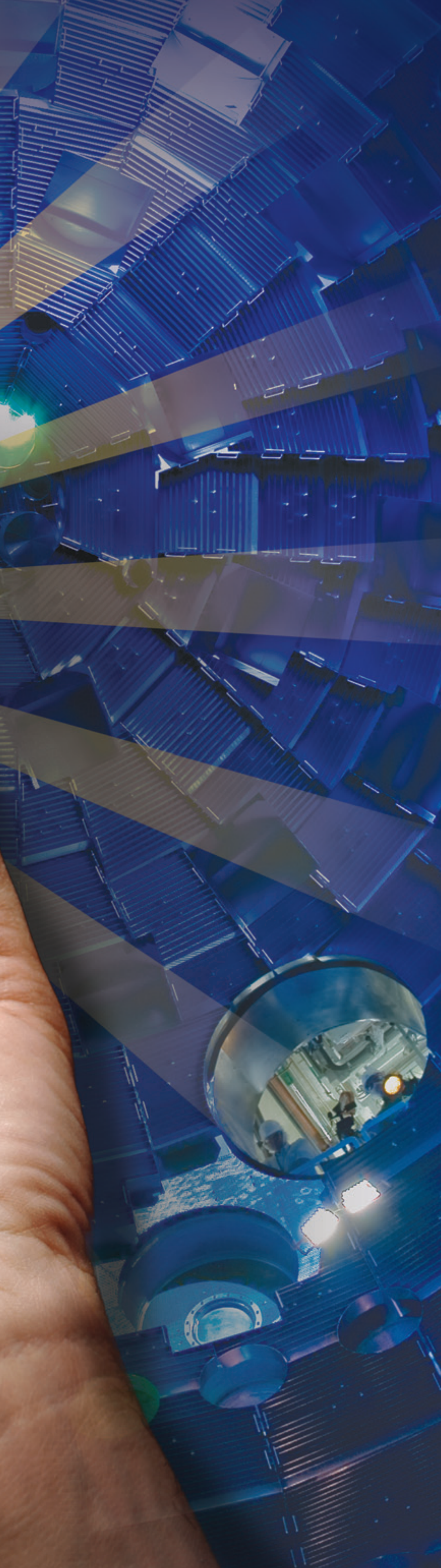
# Igniting Our Energy Future

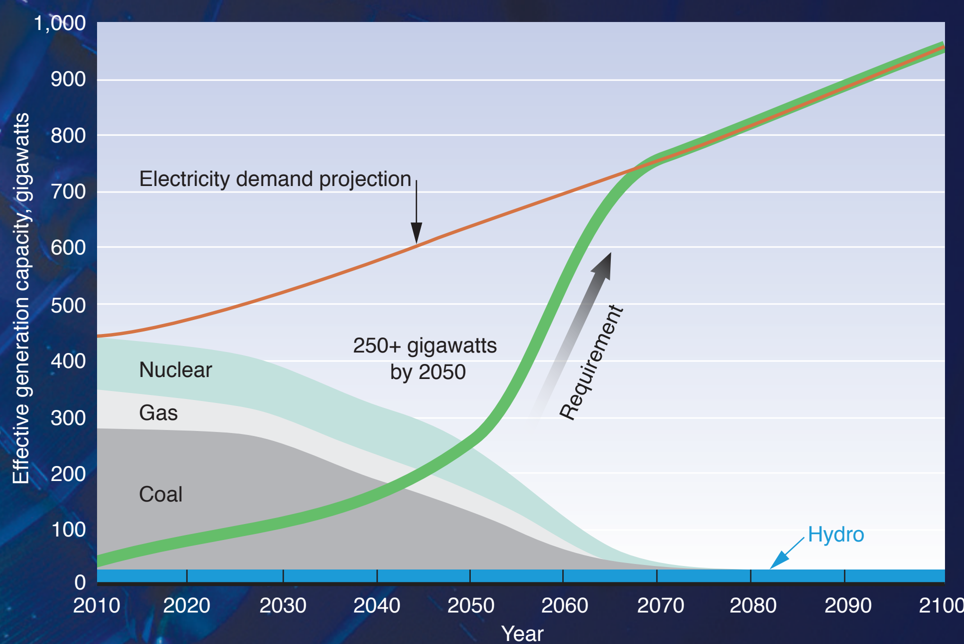
*Livermore researchers are forging a commercial pathway for a revolutionary power plant called LIFE.*



MEETING the nation's—and the world's—growing demand for electricity is one of the most urgent challenges facing society and the scientific community. Even with improvements in energy efficiency and conservation, a critical need exists to reduce dependence on imported fuels, decrease emissions, and stabilize greenhouse gas concentrations. Safe, environmentally sustainable, commercially attractive sources of baseload electricity are needed with an inherent security of supply and the capacity to meet the level of demand. Renewable sources such as solar, wind, and hydro will play an increasingly important role, but they are not expected to meet the majority of global baseload electricity needs.

The main alternative to burning fossil fuels is nuclear energy. Although attractive on many counts (no carbon emissions, for example), conventional nuclear fission plants face significant challenges such as cost to build; time to license; safety and proliferation issues associated with operations; enrichment; reprocessing; and high-level, long-lived nuclear waste.

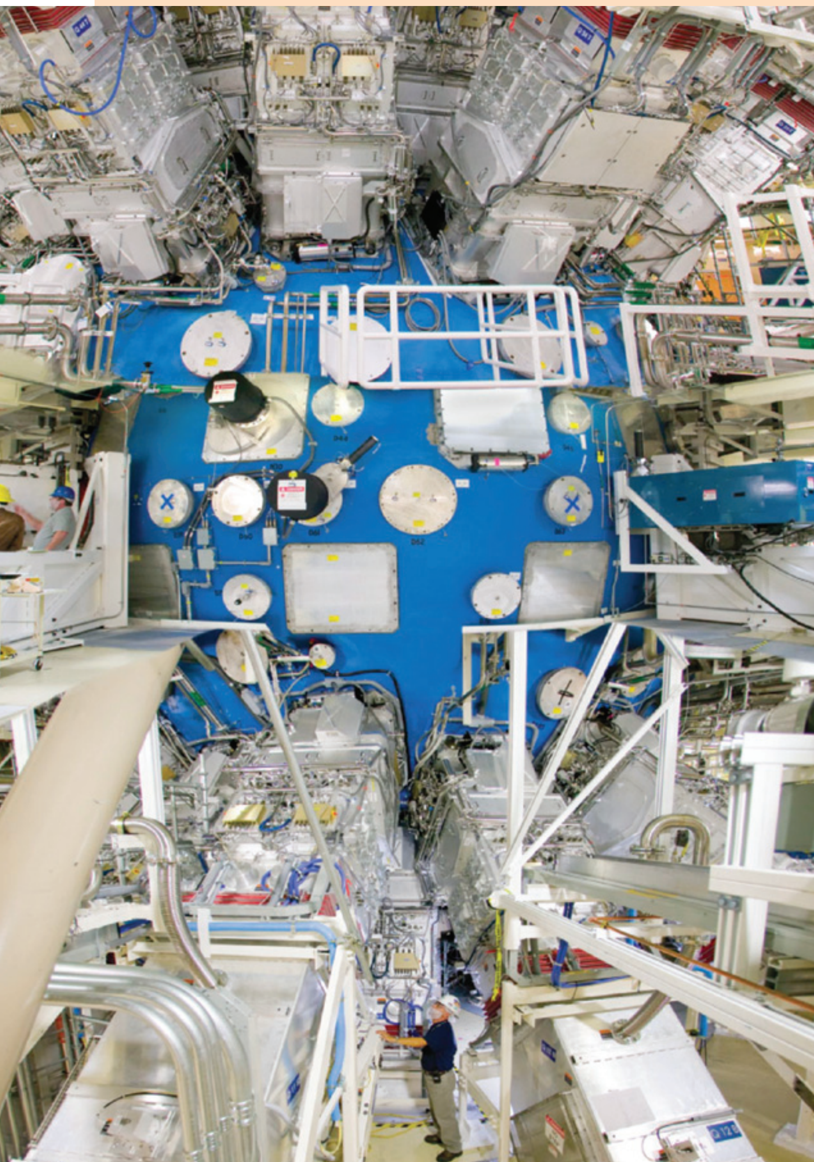
The U.S. energy situation becomes particularly acute in the period leading up to the middle part of this century, when the current fleet of nuclear and coal power plants will need to be replaced. "As a national lab, we must respond to the requirement to transform the energy landscape and do so soon enough to make a difference," says physicist Mike Dunne,




Experts predict the U.S. energy situation will become particularly acute in the middle part of this century, when the current fleet of nuclear and coal power plants will need to be replaced (source: U.S. Energy Information Agency's Annual Energy Outlook, 2009). Based on these power plant retirement curves, a LIFE fleet, beginning with an initial plant in the 2020s, could comprise 25 percent of newly built U.S. electrical generation plants by 2050 and a significantly greater fraction thereafter. Estimates of LIFE's capital and operational costs are strongly competitive with other baseload power plants.

## Making History with the National Ignition Facility

The LIFE plant design builds on the geometry and performance of the National Ignition Facility (NIF) located at Lawrence Livermore. Completed in 2009, NIF is the largest scientific project ever built by the Department of Energy. NIF's 192 laser beams are capable of directing nearly 2 million joules of ultraviolet laser energy in billionths of a second to a fusion target.



NIF is designed to deliver net energy gain (more fusion energy out than the laser beams deliver). The experimental program to achieve fusion and energy gain, known as the National Ignition Campaign, is a partnership between Lawrence Livermore, the Laboratory for Laser Energetics at the University of Rochester, Los Alamos and Sandia national laboratories, and General Atomics, along with collaborators such as Massachusetts Institute of Technology, Atomic Weapons Establishment in the United Kingdom, and Commissariat à l'Energie Atomique in France.

The National Ignition Campaign began experiments in 2009. On September 29, 2010, an experiment successfully demonstrated the integration of all the complex systems required for the laser to ignite fusion fuel. In the test, NIF fired 1 megajoule of laser energy into its first cryogenically layered capsule. Then, on November 2, the team fired 1.3 megajoules of ultraviolet light into a cryogenically cooled cylinder called a hohlraum containing a surrogate fusion target known as a symmetry capsule. This experiment was the highest-energy laser shot in history and the first test of hohlraum temperature and capsule symmetry under conditions designed to produce ignition and energy gain.

"From both a system integration and a physics point of view, the results from these early experiments are extremely encouraging," says Ed Moses, principal associate director of NIF and Photon Science. "They give us increasing confidence that we will be able to achieve ignition conditions in deuterium–tritium fusion targets."

NIF ignition experiments will use a centimeter-size hohlraum containing a millimeter-size, thin-walled plastic or beryllium capsule filled with a mix of deuterium and tritium (hydrogen isotopes) gas. Compression of the capsule by the radiation field in the ignition hohlraum will drive the deuterium–tritium fuel to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reaction. Energy gain has been the goal of the ignition program since NIF was first conceived.

NIF's ability to create extraordinarily high pressures, temperatures, and densities—as much as 100 million gigapascals, 100 million kelvins, and 1,000 grams per cubic centimeter density—will enable major fundamental advances in support of the Department of Energy's national security, energy security, and fundamental science missions. A cornerstone of the Stockpile Stewardship Program, NIF will execute the science experiments necessary to ensure a safe, secure, and reliable nuclear weapon stockpile without underground nuclear testing.

A scientist (bottom center) stands outside the National Ignition Facility's (NIF's) target chamber (blue), where 192 laser beams, in bundles of four, converge at the top and bottom of the target chamber and deposit their energy onto a BB-sized fuel capsule.

Livermore's program director for Laser Fusion Energy.

The Livermore-led effort to address the need for safe, secure, and sustainable energy is called Laser Inertial Fusion Energy, or LIFE. The development activities are headed by Dunne, with contributions by dozens of Livermore physicists, engineers, and materials scientists, along with major input from many other national laboratories, universities, and industry partners. LIFE draws on the success of the National Ignition Facility (NIF), the world's largest and most energetic laser system, and the sustained investment in inertial fusion energy by the Department of Energy and its predecessor agencies over the past five decades. Inertial fusion uses powerful lasers to compress and heat the hydrogen isotopes deuterium and tritium to the point of fusion and thereby liberate more energy than was required to ignite the reaction.

## On the Brink of Ignition

NIF is designed to achieve the extreme conditions needed for fusion ignition, burn, and energy gain—the key milestone in the scientific pursuit of fusion energy as a source of electricity.


(above) An artist's rendering depicts a LIFE plant. (left) A plant could consist of a 100-meter-diameter main fusion operations building (circular building), an electrical generation building housing steam turbines, a tritium building for recovering fuel for new fusion targets, a maintenance bay for chamber refurbishment, and support facilities. At center right are forced-air cooling towers 14 meters tall that could replace the giant cooling towers used in many power plants.

"Demonstration of ignition will establish that the physics underpinning laser-driven fusion energy are fundamentally sound and ready to be exploited," says Dunne. "It will mark the culmination of over 50 years' work." Ignition would provide the basis for initiating a concerted LIFE development program to construct an electricity-producing demonstration plant by the 2020s. This first-of-a-kind power plant would provide the evidence required to allow rollout of a commercial fleet of power plants in the time period when many existing U.S. plants will be retiring. "The LIFE approach marks a dramatic shift from the conventional paradigm for fusion energy, which requires multiple intermediate facilities and much longer delivery timescales," says Dunne.

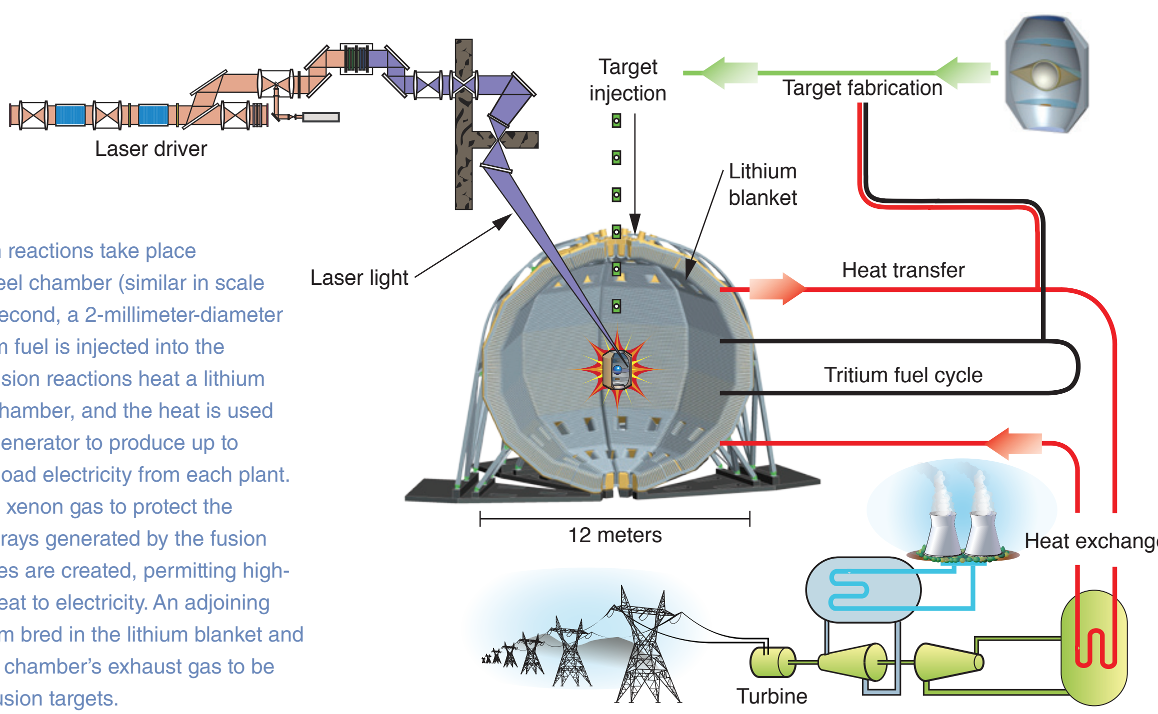
Deuterium and tritium, the fuels for LIFE, are derived from water and the metal lithium, abundant resources that can provide energy security across the globe. LIFE plants would produce no carbon-based or other harmful emissions. A principal benefit of a LIFE power plant is its intrinsic safety. No possibility would exist of a runaway reaction, a core meltdown, or the release of long-lived radionuclides. Decommissioning would only involve removal of steel and concrete structures for shallow land burial. When operations stop, the residual heat in the system does not require active cooling, so one can just walk away from the plant without any off-site consequences in the event of a natural disaster. The by-product of fusion is helium gas, which avoids the problem of spent-fuel storage.

The heart of LIFE is a laser fusion "engine," where 2-millimeter-diameter fuel capsules are injected into a chamber about 16 times every second (similar to the rate of an idling car engine). When the nuclei of deuterium and tritium fuse, the reaction creates a helium nucleus and releases a high-energy neutron. The repeated fusion reactions produce a steady stream of neutrons that heat a lithium blanket surrounding the chamber. The heat is used to drive a steam-turbine generator to produce up to 1,500 megawatts of baseload electricity from each plant.

## Cost-Cutting Consciousness

The LIFE team is currently focused on meeting the required performance and costs for the dozens of systems and subsystems comprising a power plant. More than 30 vendors have been engaged from the semiconductor, optics, laser, construction, nuclear project delivery, and power-generation industries to assess component availability, performance, and cost. The team is taking advantage of marketplace advances for such components as laser diodes.

"LIFE economics will be strongly competitive with nuclear power plants and other low-carbon sources of electricity," says Dunne. The first LIFE power plant is being designed to generate a few hundred megawatts of electricity for the demonstration of continuous operation, high availability, and overall system reliability. Subsequent plants would likely




In the LIFE design, fusion reactions take place in a 12-meter-diameter steel chamber (similar in scale to NIF). Sixteen times a second, a 2-millimeter-diameter target of deuterium–tritium fuel is injected into the chamber. The repeated fusion reactions heat a lithium blanket surrounding the chamber, and the heat is used to drive a steam-turbine generator to produce up to 1,500 megawatts of baseload electricity from each plant. The chamber is filled with xenon gas to protect the chamber from ions and x rays generated by the fusion process. High temperatures are created, permitting high-efficiency conversion of heat to electricity. An adjoining tritium plant extracts tritium bred in the lithium blanket and unburned tritium from the chamber's exhaust gas to be used for producing new fusion targets.

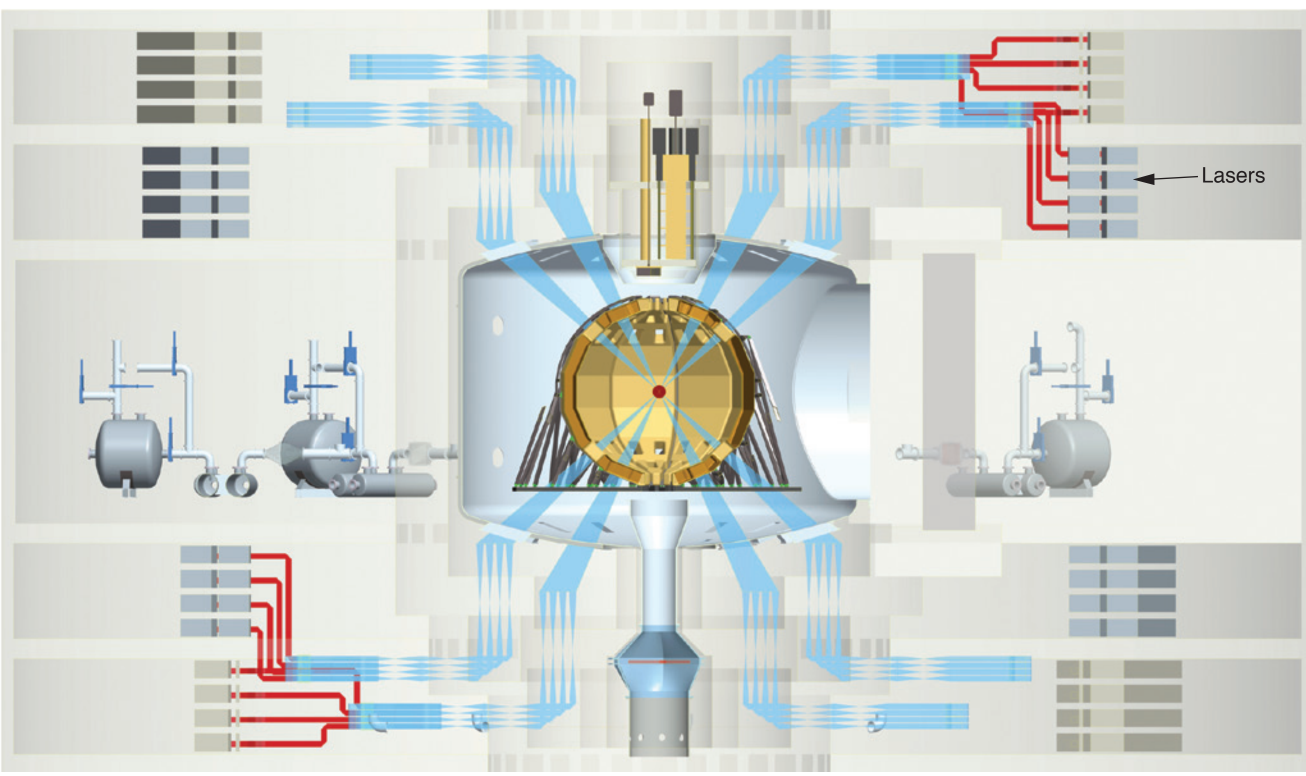
approach a gigawatt or more, benefiting from the significant economies of scale.

LIFE scientist Jeff Latkowski notes that the efficiency of the laser driver in converting energy supplied from the electrical power grid to the energy needed to compress the capsule, coupled with the energy "gain" of the capsule, must be sufficient to yield substantial net energy. The efficiency of the 2.2-megajoule laser driver is calculated to be 16 percent, coupled to a steel-blanket gain of 1.25, a thermoelectric conversion efficiency of 45 percent, and a fusion target gain of 60 (fusion energy divided by laser energy). This combination of efficiencies leads to a commercially acceptable overall plant gain of about 5.

Aiding cost efficiencies is the adoption of modular, line replaceable units (LRUs) throughout the plant. LRUs allow off-site factory construction and easy replacement of individual elements of the system, while maintaining plant operations. The LIFE strategy is to make components small, modular, and cost-effective. Modularity also permits improvements to be made throughout the lifetime of the plant, as long as the new technology fits in the same "box."

LRUs are used extensively on NIF and were previously instrumental in the atomic vapor laser isotope separation (AVLIS) project at Livermore. AVLIS used high-repetition-rate, multikilowatt lasers to separate isotopes of uranium. For more than 10 years, AVLIS demonstrated 24/7 operation with 99 percent availability. Several current LIFE and NIF managers have had experience running AVLIS. Ed Moses, principal associate director for NIF and Photon Science, for example, directed AVLIS operations for several years.

"Intense design, development, and review have led to enormous progress in the LIFE electrical power plant design over the past two years to meet performance and cost goals," says Moses. "LIFE will be based on the demonstration of fusion ignition at NIF and will use that facility's physics platform and architecture. However, the LIFE design has been transformed into a completely modular, factory-built laser system that can be put together and maintained using line replaceable units. An entire LIFE plant will be smaller than NIF and yet produce enough energy to power a city the size of San Francisco."




A cross-section of a LIFE power plant shows how it is based on the geometry of NIF. LIFE's 384 laser beamlines (twice the number as NIF) converge on a tiny target located inside the target chamber. The plant, optimized for high availability, features modular, factory-built components using existing materials and technologies.

A LIFE design team strategy session includes scientist Jeff Latkowski (standing, far left), Mike Dunne, program director for Laser Fusion Energy (standing, far right), and Ed Moses, principal associate director of NIF and Photon Science (seated below Dunne). Many Livermore physicists, engineers, and materials scientists are contributing to the LIFE design effort.

### Listening to Utilities

The current LIFE power plant design is derived from the requirements of utilities, vendors, licensing bodies, and other stakeholders. "Rigorously addressing end-user requirements produces a very different design and delivery path than conventional approaches based on technical performance alone," says Dunne. This approach drives researchers to go beyond technical performance issues to take into account such factors as costs of construction and electricity production, licensing, reliability, availability (the amount of time the plant produces electricity), maintainability, inspectability, operability, urban environmental and safety standards, and public acceptability.

LIFE managers regularly confer with electric utility chief executive officers from across the U.S. and abroad. A group of utility executives recently formed an advisory committee to share industry expertise, experience, and insights with the LIFE development team. "When visitors from the power industry tour NIF, they realize a commercial plant could be viable soon enough to make a difference," says systems engineer Tom Anklam, who heads the effort to integrate LIFE's many systems.

"We've had a staggeringly positive response from the power industry," says Dunne. "But this is a hard-nosed industry that wants to know how we go from NIF's proof of principle to operating a commercial fleet of power plants. What matters to utilities is cost to build, cost to operate, reliability, and licensing pathways."

As a result of the advisory group meetings, LIFE designers took a long hard look at their approach. "We transformed a design that looked like an incremental adaptation of NIF into a commercially viable power plant," says Dunne. The new design emphasizes integrated coupling between every major system, an effort headed by Anklam.

Engineer Valerie Roberts, deputy principal associate director of NIF and Photon Science Operations, oversaw construction of NIF. Roberts is now working on the project delivery plan. "We want a plant that industry can build easily and reliably," she says. The LIFE design currently consists of a main fusion operation building, an electrical generation building housing steam turbines, a tritium building for recovering fuel for new fusion targets, a maintenance bay for chamber refurbishment, and all the required support facilities.

An earlier version of LIFE focused on a fusion–fission hybrid design that used waste from nuclear power plants as well as weapons-grade plutonium for fuel. (See *S&TR*, April/May 2009, pp. 6–15.) Although this option remains a possibility, the team is now focusing on a pure fusion option.

Instead of enormous cooling towers that characterize many existing power plants, LIFE features advanced forced-air cooling towers just 14 meters tall. Roberts says a LIFE plant could be placed in an urban setting on a site measuring 300,000 to 400,000 square meters (75 to 100 acres). It could also be sited at a retired coal or nuclear power plant to take advantage of much of the existing electrical grid infrastructure.

### Fusion Reactions in LIFE Chamber

In the LIFE engine, fusion reactions occur in a 12-meter-diameter steel chamber similar in scale to the NIF system. The modular, factory-built first wall and blanket comprising the chamber is constructed from existing materials and rapidly replaced as needed every few years. A series of U-shaped steel tubes forms the first wall, backed by a thick blanket that allows the lithium to absorb the neutron energy and flow to a heat exchanger.

The chamber is constructed from eight modules that can be withdrawn on rails to a maintenance bay in isolation or as a complete unit. The chamber is housed inside a separate vacuum vessel, with connections only for cooling lines. By decoupling the chamber from the vacuum and optical systems, a relatively rapid exchange can be achieved.

The chamber will be filled with xenon gas to absorb ions and x rays given off by the fusion process, which otherwise would be damaging to the chamber wall materials. The gas does not interfere with the laser beam propagation or target injection.

The ability of a LIFE plant to generate high temperatures (typically 600°C) in the first wall and blanket permits high-efficiency conversion of heat to electricity. Liquid lithium running through both the first wall and blanket will capture the heat. Lithium was chosen as the LIFE coolant because when lithium atoms absorb the neutrons generated by the fusion reactions, the lithium is transmuted to tritium and helium. "A LIFE plant would breed all the tritium needed for the targets," explains Latkowski. The adjoining tritium plant would take tritium that has been bred in the lithium coolant and unburned tritium from the chamber exhaust gas for use in producing new fusion targets.

A typical LIFE plant will require up to 1.3 million targets daily. Techniques for the manufacture of large quantities of targets are being explored, along with methods to inject them accurately to the center of the target chamber at a velocity of 250 meters per second. A target factory alongside the fusion building will assemble targets from components manufactured off site. Independent analyses of target production factories show that mass production techniques should yield costs of $0.20 to $0.30 per target.

Each LIFE target will contain only about 0.7 milligrams of tritium. The site inventory of tritium will be low, with substantial segregation to ensure safe operations.

## Diodes Transform Laser System

Engineer Robert Deri leads a team that is developing a compact, efficient, cost-effective laser system to drive the LIFE power plant. Deri notes that NIF's 192 beams were designed to fire simultaneously only once every few hours. After each shot, the laser glass must cool down to ensure that the optics operate correctly for the next shot. A LIFE plant, however, must operate at a much higher repetition rate (15 hertz). To achieve this, the team is taking advantage of recent advances in laser architecture and semiconductor technology that permit high-average-power operation.

Development of high-efficiency, high-repetition-rate, diode-pumped solid-state laser beamlines is under way for several international projects. In addition, technology and experience from Livermore's AVLIS and Mercury lasers and other high-average-power solid-state lasers is being incorporated into LIFE. Mercury can fire 10 shots a second over extended periods, using cooling technology that is being implemented at a larger scale in the LIFE laser design.

Whereas NIF uses 2-meter-long flashlamps to energize the neodymium atoms in the laser glass amplifiers, LIFE would rely on laser diodes. The diodes are 20 times more efficient than flashlamps, measure 10 to 12 times smaller, and give off substantially less waste heat. "Laser diodes give us the ability to fire 15 times a second, 24 hours, 7 days a week," says Deri.

More than 100 million diodes will be required for LIFE's 384 beamlines. "We're working closely with 14 laser-diode manufacturers to lower costs because diodes will account for a substantial fraction of the laser system's cost," says Deri. He compares the team's association with industry to the cadre of NIF scientists who worked closely with laser glass companies to manufacture affordable laser optics with unprecedented purity and performance.

Deri's team has designed an entire 1,053-nanometer wavelength infrared-light beamline that fits in one truck-transportable box—a "beamline in a box." (See the figure on p. 12.) Measuring less than 11 meters long, the beamline can be handled as an LRU. The compact size would allow for off-site manufacture, ease of maintenance during operation, and even changeover of individual beamlines while the plant remains operational. Beamlines would also have the ability to enhance their output to compensate for a failed neighboring beam. Optics outside the beam box would convert incoming laser light to 351-nanometer wavelength ultraviolet light for focusing on fusion targets. An important milestone during the intense component development phase will be construction of a "LIFElet," that is, a full-scale laser beamline for testing.

## Demonstration Plant

The next step on the path to commercial LIFE plants would be a five- to seven-year technology development program, followed by a demonstration power plant generating about 400 megawatts of electricity. This plant, which could be operational by the mid-2020s, would demonstrate integrated operation of a commercial LIFE plant design. The demonstration plant would provide the required fusion environment for full-scale testing of materials, components, and systems; provide qualification and certification data for licensing of subsequent commercial plants; and drive vendor readiness for rollout of a commercial fleet.

"We aim to build a demonstration power plant. That's much different from a typical technology test facility," says Dunne. "By basing the design on evidence from NIF and using existing technology options, our strategy eliminates the costs and delays associated with a stepwise approach needed for other approaches to fusion. These approaches require multiple facilities to mitigate the risks arising from unproven physics, use of novel materials, and new technologies."

The team calculates that LIFE plants could deliver 25 percent of U.S.

electrical generation by 2050. Estimates of LIFE's capital and operational costs are highly competitive with other energy alternatives. Rollout of LIFE plants that would displace coal plants beginning in the 2030s could result in a decrease of 90 to 140 billion metric tons of carbon dioxide-equivalent emissions by the end of the century.

While LIFE researchers continue their design work, two national organizations are studying the cost effectiveness and scientific principles behind LIFE. The first study, by the Electric Power Research Institute, focuses on the best avenue toward a working fusion power plant. The second, by the National Research Council, is studying the technology goals, challenges, and path forward for inertial fusion energy.

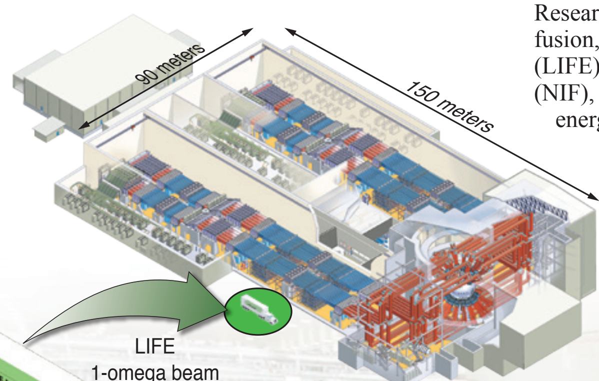
Dunne believes that a strong national partnership among industry, national laboratories, government, nongovernmental organizations, and academia is required to deliver LIFE. Livermore researchers are already working closely with General Atomics on targets; Savannah River and Los Alamos national laboratories and Princeton Plasma Physics Laboratory on design of tritium systems; the University of Rochester's Laboratory for Laser Energetics on target and laser designs; the University of Wisconsin, University of California at San Diego, and University of Illinois on target chamber design; the Naval Postgraduate School on welding of specialty steels; and industry on all aspects of the power-generation technology.

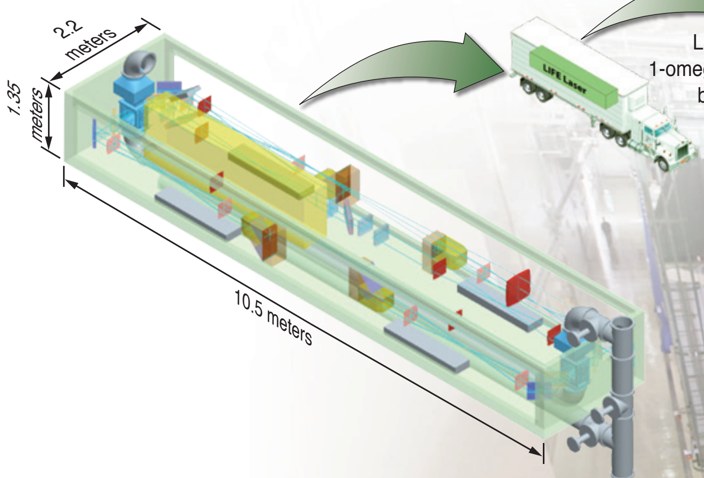
"When ignition and gain are achieved on NIF, we will have a substantive delivery plan to take us to a commercial plant," says Dunne. "We will be ready to go."

*—Arnie Heller*

**Key Words:** deuterium, Electric Power Research Institute, electricity, flashlamp, inertial fusion, laser diode, Laser Inertial Fusion Energy (LIFE), lithium, National Ignition Facility (NIF), National Research Council, nuclear energy, power plant, tritium.

***For further information contact Mike Dunne (925) 423-7955 (dunne8@llnl.gov).***




(above) This conceptual design shows how an entire 1,053-nanometer wavelength infrared-light laser beamline fits in a truck-transportable container. Because it measures less than 11 meters long, the beamline offers off-site manufacturing, ease of maintenance during operation, and even replacement while the plant remains operational. A truck holding a LIFE laser beamline is shown for size comparison next to NIF. (right) A mock-up of a LIFE "beam box" in the NIF laser bay shows the factor-of-10 size reduction compared to the NIF beamlines.