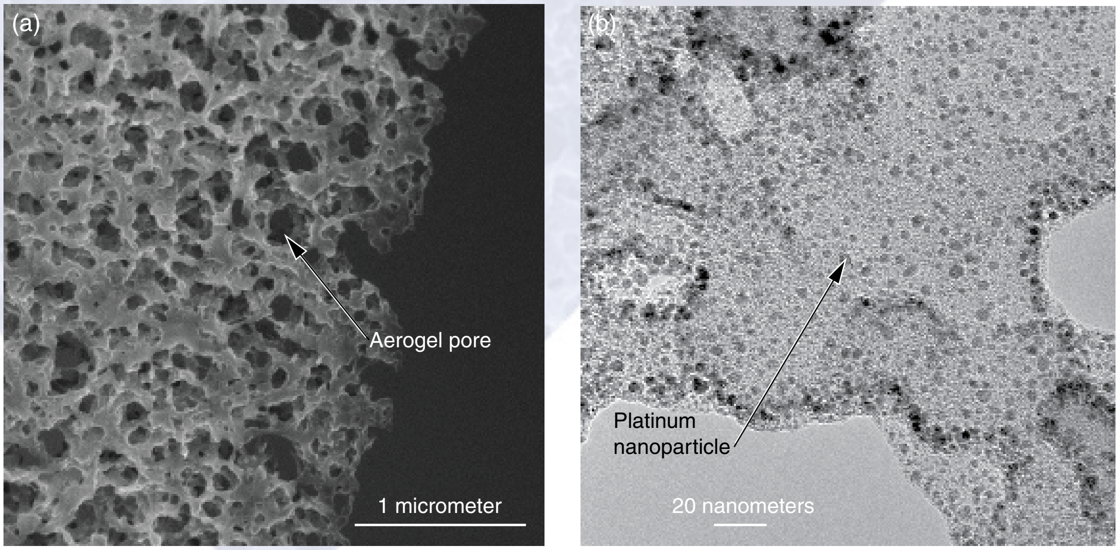
A Successful Sequence

Incorporating catalyst particles into aerogels in a controlled fashion can be challenging because of the material's extremely small pore networks. According to Juergen Biener, a materials scientist in Livermore's Nanoscale Synthesis and Characterization Laboratory who led the project, "Nanoporous materials can be difficult to dope without interfering with their structure. However, the self-limiting character of the ALD process is ideally suited for depositing particles in nanoporous materials with atomic-level control."

In ALD, chemical precursors, or species, in their vapor (gas) form are sequentially pulsed into a reaction chamber containing a sample surface—in the case of the catalysis experiments, a carbon aerogel substrate. Inside the chamber, each species chemisorbs to the sample surface one atom at a time, eventually creating a thin monolayer film. Once the first chemical occupies all available adsorption sites, the surface is passivated, and the film growth stops until the surface is reactivated by exposure to the second gas precursor. Thus, in ALD, film growth is self-limiting, that is, restricted by the number of adsorption sites on the sample surface and the number of reaction cycles.

Baumann says ALD is different from other film-producing techniques, such as chemical vapor deposition, where one or more elements are added to a substrate all at once. Chemical vapor deposition is used in the semiconductor industry to create thin films for transistors. "If we used chemical vapor deposition to coat the inner surfaces of an aerogel, the material being deposited would quickly plug the aerogel's pores, and the coating would not be uniform," says Baumann.

The platinum ALD experiments were conducted at Stanford University in the laboratory of professor Stacey Bent. Uniform disks of carbon aerogel measuring 500 micrometers thick and approximately 1 centimeter wide were placed in a warm-wall chemical reactor heated to 120°C. The team used methylcyclopentadienyl-trimethylplatinum ($MeCpPtMe^3$) and oxygen as the two precursor gases in the experiment. First, $MeCpPtMe^3$ was pulsed into the reactor for 20 minutes, providing ample time for the gas to infuse the aerogel. Then, the reactor was purged with nitrogen for 10 minutes to remove excess precursor molecules remaining in the chamber. Next, oxygen was added for another 10 minutes. The oxygen reacted with the $MeCpPtMe^3$ already on the substrate, transforming the platinum into its solid, metallic state. This step was followed by another 10-minute pulse



(a) A cross-sectional micrograph from a scanning electron microscope shows the high porosity of carbon aerogels. This sample was treated with platinum using ten atomic layer deposition cycles. (b) A higher magnification micrograph from a transmission electron microscope reveals the deposition of platinum nanoparticles with an average size of 2.4 nanometers.

of nitrogen. Because the team wanted to test how little platinum was needed to produce an efficient catalyst, the carbon aerogels were exposed to two, five, and ten deposition cycles for comparison.

Team members Sergei Kucheyev and Morris Wang characterized the ten-cycle platinum-loaded aerogels at Livermore using Rutherford backscattering spectrometry and cross-sectional transmission electron microscopy. The characterization revealed that the deposited platinum does not form a continuous thin film on the surface of the carbon aerogel. Rather, the platinum–aerogel interaction produces hemispherical platinum nanoparticles less than 5 nanometers in diameter. Forming such small platinum nanoparticles is key to a high catalytic efficiency because more of the catalyst's atoms are exposed at the surface, thus increasing the catalyst's ability to induce chemical reactions.

The catalytic properties of the platinum-loaded aerogels were then tested at the University of Bremen. Aerogel substrates exposed to the various deposition cycles were individually placed inside a glass continuous-flow reactor. A combination of nitrogen and oxygen was mixed with carbon monoxide and injected into the reactor. The team compared the conversion rates of each of the aerogels for oxidizing the carbon monoxide into carbon dioxide. Surprisingly, they found the aerogel that had undergone only two ALD cycles had the same conversion efficiency—nearly 100 percent conversion in the 150 to 250°C range—as those that had been through five and ten cycles. In other words, less platinum could be used to obtain the same catalytic effect.

Another "Noble" Cause

Baumann's interest in the platinum catalysis experiments was directly related to his work on a Department of Energy–funded project for hydrogen storage. However, Baumann and Biener have also explored the potential of other nanoporous materials such as gold for use in catalytic and other applications. "As we learn more about the surface chemistry of these materials, we can more fully understand their unique properties," says Biener.

According to these scientists, the potential use for nanoporous materials is virtually untapped. As Baumann, Biener, and other researchers continue their work on nanoporous structures, the scientific and technological innovations they bring about could have a significant effect on the way electric, catalytic, and waste management processes are performed today. In the future, nanoporous materials such as platinum-loaded aerogels could play a key role in applications for water treatment, hydrogen storage technology, and more efficient fuel cells that use less but do more.

—Caryn Meissner

Key Words: atomic layer deposition (ALD), carbon aerogels, catalysis, catalyst, fuel cell, hydrogen storage, nanoporous materials, oxidation, platinum.

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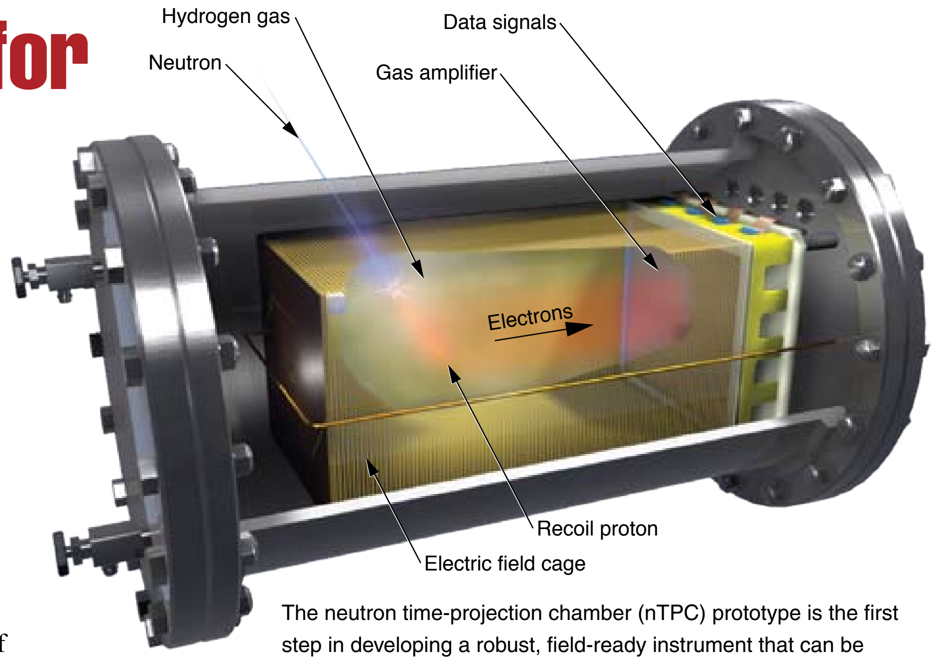
A Time Machine for Fast Neutrons



The neutron time-projection chamber (nTPC) prototype is the first step in developing a robust, field-ready instrument that can be used outside a laboratory to detect neutron sources. (Rendering by Sabrina Fletcher.)

ALTHOUGH time-projection chambers (TPCs) may sound like futuristic time machines, in reality they are unique particle detectors that could help improve national security. Developed in the 1970s, TPCs are gas-filled devices that measure charged-particle trajectories in three dimensions. The instruments are used in high-energy physics experiments to track particles after they are "smashed" together inside particle accelerators. Such interactions produce complex assortments of particles with energies typically ranging from tens of megaelectronvolts to many gigaelectronvolts. Scientists measure the energy deposited in the TPC gas to identify specific particles.

In general, TPCs are highly technical devices with easily damaged components. Until now, they have only been used in laboratories by trained scientists. In collaboration with other research institutions, the Laboratory is developing a neutron TPC (nTPC) that will function in a much different environment to specifically detect neutrons. According to Mike Heffner, a Laboratory physicist who leads the nTPC development team, "We are creating a robust, field-ready nTPC that can be used by nonexperts to locate fissile materials in nonproliferation and nuclear counterterrorism efforts."

The machine is designed to detect fast neutrons—those with an average energy of 2 megaelectronvolts. These particles are naturally emitted by cosmic ray interactions and through the decay of fissile material. Using nTPC, authorized personnel could detect the presence of neutrons emitted from a radioactive source within minutes. In addition, the nTPC prototype can indicate the direction of a neutron source from up to 20 meters away.

Particles on the Move

The nTPC prototype contains hydrogen gas, a lightweight medium that interacts with fast neutrons. When a fast neutron enters the gas, it has a high probability of colliding with a hydrogen atom, which consists of one proton bound to an electron. Similar to the way billiard balls ricochet off the cue ball in a game of pool, the collision causes the proton to recoil away at an angle as the neutron knocks it away from its electron in a process known as elastic scattering.

In the collision, the neutron loses energy and typically leaves the gas unit without inducing further elastic scattering. However, as the newly liberated proton travels along its path, it ionizes the gas, separating the protons and electrons of other hydrogen atoms. This process creates an ionization track as the proton moves through the medium. Every time the recoiling proton ionizes a hydrogen atom, the proton loses energy. Thus, the ionization is proportional to the energy loss of the proton. "After tens of thousands of atoms have been stripped of their electrons, the proton no longer has enough energy to ionize the gas," says Heffner. The nTPC detects the electrons from the ionization track to determine the proton's trajectory and ionization energy loss. This data is then used to help determine the incoming neutron's trajectory and energy.

An external "cage" surrounding the gas produces a uniform electric field that forces the electrons to drift toward the ground end of the detector, where an amplification structure is located. The amplification structure consists of a grid of anode wires positioned orthogonally to charge-sensitive copper strips. This grid is used to record the amplified electric charges and provide a two-dimensional (2D) set of coordinates for each cluster of electrons. The amplified electric charge is proportional to the energy produced in the initial ionization event. Amplification is necessary because the electron signal produced in the primary ionization event is not strong enough to be detected amidst the inherent noise of the system.

In the nTPC prototype, an electron's velocity is approximately one centimeter per microsecond as it drifts toward the grid. Because the drift speed remains constant, researchers can accurately determine the distance the electrons travel before being recorded by the amplification structure. Thus, time projection chambers get their name from the fact that time is used to project back to where the initial ionization event occurred.

Computers are needed to translate the complex data generated into a 3D representation of each ionization track. "We use compression algorithms to manage the volume," says Heffner. "Depending on the strength of the neutron source and its location, we can estimate the direction of the neutron source within minutes."

"Pointing" to the Source

Kinematics—how particles move through an environment—plays a critical role in determining the direction of a neutron source. The nTPC researchers are particularly interested in the kinematics of the neutron–proton collision. When the neutron hits the hydrogen atom, the proton is knocked out at an angle. "We have no control over how the neutron will hit the proton, so the proton could be knocked out at almost any angle forward of the incoming neutron direction," says Heffner.

For each collision, the nTPC's fast electronics record a set of data, including the proton's angle. Computers transform the data into a histogram, where the x axis represents the angle and the y axis indicates how many collisions have occurred for each angle. Using the histogram, the team can average all of the recorded angles to identify the source's direction. "The greater the number of collisions we record, the more accurately we can detect the direction of the neutron source," says Heffner. "However, just ten neutrons are enough to reduce the directional uncertainty to a 16-degree cone."

From the Lab to the Field

To test the nTPC prototype, Livermore researchers exposed the detector to a californium-252 source equivalent in neutron output to approximately 6 kilograms of weapons-grade plutonium. Inside a laboratory, the team first ran nTPC with the californium source stored in a shielded container to assess the amount of background radiation being generated from neutrons naturally occurring in the environment. The californium-252 source was then removed from the container and placed in various locations several meters from the nTPC. "We detected neutrons from the radioactive source 10 and 20 meters away," says Heffner.

The nTPC has three main advantages. First, the machine provides fast proximity searching because it can "point" in the direction of the sources. Second, it provides improved suppression of background radiation from sources such as cosmic rays and those naturally given off by the decay of isotopes in the environment. Third, nTPC can track multiple neutron sources in the same area.

With innovation and ingenuity, Heffner and his team have found a way to adapt a well-known technology used in high-energy physics experiments to a device for detecting fissile materials. "The prototype nTPC is the initial step in developing a robust, field-ready instrument that can be used outside a laboratory," says Heffner. It may not be a fancy time machine, but nTPC is proving to be a potentially valuable tool for protecting our national security.

—Caryn Meissner

Key Words: detector, fissile material, high-energy physics, ionization track, kinematics, neutron time-projection chamber (nTPC), radioactive source.

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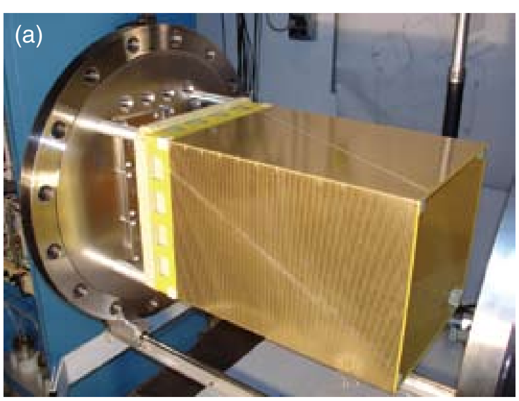

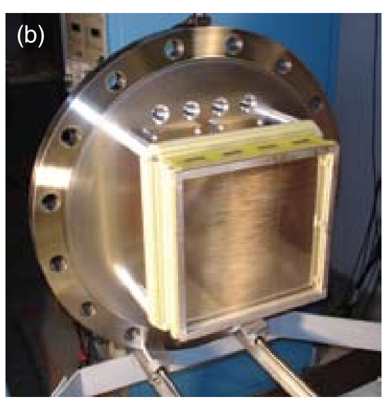

(a) The neutron time-projection chamber contains hydrogen gas, which is surrounded by a "cage" that produces a uniform electric field to pull electrons toward the ground end of the machine. (b) A structure at the ground end of the chamber amplifies the electric charge. The amplification structure consists of a grid of anode wires positioned orthogonally to charge-sensitive copper strips. This grid is used to record the amplified electric signals and provide a two-dimensional set of coordinates for each cluster of electrons.

Awards

Rick Ryerson, leader of the Basic Energy Sciences–Geosciences Program, has been named a **Fellow** of the **American Geophysical Union** (AGU), a worldwide scientific community that advances the understanding of Earth and space for the benefit of humanity. Ryerson's citation reads: "for contributions to our understanding of transport processes in minerals, magmas, and crustal rocks at all scales."

Ryerson's current work includes mineral–fluid equilibrium and diffusion kinetics in Earth's interior, focusing on geochemical applications of high-spatial-resolution secondary-ion mass spectrometry. "I've been very fortunate to have had a long association with Livermore's branch of the Institute of Geophysics and Planetary Physics [IGPP]," says Reyerson. "The IGPP and the Laboratory Directed Research and Development Program allowed me to support an energetic group of postdocs and students, foster collaborations with various University of California campuses, and help provide access to unique Lab facilities such as the Center for Accelerator Mass Spectrometry."

AGU awards fellowships to scientists who have attained acknowledged eminence in one or more branches of geophysics. It elects no more than one-tenth of a percent of its membership as fellows.

Laboratory scientists and engineers captured three awards for **Excellence in Technology Transfer** from the **Federal Laboratory Consortium for Technology Transfer**. The three awards represent the most won this year by any laboratory among the more than 250 federal government laboratories and research centers that comprise the consortium. Livermore won its awards for a process that removes silica from geothermal waters, a pneumothorax detector, and a unique technology transfer effort that could strengthen U.S. maritime security.

"On behalf of the Industrial Partnerships Office [IPO], it is my pleasure to offer congratulations to the Lab employees who have been honored," said Erik Stenehjem, director of IPO. "These awards are one of the ways we show the federal laboratory community the impact of our technology-transfer activities with industrial partners."

Mark Seager, assistant department head for Advanced Technologies, has been selected by ***Federal Computer Week*** magazine as one of this year's "**Federal 100**" top executives from government, industry, and academia who had the greatest impact on government information systems in 2008. Seager was selected because of: "the difference you made in the way agencies, companies, and government officials develop, acquire, manage, and use information technology."

The nomination was submitted by industry collaborators for Seager's leadership of the Hyperion Project, a collaboration with 10 industry leaders to advance next-generation Linux high-performance computing clusters. The Hyperion Project is a large-scale testbed for high-performance computing technologies critical to the National Nuclear Security Administration's work to maintain the aging U.S. nuclear weapons stockpile without underground nuclear testing, and industry's ability to make petaflops (quadrillion floating operations per second) computing and storage more accessible for commerce, industry, and research and development.

Abstracts

Safe and Sustainable Energy with LIFE

Lawrence Livermore researchers are exploring the idea of a revolutionary approach to nuclear power based on the National Ignition Facility (NIF), the most energetic laser in the world. Known as Laser Inertial Fusion Energy (LIFE), the system is a logical extension of NIF and the fusion yields it will generate from planned ignition experiments. LIFE could be used for multiple energy missions depending on its specific configuration. Using a lithium-based molten salt blanket, a LIFE engine can make electricity directly from fusion as well as generate enough tritium for use in the fusion targets. By adding a subcritical fission blanket, a LIFE engine can be converted into a nuclear waste burner capable of extracting energy from spent nuclear fuel from existing nuclear power plants. Such a LIFE engine can also burn fertile fission fuels such as depleted uranium or thorium in a subcritical, once-through, closed fuel cycle that increases the energy productivity of the fission fuels by a factor of 20. An integrated prototype plant would demonstrate LIFE's energy-production systems operating 10 to 15 times a second. This prototype plant would be configured to feature several aspects of operations from pure fusion to hybrid fusion–fission operation at plant performance specifications. If successful, by 2050, LIFE engines could be powering a substantial part of the U.S. and worldwide energy grid.
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Simulated Rehearsal for Battle

Livermore's Joint Conflict and Tactical Simulation (JCATS) is the most widely used tactical model in the world. It simulates soldier-on-soldier combat with opponents that replicate known enemy tactics and responses. JCATS's capabilities can be "federated" with other models that simulate fire from friendly and enemy artillery, air defense, logistics, and intelligence data. Together these tools create a remarkably accurate picture of battle operations. Another model, the JCATS Low Overhead Driver (JLOD), inexpensively adds civilian activity, merchant ships, and other "clutter" that make simulations more realistic. With JLOD and JCATS working together, a simulation can span global operations while simultaneously focusing on individual players at facilities on opposite sides of the world. JCATS is used by the North Atlantic Treaty Organization, several branches of the U.S. armed forces, and in most U.S. joint operations simulations. The Department of Defense has sold JCATS to 20 allied countries who use it for military and civilian training and planning scenarios.
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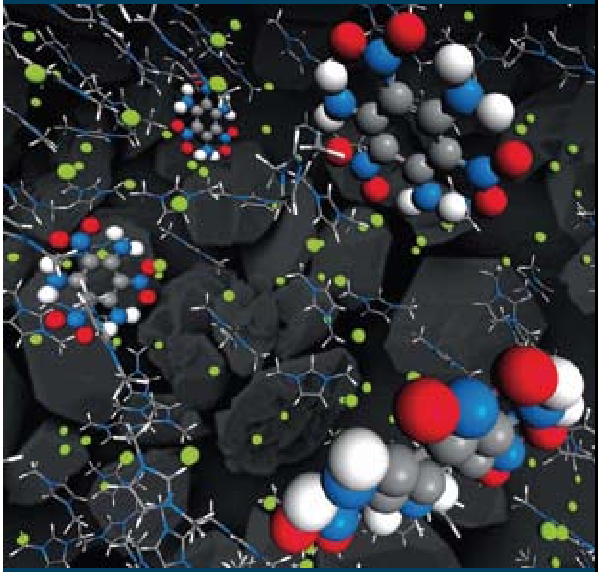
Coming Next Issue

Recycling High Explosives



Computer modeling helps chemists develop a method to recycle a valuable high explosive called TATB.

Also in June

• Postdoctoral researchers apply their expertise to the Laboratory's scientific and technical endeavors.

• A new imaging technique illuminates bacterial metabolic pathways and complex relationships.

• Laser-driven ramp compression may one day reveal the interior structure of Earth-like planets in other solar systems.

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