Printed on recycled paper.

University of California
Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

Nonprofit Org.
U.S. Postage
PAID
Albuquerque, NM
Permit No. 853

March 1998

Science & Technology REVIEW

Lawrence
Livermore
National
Laboratory

Targeting Laser Technology for NIF

Also in this issue:

- **Carbon Dioxide's Role in Global Warming**
- **Software for Safety-Critical Systems**
- **LLNL's Strategy for EUV Lithography**

About the Cover

Researchers at Livermore's National Ignition Facility (NIF) are developing, testing, and validating many technologies especially for the new facility, which will be completed in 2003. For example, technician Wanda Dallum holds a flashlamp—the largest commercially made—one of 7,680 flashlamps to be used in the NIF amplifier modules. In the background, one of the main amplifier modules glows during a test of flashlamps. This image is part of an animated sequence that can be seen on the Internet at *http://lasers.llnl.gov/lasers/1st/SSL/*.

Cover design: George Kitrinos

What Do You Think?

We want to know what you think of our publication. Please use the enclosed survey form to give us your feedback. On this month's form, we show results of the past year's survey forms.

Electronic Access

S&TR is available on the Internet at *http://www.llnl.gov/str*. As references become available on the Internet, they will be interactively linked to the footnote references at the end of each article. If you desire more detailed information about an article, click on any reference that is in color at the end of the article, and you will connect automatically with the reference.

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published ten 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.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 422-8961. Our electronic mail address is *hunter6@llnl.gov*.

Prepared by **LLNL** under contract
No. W-7405-Eng-48

S&TR Staff

Scientific Editor
J. Smart

Managing Editor
Sam Hunter

Publication Editor
Sue Stull

Writers
Arnie Heller, Sam Hunter, Sue Stull, Katie Walter, and Gloria Wilt

Art Direction and Design
George Kitrinos

Internet Designer
Kitty Tinsley

Compositor
Louisa Cardoza

Proofreader
Al Miguel

S&TR is a Director's Office publication, produced by the Technical Information Department, under the direction of the Office of Policy, Planning, and Special Studies.

Printed in the United States of America

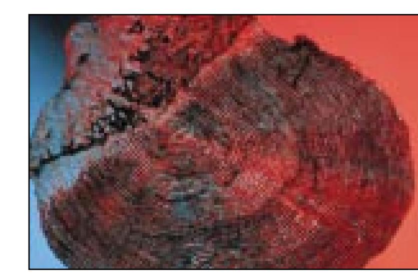
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-52000-98-3
Distribution Category UC-700
March 1998

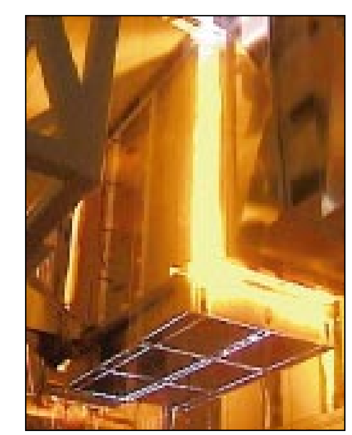
Science & Technology REVIEW

March 1998

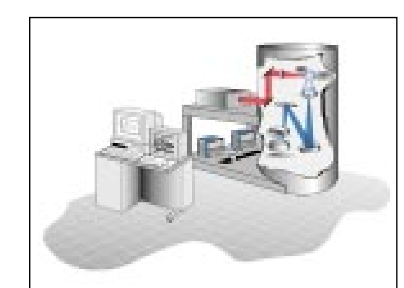
Lawrence Livermore National Laboratory



Page 14



Page 4



Page 24

Laser for safer airplanes, more durable hip implants

Airplane components, hip implants, and other products are in for a big shock from a powerful laser developed at the Laboratory. Early expected results: safer airplanes and more durable hip implants, achieved through a metal-working process that will employ the new laser.

Livermore researchers have developed a neodymium-doped glass laser with 600 watts of average power, capable of firing 10 pulses per second compared with 1 pulse every 2 seconds from the best commercial lasers. Laser peening, or surface treating, won't replace conventional shot peening, but it will be used in areas where deeper depths of compressive stress are needed.

The Lab and a New Jersey firm, Metal Improvement Co. Inc., have signed a license agreement and cooperative research deal to adapt laser technology to peen metal.

Historically, metals have been peened by bombarding the material with metal balls as small as salt grains to induce compressive stress that prevents metal fatigue and reduces corrosion. Laser peening was developed in the 1980s but never went into production because of high cost and slow lasers.

The new laser could have an impact in the aviation industry, where it could be used for peening jet engine components such as rotors, disks, blades, and shafts. It may ultimately help the military to address its number-one propulsion concern—high cycle blade fatigue. Another use could be in the medical industry to treat surfaces of hip-joint implants.

The Livermore laser technology has been funded by the Department of Energy, the Defense Advanced Research Projects Agency, the U.S. Navy, and the U.S. Air Force's Phillips Laboratory.

Contact: Public Affairs Office (510) 423-3107 (wampler1@llnl.gov).

PHENIX magnet tested

The search for the elusive quark–gluon plasma, a form of matter believed to hold subatomic matter together, took a major step forward with the successful testing of the first of three magnets for the PHENIX (Photon Electron New Heavy Ion Experiment) Detector System. A team of Livermore scientists was responsible for the design, supervision of fabrication, and testing of the magnet system, which will be part of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.

Heavy-ion particles produced by the RHIC accelerator collide in the center of the central magnet of PHENIX and produce a distinctive signature associated with the collisions. From resulting data, scientists hope to pinpoint the presence and behavior of the quark–gluon plasma.

The National Academy of Sciences calls the RHIC and PHENIX experiment "the No. 1 priority for nuclear physics going into the 21st century."

Contact: Bob Yamamoto (510) 422-5736 (yamamoto1@llnl.gov).

Workers unearth 10,000-year-old fossils

Bones from what is thought to be a mammoth were unearthed at the National Ignition Facility (NIF) construction site in December and January. Compacting the soil in a utilities trench more than 30 feet below ground level caused some soil to fall away, revealing a tusk and some back and hip bones.

The find is a more complete mammoth skeleton than usual, says principal scientist Mark Goodwin of the Museum of Paleontology at the University of California, Berkeley. "It's significant because we [also] have a partial skull and nearly complete lower jaw. It gives people a slice of life of what California was tens of thousands of years ago. It's our fossil heritage." The tusk alone weighs some 150 to 200 pounds. Goodwin estimated that the bones may be between 10,000 and 75,000 years old.

An excavation team carefully exposed and cleaned the bones, applied a hardening varnish, and covered the bones with a layer of wet paper towels followed by strips of burlap dipped in plaster for the move to Berkeley's Museum of Paleontology, where they will be further cleaned and preserved.

Contact: Public Affairs Office (510) 422-4599 (garberson1@llnl.gov).

Lab hosts demining talks

The Lab held a two-day conference to study issues and technologies for finding and disarming land mines. International experts talked about the economic, psychological, and physical effects of land mines, which kill 2,000 people worldwide each month. Lab scientists are currently working on a number of possible solutions—from mine-detecting robots using micro-impulse radar to detect buried land mines to ground-penetrating radar and infrared, nuclear, and chemical sensors.

Contact: David Eimerl (510) 422-7505 (eimerl1@llnl.gov).

Largest construction contract for NIF

Hensel Phelps Construction Co. of San Jose, California, has been awarded a $65.5-million contract to complete architectural build-out and finishing of the structure to house NIF, the world's largest laser. The contract is the largest single subcontract for the NIF construction project. Slated for completion in 2003, the facility is a stadium-sized, $1.2-billion, 192-beam laser complex now under construction at the Laboratory.

The new contract covers build-out and finishing of the main laser building, including mat and foundation slabs in two laser bays; installation of all interior walls and doors; heating, ventilating, and air-conditioning systems; plumbing and piping for water and other utilities; fire protection; power and communication duct banks; complete electrical systems; central plant boilers and chillers; and site finishing work.

Contact: Public Affairs Office (510) 423-3117 (yano1@llnl.gov).

Developing the World's Largest Precision Optical Instrument

THE National Ignition Facility (NIF) Project is being built as a major component of the Department of Energy's Stockpile Stewardship Program to preserve confidence in the safety and reliability of remaining U.S. nuclear weapons and to preserve core nuclear weapons competencies in the absence of nuclear testing.

NIF is the largest and most complex project the Laboratory has ever undertaken. It will contain the world's largest laser, which will be the world's largest precision optical instrument of any kind, having more than three-quarters of an acre of precision optical surfaces. With many missions and objectives, this gigantic laser must still be very flexible and precise. As we have learned from our Nova laser, NIF must have precision temporal control, coherence control, and focal spot beam control. The NIF laser cannot be merely an experiment; rather, it must be the precision tool used for the experiments on fusion targets. It must perform reliably over a wide variety of specifications and be available at the planned shot rate.

The cover article of this issue, beginning on p. 4, addresses the extensive laser development program we have planned and are now completing to ensure that the NIF laser will indeed perform as planned and will meet its budget and schedule. Assuming ignition and gain are achieved, NIF will also be the scientific proof of principle of using inertial fusion as an energy source. Although it will require many technology developments, inertial fusion energy will not contribute to global warming, a very serious world issue (see article beginning on p. 14). Finally, NIF will open doors for the basic sciences in the study of high-energy-density physics, the physics of the stars.

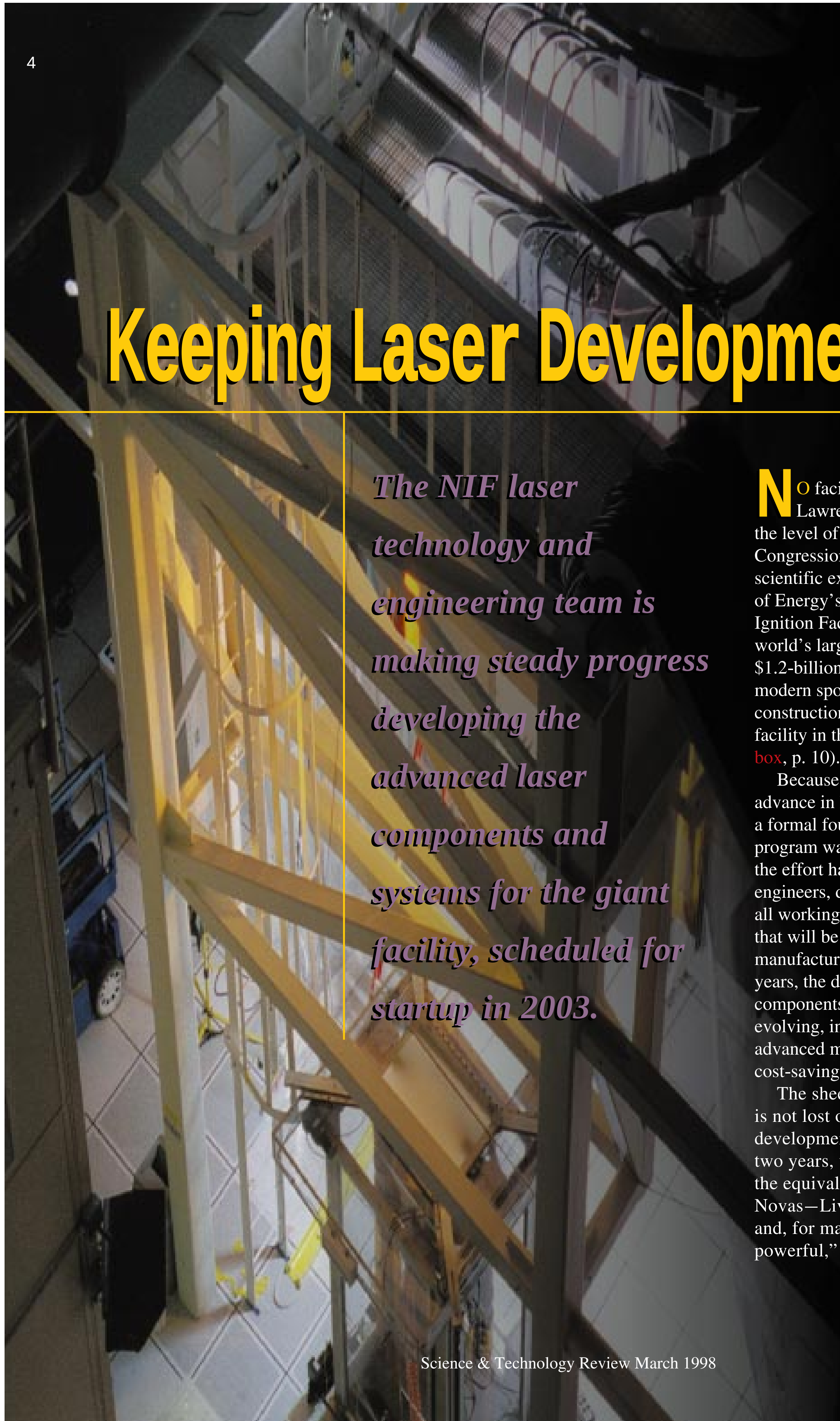
In the face of such a daunting task, we are nonetheless confident that NIF will be successful. Over the last 25 years, Livermore has built a world-renowned collection of laser scientists, engineers, and technological capabilities; we also have an excellent infrastructure to support it. This outstanding combination of science and engineering makes the massive NIF undertaking a logical extension on a grand scale of what we have accomplished before.

Critical partners are helping us accomplish this undertaking and critiquing our work. France has been an important partner in developing the laser and optics technology for NIF and for their own planned counterpart, the Laser Mégajoule, which is a part of their stewardship program. We have also had valuable contributions from Sandia National Laboratories in pulsed-power technology and from the University of Rochester and Los Alamos National Laboratory in optics technology. Their overall contributions to the project both technically and managerially are significant.

Building NIF helps the Laboratory maintain its leading role in the science and technology of lasers and optics. NIF is pressing the state of the art in many areas. For example, we had to develop the world's largest optical amplifiers and optical switches to make NIF possible at an affordable cost. The optical pulse-generation system for NIF will be a major step in laser control and flexibility. On Beamlet, the one-beam testbed, we had to prove the performance of new optics that run at very high optical fluence.

These developments create new opportunities for the Laboratory and for the companies we are working with. An example of such spinoffs in inertial confinement fusion is our extreme ultraviolet lithography program (see "Keeping the 'More' in Moore's Law," pp. 24–26), which grew out of our target physics diagnostic work and now promises to change the way semiconductor circuits are made. Building NIF keeps the Laboratory squarely in the worldwide leadership role in this field as we approach the next millennium.

E. Michael Campbell is Associate Director, Laser Programs



Keeping Laser Development on Target for the National Ignition Facility

The NIF laser technology and engineering team is making steady progress developing the advanced laser components and systems for the giant facility, scheduled for startup in 2003.

No facility in the 46-year history of Lawrence Livermore has triggered the level of publicity, public and Congressional scrutiny, and sheer scientific excitement as the Department of Energy's forthcoming National Ignition Facility (NIF), by far the world's largest laser. This enormous $1.2-billion facility, the size of a modern sports stadium, is the largest construction project and permanent facility in the Laboratory's history (see box, p. 10).

Because NIF represents such a large advance in laser size and performance, a formal four-year laser development program was launched in 1995. So far, the effort has tapped 250 scientists, engineers, designers, and technicians, all working to provide validated designs that will be transferred to industry for manufacturing. Over the past three years, the designs of hundreds of components have been steadily evolving, incorporating numerous advanced materials, technologies, and cost-saving features.

The sheer scale of the undertaking is not lost on the NIF laser technology development team. "Every month for two years, we're going to be building the equivalent of approximately two Novas—Livermore's 10-beam laser and, for many years, the world's most powerful," notes Dick Hackel, associate program leader for Livermore's Laser Science and Technology (LS&T) Program.

Taking a Big Leap

Physicist Howard Powell, head of the LS&T Program, points out that NIF's projected power, enough for laboratory fusion experiments to achieve energy break-even and gain for the first time, necessitates a laser facility with unparalleled levels of sophistication. "We're going from working with Nova's 10 beams to manipulating 24 sets of 'bundles' containing 8 beams apiece. That's a big leap."

The size of NIF has required new, multibeam components and controls and new techniques for troubleshooting and maintaining the giant laser. The effort includes readying component replacement strategies based on the concept of modular line-replaceable units. Additionally, unprecedented attention is being paid to maintain cleanliness throughout the huge system to prolong the life of all components.

Powell points out that some of the laser technology development has been done in collaboration with colleagues from the French Commissariat à l'Energie Atomique (CEA), other DOE national laboratories, and the University of Rochester. The French agency plans to build its Ligne d'Intégration Laser by 2001 and its Laser Mégajoule with specifications similar to NIF's by 2010. Other productive collaborations include those forged with literally hundreds of vendors. Beginning next year, these companies will be manufacturing tens of thousands of NIF components, many of them to unprecedented levels of performance.

Fundamental to the development work has been a one-beam scientific testbed called Beamlet (see box, p. 8) that has permitted the online evaluation of the NIF laser design and operating specifications. Complementing Beamlet is Amplab, a complete working prototype of a NIF amplifier module for an eight-beam bundle.

As final design changes are made and prototypes are built and tested, an important focus has been on ensuring performance and reliability. "We're going to be buying at least 192 of most items, so we want to make sure the parts work exactly as we specify," notes Powell.

Driving Down Costs

Another major focus has been substantial cost reduction. New approaches to component design were required to reduce costs without impacting performance.

"Cost drives every design. We're always questioning whether we can make it more compact or with fewer parts. Although the NIF facility will be enormous, it will be literally packed with components," says Richard Sawicki, NIF associate project engineer for special equipment.

Some cost-effective measures have been relatively simple, such as making the laser beams square so they can be packed closer together to save space and multiplexing some components, such as the flashlamps in the main amplifiers. Other cost-saving measures, such as the multipass laser design, in which the beams are passed through the same amplifiers several times, are more complex; yet this design will save millions of dollars by reducing the number of amplifiers and facility space needed. Other designs emphasize the sharing of components wherever possible or mechanical structures that support several systems simultaneously.

Cost-cutting efforts rely increasingly on computer-aided design. "When we built Nova, the designers used pencil and paper and built a lot of full-scale models," notes Sawicki. In contrast, NIF parts are designed and scrutinized on computer by a team of a hundred designers using the latest three-dimensional engineering software. Even entire systems, on the scale of hundreds of meters, are modeled on computers to make sure there is adequate room to move equipment in and out.

Another major computer role is simulating the evolution of the beam as it propagates through every laser system. Livermore codes that model the work of the flashlamps and amplifiers as well as the beam itself are saving crucial development time. After analyzing the predicted performance, cost, and safety of over 100,000 design variations of the amplifier systems, the codes also were used to choose the optimum laser design.

Birth of a Pulse

The main laser components in NIF (Figure 1) take a low-power laser pulse from the master oscillator, shape and smooth it, amplify it enormously, and precisely direct it at a minuscule target called a hohlraum. Major laser components include the optical pulse generator, the amplifiers, the pulsed-power system to drive the amplifiers, the optical switch, a final optics assembly to convert frequency to ultraviolet and focus the beams, and the beam control system. Each of these key components has required significant technology advancements.

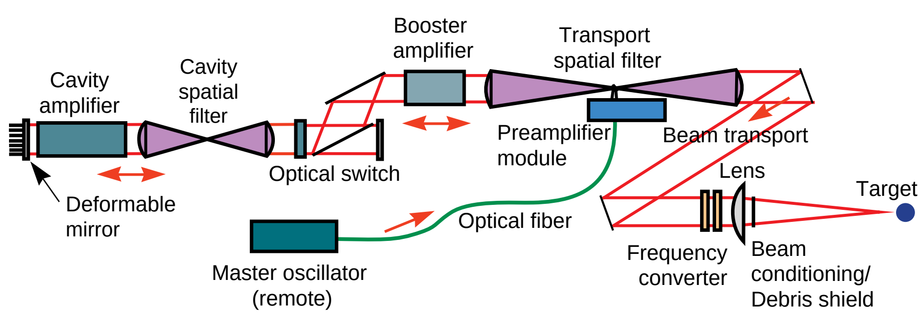


Figure 1. The layout of NIF's major components through which a pulse of laser light travels from injection to final focus on the target.

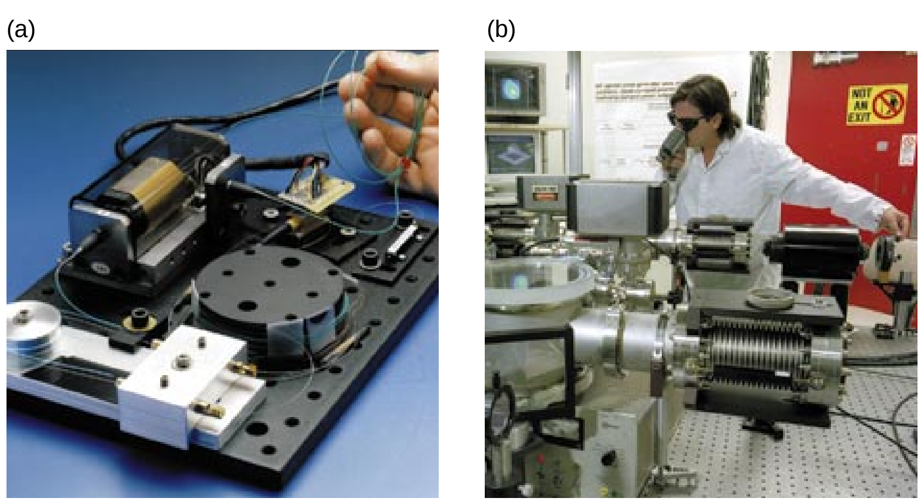


Figure 2. (a) NIF's low-power pulse is first amplified by these ytterbium-doped optical fibers (seen glowing blue at lower left). (b) The pulse is then amplified to 22 joules by four-pass amplifiers (here tested in the laboratory by technician Mike Martinez), which are part of the preamplifier module (PAM).

The primary function of the optical pulse generation (OPG) system, NIF's "front end," is to generate, amplify, and shape the laser beams before they enter the main amplifiers. The OPG system, which uses fiber optics technology extensively, was designed to be highly versatile to satisfy the broad range of NIF experimental requirements.

NIF's laser pulse will be born in the master oscillator room (Figure 2). Here, a small, compact oscillator made of ytterbium-doped optical fiber generates weak laser pulses (a few nanojoules with a beam diameter of a few micrometers). The oscillator pulse is shaped in time and broadened over multiple colors, which are used to smooth the intensity of the laser spot on the target. Each of the pulses is then transported to preamplifier modules (PAMs) for amplification and beam shaping.

Each PAM first amplifies the pulse by a factor of about a million, to a millijoule, and then boosts the pulse once again, this time to a maximum of 22 joules, by passing the beam four times through a flashlamp-pumped amplifier (Figure 3). The most challenging aspect of OPG development, according to engineer John Crane, has been the four-pass amplifier design. With an eye on cutting costs, NIF managers decided last year to reduce the number of PAMs from 192 to 48, with one PAM feeding four separate beamlines. As a result, the PAM's output energy requirement went up substantially. Laboratory testing of complete PAM prototypes with more powerful amplification has been validated, says Crane.

To perform the range of experiments needed on NIF, the PAMs must perform three kinds of shaping of the input laser beams.

- Spatial shaping to make the square beam more intense around the edges to compensate for the higher gain profile in the center of the large amplifiers.
- Spectral shaping and beam smoothing to eliminate both hot spots and dark spots at the focus by manipulating the focal beam pattern with fast changes in wavelengths.
- Temporal shaping to ensure that the laser pulse delivers energy to the target with a prescribed time-history for efficient ignition.

Amplifying the Beam

The two large amplifier units in each NIF beamline are designed to efficiently amplify the nominal 1-joule input pulse from the OPG system to each of the 192 beams to the required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics.

The amplifiers, with 16 glass slabs per beam, are arranged in two units—the so-called cavity amplifier and the booster amplifier. Together, they are the laser system's central component. "The main amplifiers provide 99.9% of NIF's power and energy, so their performance is crucial," says development scientist Chris Marshall. When fully integrated with optics, flashlamps, pulsed power, and other related components, the amplifiers are also the costliest NIF system.

"We've never built laser amplifiers on this scale," comments NIF system engineer Doug Larson. "These are truly huge." Indeed, at eight times the size of Nova's amplifiers, NIF's amplifiers use 42-kilogram slabs, 3.4 by 46 by 81 centimeters, of neodymium-doped phosphate glass set vertically on edge at Brewster's angle, to create a polarizing effect, so that the laser beams have very low reflective losses while propagating through the glass. The slabs are stacked four high and two wide to accommodate a bundle of eight beams (Figure 4).

The slabs are surrounded by vertical arrays of flashlamps. Measuring nearly 180 centimeters (6 feet) of arc length,

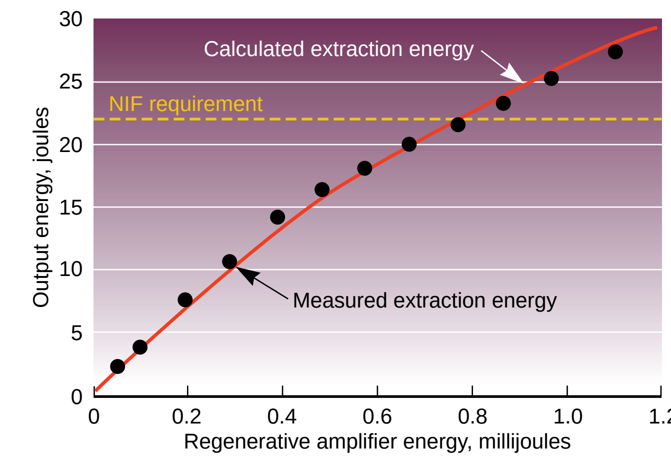


Figure 3. Demonstrated output energy of the prototype PAM exceeds the required 22 joules. The circles indicate measured output energy, while the continuous line indicates calculated energy.

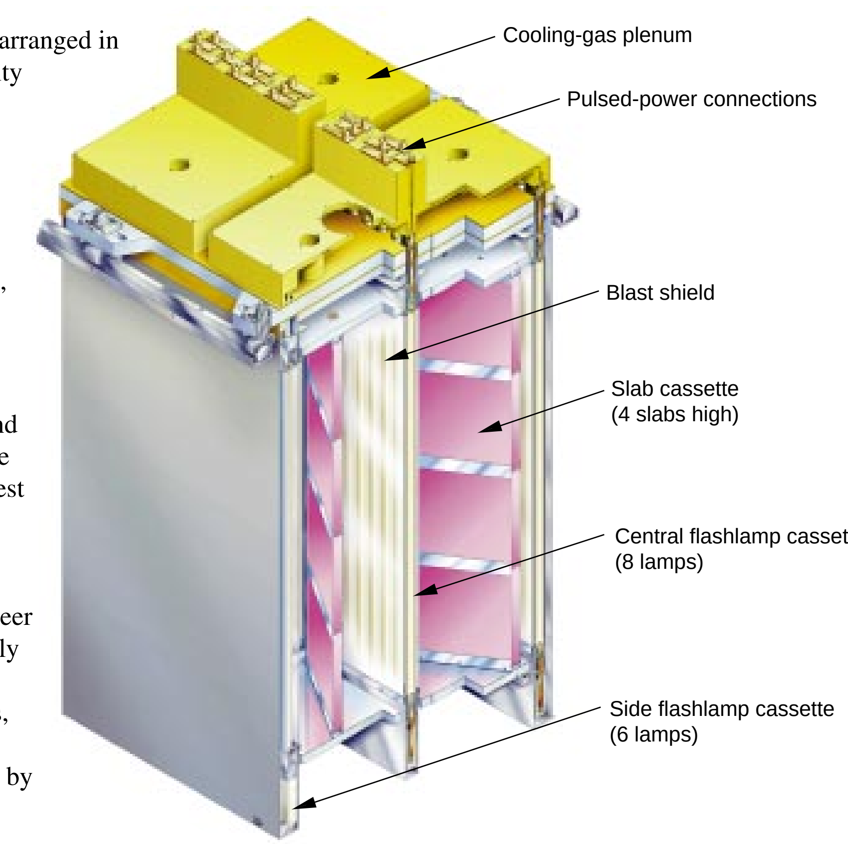


Figure 4. This cross section of a NIF amplifier module shows how the neodymium-doped phosphate glass slabs accommodate a bundle of eight beams traveling in parallel. The beams pass through 16 such amplifiers on their way to the target.

NIF's 7,680 flashlamps are the largest commercial units ever made (Figure 5). Each driven with about 30,000 joules of electrical energy, the flashlamps excite the neodymium in the laser slabs to provide optical gain in the infrared spectrum. Some of the energy stored in the neodymium is released when the laser beam passes through. With a combination of increased efficiency, fewer amplifiers, and the use of larger flashlamps, NIF will need less than twice the number of flashlamps of Nova, even though the laser system will produce some 40 times more output energy.

The flashlamps will be cooled with nitrogen gas between shots to indirectly cool the amplifier slabs and reduce beam distortions in order to meet the requirement of one shot every 8 hours.

(a)

(b)

Figure 5.
(a) Technician Wanda Dallum holds a flashlamp, the largest commercial unit ever manufactured.
(b) Technicians install a cassette of flashlamps in Livermore's Amplab.

Beamlet: An Invaluable Testbed for NIF

To be sure that NIF's major laser design will function as proposed, Laser Programs' project leaders decided in 1990 to develop and assemble a scientific prototype well in advance of construction. Completed in 1994, the Beamlet laser has been used to test and refine NIF's laser design and to test early prototype parts.

Because constructing a full bundle of beams and associated amplifiers was not feasible, Beamlet consists of a single beam. Beamlet does, however, include the main laser amplifiers as an array stacked two high and two wide, a prelude to the four-high, two-wide amplifiers now being developed for NIF. To reduce Beamlet costs, only one of the four apertures in the array contains high-quality laser glass. In addition, the amplifiers and other hardware rest on the floor rather than hang from a support frame as in the NIF design.

By simulating NIF operating conditions, Beamlet has demonstrated the viability of most of the NIF laser requirements, including the output power and focal parameters of the laser light and high-efficiency conversion of the laser light from 1.05 to 0.35 micrometers for illuminating the target. The results from Beamlet, Amplab, dozens of small laboratories, and computer design codes give laser scientists and engineers substantial confidence that NIF will meet its projected performance specifications.

The Beamlet Demonstration Project has been ongoing since 1990 to develop, test, and refine NIF's laser design and hardware.

This is the first time such active cooling will be used in Livermore's fusion lasers. To ensure cleanliness, hermetically sealed blast shields will protect the laser slabs from possible contamination generated in the flashlamp cavities.

The amplifiers' frame assembly units are supported from an overhead aluminum space frame to enable bottom access for cleaning and maintenance. A cassette of four slabs stacked one above the other and an eight-wide flashlamp cassette slide into the unit to form an amplifier column. These cassettes are installed and removed using a special ultraclean maintenance and assembly cart being developed at Livermore (see Figure 6).

Amplab, one of the most visible centers of the entire development program, is the key facility for testing the main amplifiers. A multimillion-dollar facility jointly developed by Livermore and the French CEA, Amplab began construction in 1996, with full-scale testing commencing in 1997.

Amplab consists of a miniature laser bay, with a full-scale 4-by-2 amplifier bundle, is only three slabs long and has flashlamps and a prototype cooling system. "We're using the minimum number of amplifier modules needed to validate the performance of our design," explains Marshall. He points out that Amplab complements the function of Beamlet, which is testing a single, complete, integrated beamline with the same optical arrangement as planned for NIF but with different hardware.

Amplab testing is providing essential information on the energy gain and performance of the amplifiers; extent to which they distort the laser light; mechanical fit of a myriad of associated components; thermal recovery of the transmitted beam after a shot; and degree of cleanliness in assembly, maintenance, and use. The testing regime is also revealing important differences in hardware provided by various vendors.

Storing the Energy

The power conditioning system provides the energy for the flashlamps with the highest-energy array of capacitors ever built. The system's design is a collaboration among Sandia National Laboratories in Albuquerque, Lawrence Livermore, and industry. Sandia is responsible for designing the system, developing the switch, and testing the integrated module at its dedicated facilities, while Livermore is responsible for developing capacitors, power supplies, and other components. Ultimately, Sandia will lead the assembly installation and checkout of the NIF power-conditioning modules (Figure 7).

The power-conditioning system will occupy four capacitor bays, each 15 by 76 meters (50 by 250 feet), adjacent to each laser cluster. The system must deliver three pulses to each flashlamp: a triggering test pulse, a preionization pulse to prepare the lamps for main discharge, and a main pulse to provide energy to the flashlamps.

Twenty capacitors will be housed in 1.7-megajoule modules that power the flashlamps in parallel. Eight such modules are needed to power each laser bundle of eight beams. All together, NIF's capacitor bank will store some 330 megajoules of energy, several times larger than Nova's bank.

According to engineer Mark Newton, "We're working to reduce the system

Figure 6. A technician, using a specially designed, ultraclean maintenance and assembly cart, inserts a cassette of four slabs into a frame assembly unit in the Amplab.

Figure 7. NIF's 1.7-megajoule power conditioning modules, each housing 20 advanced capacitors, are being tested by Sandia National Laboratories, Albuquerque.

At a Glance: the National Ignition Facility

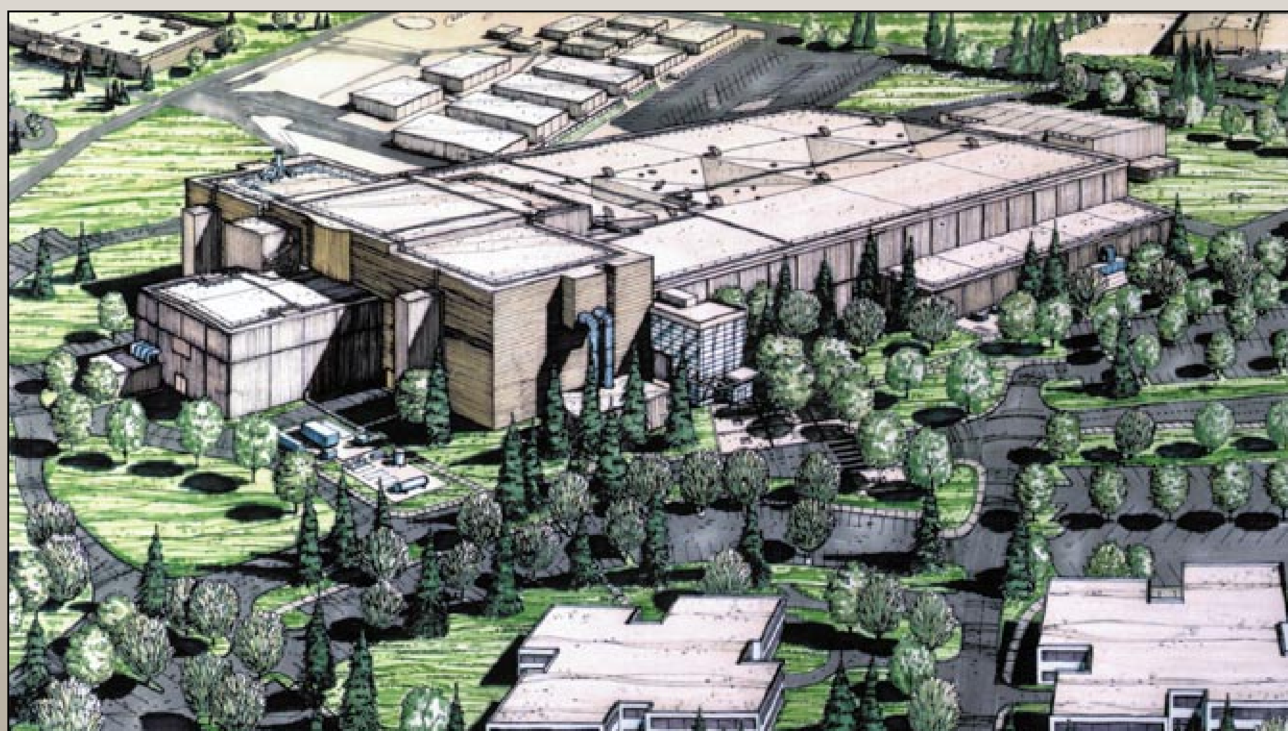
The Department of Energy's National Ignition Facility will be an enormous facility, about 200 meters long by 85 meters wide (550 by 300 feet), a little smaller than a typical domed football stadium. NIF's laser system will have 192 beams, each with a square aperture of about 40 centimeters per side and arranged in 24 beamlines of 8 beams each. Together the beams will produce 1.8 million joules (about 500 trillion watts of power, greater than 100 times the U.S. peak generating power) of laser light in the ultraviolet region at a wavelength of 0.35 micrometer for four billionths of a second.

To achieve this power, the beams will precisely compress and heat to 100 million degrees a capsule 1 to 3 millimeters in diameter containing deuterium–tritium fuel. The result will be ignition (self-heating and enhanced combustion of the fusion fuel) for the first time in a laboratory, liberating up to 10 times the energy required to initiate the reaction.

This sequence of events will last long enough for researchers to make accurate measurements of the nuclear reaction's temperature, pressure, and other properties. By providing these data, NIF will play a significant role in the DOE's science-based Stockpile Stewardship Program to assure the safety and reliability of the nation's nuclear weapons. The facility will also be used by scientists researching inertial confinement fusion energy and basic science such as astrophysics.

As Department of Energy Secretary Federico Peña commented at groundbreaking ceremonies last April, "NIF will unleash the power of the heavens to make Earth a better place."

NIF's total project cost is $1.2 billion, with design and construction managed by a partnership of Lawrence Livermore, Sandia, and Los Alamos national laboratories, and the University of Rochester. Engineering design began in 1996, construction began in 1997, and startup of one bundle of eight beams is planned for 2001. All 192 beams should be available for experiments by the end of 2003.



Artist's rendering of NIF illustrates the facility's immense scale. The two facilities in the foreground currently house Livermore's Business Operations and Human Resources departments.

cost to well below that of Nova in terms of dollars per joule." To that end, Newton and associates are incorporating the latest capacitor technologies, handling the energy in larger units, and qualifying as many vendors as possible.

The capacitors will use a "self-healing" technology previously tested on Beamlet. Developed over the past decade for various national security uses, this technology has failure characteristics that are more predictable than those of conventional capacitors, resulting in better capacitor bank designs at lower cost. This type of capacitor is known as self-healing because its "soft" failure mode (small internal faults) causes a gradual loss of capacitance over the capacitor's lifetime.

The pulsed power is switched via giant current-capacity switches and transmitted overhead to the amplifiers via coaxial cables. The NIF switches, one per capacitor module, must reliably handle 500 kiloamperes. NIF engineers are also working with U.S. and Russian experts to develop switches that could have a longer lifetime.

A Large Optical Switch

A key component in the laser chain is a kind of optical switch called a Pockels cell, which allows the beam to pass four times through the main amplifiers. This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the Pockels cell allows light to pass through or reflect off the polarizer. The NIF Pockels cell will essentially trap the laser light between two mirrors as it makes four one-way passes through the main cavity amplifiers before being switched out.

The Pockels cell used in the NIF laser is a new type, called the plasma electrode Pockels cell (PEPC, like the soft drink), developed at Lawrence Livermore (Figure 8). "The PEPC makes possible NIF's multipass architecture," says engineer Mark Rhodes.

Rhodes explains that Pockels cells used to be limited to small diameters (Nova's was 5 centimeters) because conventional designs required a KDP crystal about the same thickness as the beam diameter. NIF beams are 40 centimeters square, so crystals this thick would take too much space.

Instead, the PEPC uses a thin plate of KDP sandwiched between two gas-discharge plasmas that are so tenuous they have no effect on the laser beam passing through the cell. Nonetheless, the plasmas serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently.

The NIF design calls for four PEPCs stacked vertically in a single replaceable

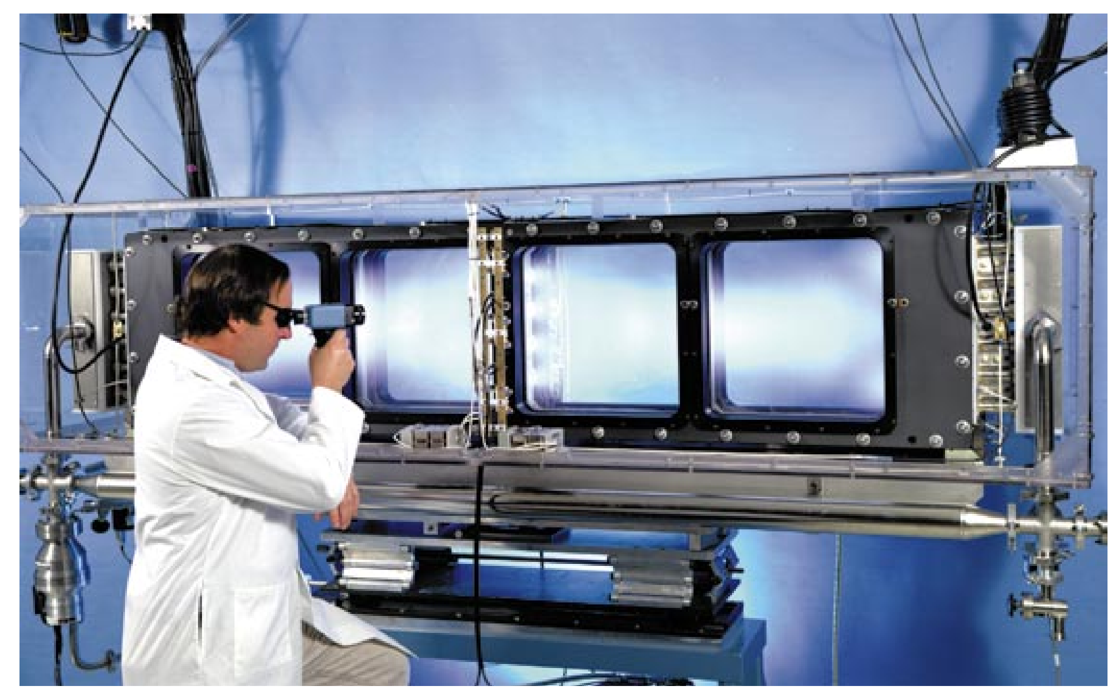


Figure 8. Each of NIF's plasma electrode Pockels cells (being tested here horizontally), acting as a giant light switch for four beams, will be arranged vertically in a single replaceable unit.

unit, but electrically the PEPCs are two independent 2-by-1 Pockels cells. The Beamlet's Pockels cell, which successfully uses a 37-centimeter aperture, continues to function reliably after nearly three years of operation.

Laser Alignment and Control

As the NIF beams make the four passes through the amplifiers, they accumulate wavefront aberrations due to distortions in the amplifier glass and other optics. As a result, NIF engineers needed to develop a way to compensate for these distortions to produce a well-controlled, focused beam.

The answer lay in a device called a deformable mirror, an adaptive optic that uses an array of actuators to bend its surface to compensate for wavefront errors. Advances in adaptive optics in the atomic vapor laser isotope separation (AVLIS) program demonstrated that a deformable mirror could meet the NIF performance requirement at feasible cost. Livermore researchers, led by physicist and systems engineer Erlan Bliss, developed a full-aperture (40 centimeters square), deformable mirror that was installed on Beamlet in early 1997 (Figure 9). Prototype mirrors from two vendors are scheduled to be tested in March 1998.

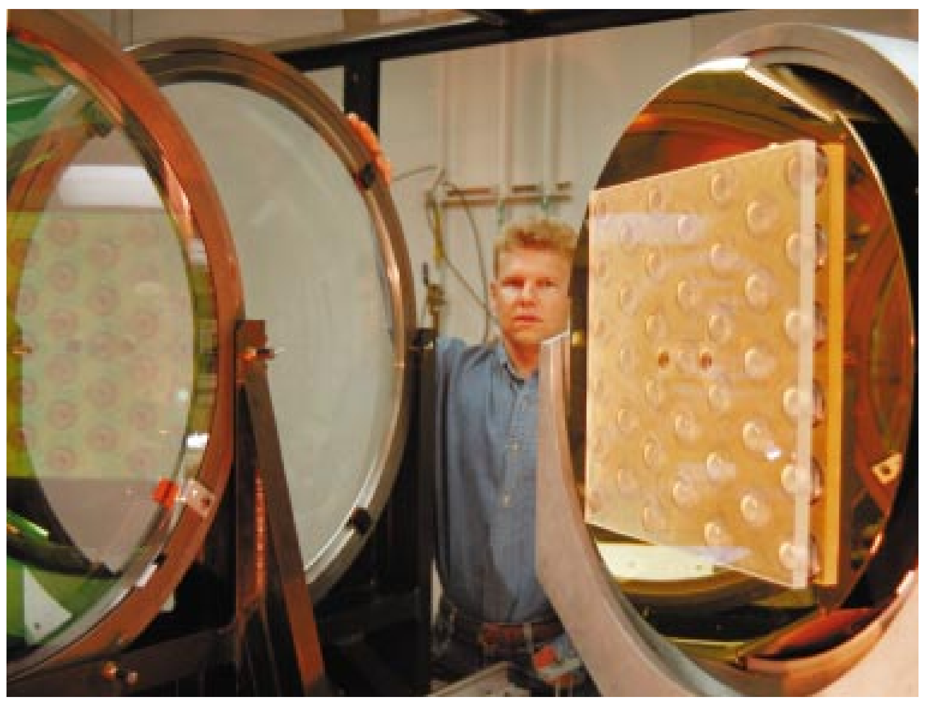


Figure 9. This full-aperture, 40-centimeter-square, deformable mirror (tested here by engineer Scott Winters) uses an array of 39 actuators to bend its surface to compensate for wavefront errors picked up by the beam.

The deformable mirror is but one element of a comprehensive, computerized system to align and control each beam so that it accurately delivers its energy to the target. New alignment concepts and simplifications of previous laser systems were designed for more reliable performance at reduced cost per beam. Aiding the effort is a one-tenth-scale layout of a NIF beamline, built to test new alignment concepts and components and software. The model uses full-size components at most critical locations, allowing the alignment system to be validated using prototype NIF hardware.

The scope of beam control for NIF is well beyond that of Nova or any other laser because of the 192 beams. That means that the alignment time per beam must be reduced to achieve a reasonable shot rate, which will help to control costs.

"With 192 beams, the challenge is to build a very reliable, simple, and robust system so we can align the main laser section easily and confidently in about 30 minutes," says engineer Rich Zacharias. "The system has to be autonomous because we can't afford an army of technicians to baby each beam." Zacharias says each of the beams must be aligned at multiple points along the way, requiring a system of 12,000 actuators.

Heading toward 2001

"The laser development and engineering design team has done a terrific job," says NIF project manager Jeff Paisner, "but it still has to meet a

challenging schedule in order to complete detailed designs by the end of fiscal 1998." Procurement of laser hardware is slated for 1999, and preliminary laser assembly in the facility is scheduled for 2000. By 2001, a complete bundle of eight beams is scheduled to be installed and thoroughly tested. Once the installation team has been trained and the bundle's performance demonstrated, the 23 other bundles will be installed.

"The year 2001 may sound like it is way off in the future, but for us," Paisner says, "it's just around the corner."

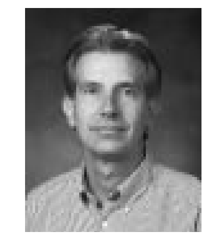
—Arnie Heller

Key Words: Amplab, amplifier, Beamlet, beamline, deformable mirror, flashlamp, fusion, laser, National Ignition Facility (NIF), Nova, Pockels cell, power conditioning, pulsed power.

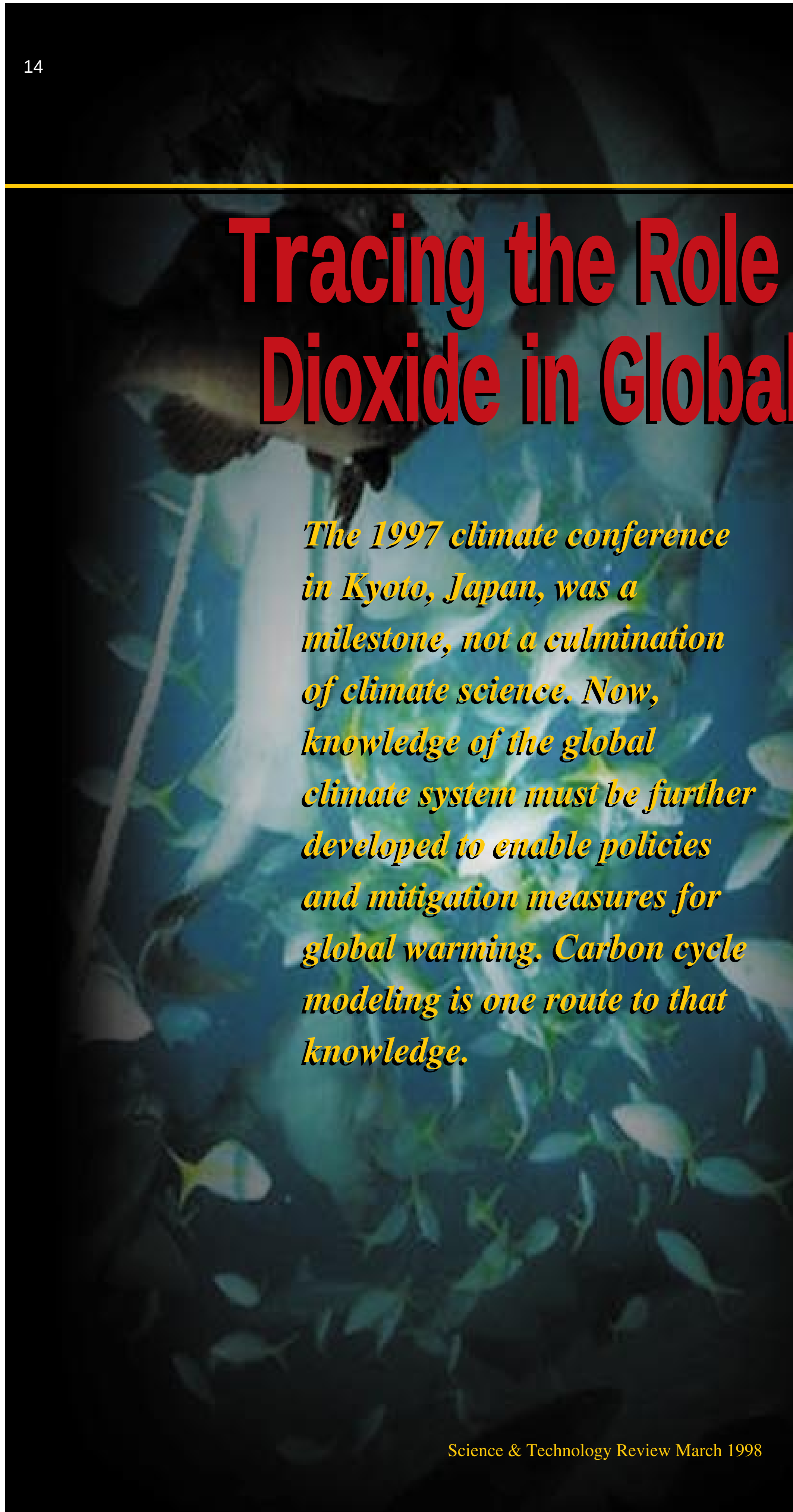
For further information contact Howard T. Powell (925) 422-6149 (powell4@llnl.gov) or Richard H. Sawicki (925) 423-0963 (sawicki1@llnl.gov).

About the Scientist and Engineer

HOWARD T. POWELL is the program leader for Laser Science and Technology in Livermore's Laser Programs Directorate, where he leads development activities in lasers for inertial confinement fusion and for advanced high-average-power, diode-pumped, and ultrashort-pulse lasers. Powell received his Ph.D. in applied physics from Cornell University in 1971 and his B.S. in physics from California Institute of Technology in 1966. Before coming to Livermore in 1973, Powell worked for McDonnell Douglas Research Laboratories. Powell has worked and published extensively on the development of laser and optics technologies: excimer lasers; solid-state lasers; precision laser control, laser-beam smoothing, and petawatt laser for Nova; and the large amplifier, flashlamp, and optics technologies for the National Ignition Facility.



RICHARD H. SAWICKI, associate project engineer for NIF special equipment, has supported NIF development since joining the Laser Systems Engineering Division in 1983. His duties include having responsibility for the precision laser and target-system hardware. Since joining the NIF project in 1994, he has been involved with planning the conceptual design and technology development. Prior to those assignments, Sawicki had responsibility for R&D and production planning for the dye laser and uranium separator systems in the Atomic Vapor Laser Isotope Separation project and evaluated the dynamic structural response of various weapon and target systems in the Nuclear Test Engineering Division. Prior to joining the Laboratory in 1980, Sawicki worked on design and thermostructural analyses for high-technology systems in the aerospace industry. He received his B.S. in engineering from Dartmouth University in 1971 and his M.S. in machine design from the University of California, Los Angeles, in 1974.



Tracing the Role of Carbon Dioxide in Global Warming

The 1997 climate conference in Kyoto, Japan, was a milestone, not a culmination of climate science. Now, knowledge of the global climate system must be further developed to enable policies and mitigation measures for global warming. Carbon cycle modeling is one route to that knowledge.

As scientific debate continues over the causes, mechanisms, and extent of global warming, the nations of the world have begun acting on the plausible assumption that human activities, particularly the release of significant amounts of greenhouse gases into the atmosphere, are leading to global warming. While not conclusive, evidence has been mounting that human-induced climate change is occurring.

At the Kyoto climate conference in December 1997, policymakers, climate experts, and industrial leaders came together to seriously consider future global climate. Their goal: to negotiate limits on the future release into the atmosphere of carbon dioxide (CO_2), the most plentiful greenhouse gas, in order to prevent further human-driven climate change. The conferees took to heart the latest scientific findings on global climate processes that have resulted, in large part, from climate models.

Climate models are a major tool that scientists use to understand the complex web of climate mechanisms. However, important uncertainties remain. Scientists at Lawrence Livermore are actively seeking answers to the questions of how much climate is changing and how much CO_2 is stored naturally in the atmosphere and oceans, ultimately helping to resolve the larger uncertainty: what effect human activities have on our environment.

Climate modeling began in the 1960s, when the National Oceanic and Atmospheric Administration initiated development of general circulation models—complex mathematical descriptions of the physics and dynamics of the atmosphere and oceans. Since then, climate scientists here and elsewhere have been refining these models and formulating an entire hierarchy of other models to elucidate global climate. Their ultimate goal is a virtual global climate system, a model that will allow them to confidently predict future global and regional climate.

Development of such a model is far from complete. But with global climate change at the forefront of public attention and policymaking agendas, climate scientists must provide input to policymakers based on today's imperfect models while pressing forward to improve them. Indeed, they are working under some urgency, for the world now appears ready to take action against global warming.

One important question that models of the carbon cycle answer is what the future atmospheric concentrations of CO_2 may be. Carbon dioxide, a major greenhouse gas, is important to Earth's energy balance and climate. Because CO_2 concentrations have been increasing rapidly, climatologists have pinpointed CO_2 as a major cause of the increase in global temperatures observed since 1860, when complete temperature records began. It is no wonder, then, that the global carbon cycle has become a vigorous area of study for the Climate System Modeling Group in Lawrence Livermore's Earth and Environmental Sciences Directorate. (See *S&TR*, October 1996, pp. 6–13, for an overview of climate work in the Atmospheric Sciences Division, much of which stems from Livermore's multidisciplinary capabilities in scientific computation, nuclear testing, and atmospheric science.) The group also collaborates with Department of Energy sponsors and universities.

Determining Carbon's Fate

In nature, carbon is plentiful and dynamic. Its natural cycle is thought to have been in a relatively steady state for thousands of years until the industrial revolution. Then, humans perturbed the carbon cycle by clearing forests and burning fossil fuels (coal, oil, and natural gas), which increased the CO_2 content of the atmosphere. How has this anthropogenic change disrupted Earth's climate? To find out, scientists are obtaining a better understanding of how the climate system functions and tracking CO_2 released into the environment by humans.

Philip B. Duffy, group leader of the Climate System Modeling Group, says that their work includes modeling how a portion of anthropogenic CO_2 remains in the atmosphere and how the rest of it is taken up by the oceans and terrestrial ecosystems. Tracking CO_2 is neither simple nor easy: measurements of CO_2 in the ocean and terrestrial biosphere are scarce; CO_2 released by humans is indistinguishable from naturally occurring CO_2; and the natural fluxes of carbon between ocean, atmosphere, and terrestrial biosphere are poorly understood.

Lawrence Livermore modelers have been formulating and testing a suite of models to reproduce carbon absorption, transport, and storage processes. The models cannot possibly incorporate all climate factors everywhere—even Livermore's advanced supercomputers cannot provide that resolution—so modelers must select the most important climatic factors and influences and represent them as well as possible.

The goal of the carbon cycle models is to predict the future behavior of carbon in the climate system. The models are tested by "hindcasting" the behavior of the carbon cycle from the historical past to the present. If model simulations match past records and observations, then model calculations predicting the future will merit confidence.

The Ocean Carbon Cycle

The Climate System Modeling Group's work involves both terrestrial and ocean carbon cycles, with current emphasis on the ocean. The ocean is an important regulator of climate as well as a major absorber of excess CO_2. Livermore modelers, having access to powerful, next-generation computers from the Department of Energy's Accelerated Strategic Computing Initiative, are able to formulate models that represent ocean currents, eddies, and interactive processes with more fidelity than previously possible. Their most recent ocean models reflect the advance of climate simulation techniques and skills. The projects described here demonstrate the approaches that modelers use to test hypotheses about carbon cycle dynamics, understand process interactions, and refine representations of the processes to derive accurate and useful models.

Improving Convection Models

The ocean is a large "sink" for anthropogenic CO_2. A model that can accurately simulate how the ocean absorbs anthropogenic CO_2 is prerequisite to predicting future atmospheric CO_2 concentrations and rates of global warming. But according to climate modelers Duffy and Ken Caldeira, current ocean models may overpredict the amounts of CO_2 that oceans absorb. One reason is that models do not accurately represent convection, the rapid vertical mixing of water that occurs when dense water overlies less dense water. They saw the effects of that inaccuracy in models involving sea-ice formation, which is a major cause of ocean convection.

When sea ice is forming, it expels salt into surrounding surface water. The saltier, denser water triggers convection, sinking the surface water and CO_2 it contains into the depths of the ocean. Surface ocean concentrations of CO_2 are thus reduced, and more CO_2 transfers from the air to the sea.

In the real ocean, convection occurs in horizontal regions that are meters or hundreds of meters across. Because ocean models cannot accurately represent such small features, some significant inaccuracies can arise in their simulations. Duffy and Caldeira thought that the modeled transfer of CO_2 from air to sea was probably too great because the models simulated excessive convection. If the instabilities resulting from expelled salt were treated more carefully, model results might better represent reality.

The two modelers tested their hypothesis by performing a pair of simulations that compared the standard treatment of convection to a "test" simulation in which the model's convection mechanism was partially suppressed. In the standard "control" simulation, salt released during sea-ice formation is placed in the model's top layer (which is 25 meters thick), and the model's convection mechanism mixes it into the rest of the ocean. Because the convection mechanism is clumsy, excessive convection occurs. This in turn causes excessive ocean absorption of carbon.

In their test simulation, Duffy and Caldeira dispersed expelled salt uniformly over a broader area—from the surface down to a depth of 160 meters—and suppressed the model's convection mechanism (Figure 1). This simulation produced much more realistic results for simulated convection, salinity, circulation, and absorption of chlorofluorocarbons (CFCs).

Then CFC uptake was simulated as an indirect test of the model's ability to simulate ocean uptake of anthropogenic CO_2. No direct method is possible because anthropogenic CO_2 cannot be reliably distinguished from natural CO_2 in the ocean. By contrast, CFCs have no natural background concentration in the ocean. Moreover, CFC uptake is very closely related to the ocean's absorption of human-induced CO_2, as Figure 2 shows.

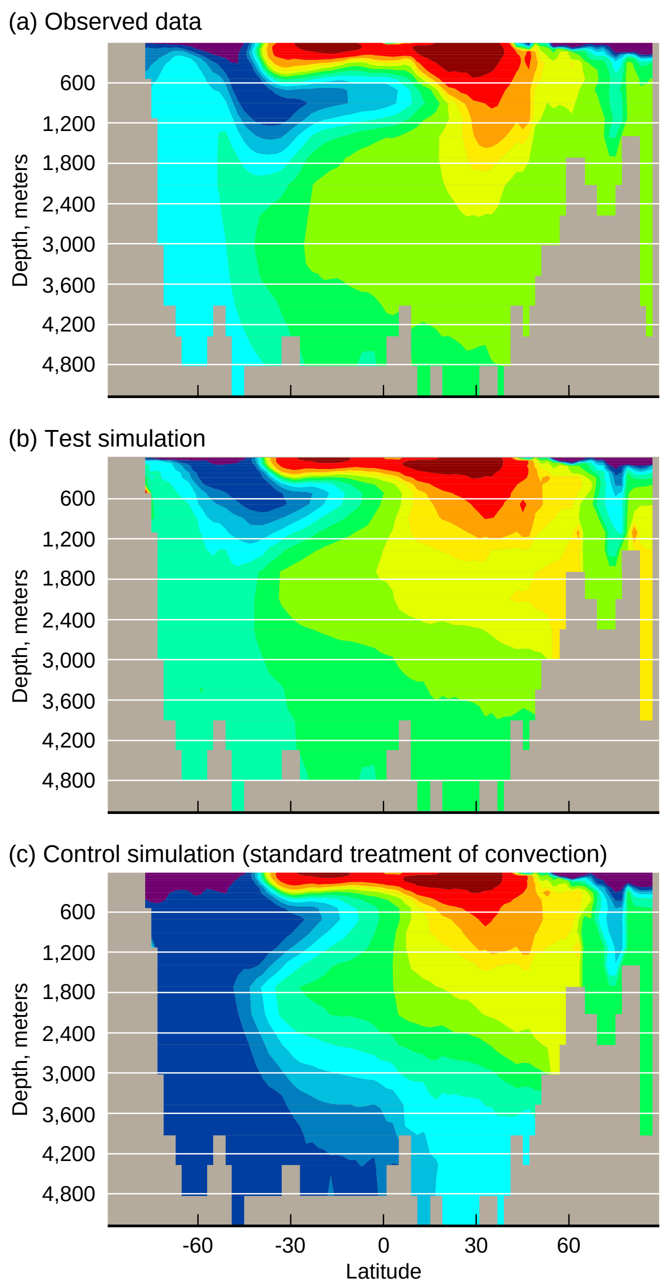


Figure 1. Salinity from (a) observed data collected in the Atlantic Ocean is compared to Livermore (b) test and (c) control simulations. The test simulation's more realistic portrayal of ocean convection is one of several improvements to Livermore's ocean circulation and carbon cycle model.

Because of this close relationship, Caldeira and Duffy reasoned that the standard model treatment of ice formation, which results in excessive simulated ocean uptake of CFC, also produces excessive uptake of anthropogenic CO_2. In addition, the improved treatment of ice formation, which produces greatly improved simulated uptake of CFCs, should also produce more accurate calculations of the uptake of anthropogenic CO_2. Further simulations are planned to verify these results.

Modeling Marine-Biology Effects

Marine biological processes play a large role in ocean carbon cycle dynamics, but they have been incorporated only recently into climate models. The inherent difficulties of mathematically describing their spatial and temporal effects have been a challenge. As a result of inadequate modeling of these processes, climate scientists have not been able to study the influences of marine biology and feedback responses to them. They have not known how the processes would affect the ocean carbon cycle.

Caldeira has a project under way to investigate some of these processes and clarify some of the uncertainties surrounding ocean and marine-biology interactions. He is using recently collected remote sensing and satellite data to model the interplay between sunlight, plankton (barely moving plant and animal aquatic organisms), and the ocean's absorption of CO_2.

Earlier models have established connections among solar radiation, plankton, and ocean circulation dynamics. With newly available data, Caldeira is studying these intertwinings further, considering feedback interactions in the process. For example, when sunlight penetrates the ocean layers and heats the deeper waters, convective mixing results and causes two other effects. First, CO_2 in the surface waters downwells and must be replaced by CO_2 transferred from the air to the sea; second, nutrients from the depths well up to the surface. Additional nutrients increase plankton growth. In time, the increased volume of plankton blocks solar penetration, so the sunlight heats only the surface waters. This inhibits CO_2 downwelling, nutrient transport to the surface, and plankton growth. Does the ocean then return to its steady state, or does the cycle continue through other ecosystem dynamics? And what is the cumulative effect on the ocean's absorption of CO_2?

Caldeira's study will systematically simulate the interactions among solar radiation, plankton, and ocean dynamics; the feedback resulting from those interactions; and the impacts of the feedback on the predicted response of the ocean carbon cycle to climate change. The simulations will replicate the time frame from the preindustrial ocean carbon cycle (before 1765) to the present. The simulations will also calculate future atmospheric CO_2 content based on several emission scenarios that may result when CO_2 stabilization policies are implemented.

CO_2 by Radiocarbon Proxy

Radiocarbon, or ^{14}C, has provided much of our knowledge about the rates of carbon exchange from the atmosphere to the oceans and land, and it yields

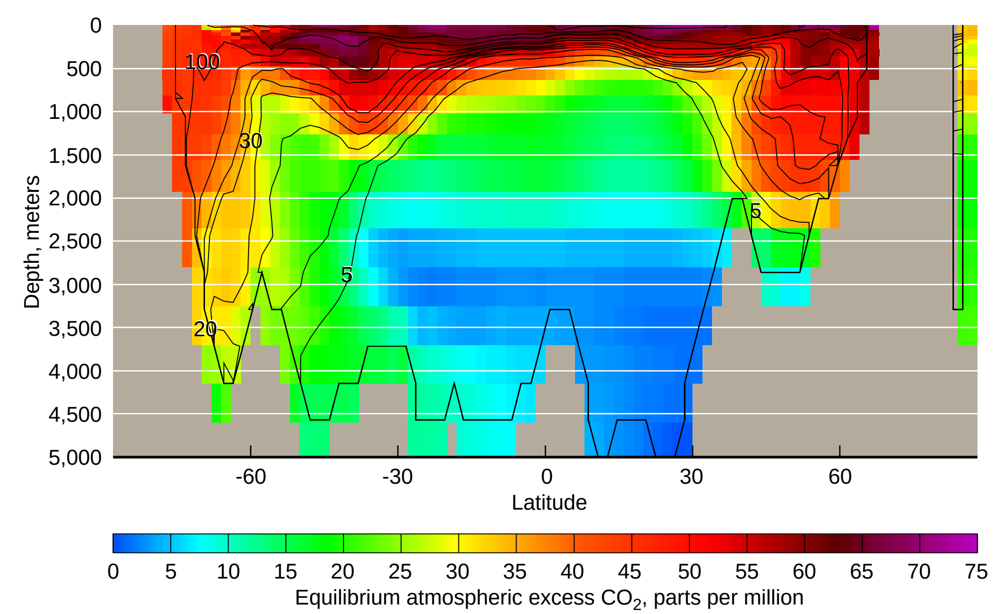


Figure 2. Livermore climate modelers performed simulations of chlorofluorocarbons (CFCs, shown as contour lines) and CO_2 (colored areas) to demonstrate their similarities in distribution in ocean waters. The similarities between ocean distributions of CFCs and anthropogenic CO_2 mean that model simulations of CFCs are a good indirect test of their ability to simulate anthropogenic CO_2.

important information about the ocean circulation. The radioactive half-life (5,730 years) of ^{14}C is comparable to the time span taken by surface ocean water to circulate to the ocean bottom and back. This means that the spatial distribution of ^{14}C in the water yields significant knowledge about ocean circulation—water that has not been near the surface recently has significantly lower ^{14}C concentrations because of radioactive decay.

For climate modelers, data on ^{14}C distributions took on additional usefulness as a result of the atmospheric nuclear tests conducted mostly in the period from 1954 through 1963. The concentration of ^{14}C in atmospheric CO_2, which had remained fairly constant for the previous thousand years, was doubled by those nuclear tests in less than 10 years. Since the end of the tests, ^{14}C concentrations have been decreasing as atmospheric CO_2 moves into other carbon reservoirs. This infiltration of nuclear-testing ^{14}C into carbon reservoirs can provide valuable information on carbon exchange. In particular, if the rate of nuclear-testing ^{14}C transfer from the atmosphere to the oceans and land could be accurately predicted, climate scientists would be able to predict the rate at which the oceans and land absorb human-induced CO_2 because essentially the same physical rules govern the transfer processes. Thus, understanding ^{14}C transfer is another route to determining rates of future greenhouse warming.

Models to simulate this transfer process make use of the estimated amounts of ^{14}C created by nuclear tests; they also make use of nuclear-testing ^{14}C data that were actually measured in the troposphere and stratosphere. If the models are accurate, the total amount of nuclear-testing ^{14}C transferred to the oceans, land, troposphere, and stratosphere should equal the estimated inventory of nuclear-testing ^{14}C, and the amounts transferred to the troposphere and stratosphere should approximate the measured data.

Early models simulating this transfer matched observed data only in part. In 1995, Duffy, five collaborators from Lawrence Livermore, and one from the University of Illinois tackled the problem of transfer. They used different and relatively more sophisticated multidimensional models of the ocean, stratosphere, and land, which they ran using observed data on tropospheric concentrations of ^{14}C as the model boundary conditions. Their simulations, for the period from 1955 through 1990 (Figure 3) are well within previously recognized uncertainties. This exercise proved that contemporary models can accurately account for all the bomb-produced ^{14}C in the climate system.

Radiocarbon by Salmon Proxy

To validate models of how the ocean absorbs nuclear-testing ^{14}C, modelers must be able to distinguish between how much of the total ^{14}C now in the ocean is bomb-produced and how much is natural. The modelers therefore need to know the natural ^{14}C concentrations before the weapons tests and how quickly the ^{14}C entered the oceans. The problem is that few open-ocean measurements of that period have been taken.

Tom Brown of Livermore's Center for Accelerator Mass Spectrometry, working with the Livermore ocean modelers and ocean and fishery scientists from the University of Washington, came up with a way to provide the "pre-bomb" ^{14}C data. In 1997, they measured the ^{14}C content of archived salmon scales using Livermore's accelerator mass spectrometry capability (see *S&TR*, November 1997, pp. 4–11), which can measure minute isotopic quantities with high precision. The salmon-scale measurements are proxy indicators for the ^{14}C levels, and even the ^{13}C-to-^{12}C ratios, of the surface waters of the oceans during the time period the salmon dwelled in the waters.

Fishery scientists have been collecting and archiving salmon scales for nearly a hundred years for various research purposes. The scales are particularly suitable for developing time-history data of ocean waters because the salmon's seasonal migration patterns are known. And because salmon live and feed on plankton and small fishes in the uppermost surface waters of the ocean, the scales can be equilibrated with the ^{14}C content of the surface waters. Furthermore, the sections of the scales that grow while salmon live in the open ocean are identifiable—they appear as

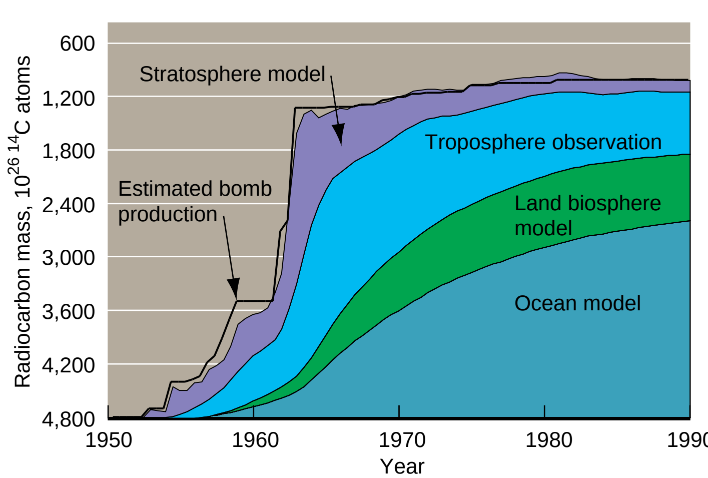


Figure 3. The Livermore-modeled estimates of nuclear-test radiocarbon in the ocean, land, and atmosphere closely match estimates of the total radiocarbon inventory calculated from atmospheric tests.

bands of different thickness roughly corresponding to seasons (Figure 4).

By selecting and measuring appropriate sections of the scales, Brown obtained estimates of ^{14}C content of North Pacific surface waters, averaged over the very large areas of the salmon's seasonal migration patterns and over the 1- to 2-year time spans represented by the sections. The ^{14}C measurements show excellent agreement with the few direct, open-ocean measurements available of ^{14}C content and clearly show the rise in ^{14}C content from the atmospheric nuclear tests (Figure 5). By providing rare estimates of "prebomb" values and the initial increase of ocean ^{14}C concentrations, Brown's measurements are a valuable help to climate scientists trying to predict future uptake of CO_2 by the ocean as well as future climate.

Fossil Fuel Affects ^{14}C Fluxes

Burning fossil fuel may appear to have no effect on atmospheric radiocarbon content because fossil fuel contains no ^{14}C. However, global processes are rarely that simple or linear. Caldeira and Duffy collaborated with Greg Rau from the University of California at Santa Cruz to formulate a model to quantify radiocarbon fluxes. Their model predicted significant, though indirect, effects of fossil-fuel burning on global distributions of ^{14}C. More important, if its prediction of increased ^{14}C levels by 1998 is correct, this model will soon become a test for global carbon-cycle models.

The model's calculations of changes induced by land clearing, fossil-fuel burning, and atmospheric nuclear tests show that, in the very near future, ^{14}C in the atmosphere will begin to increase. Even though ^{14}C, which increased between 1954 and 1963, has been steadily declining, that decline will be reversed if humans do not change their habits in burning fossil fuel.

Caldeira, Duffy, and Rau used a simplified model of the atmosphere, land, and ocean. The model—driven by carbon fluxes from land clearing, fossil-fuel burning, and atmospheric nuclear tests—was used to simulate changes that would occur in the face of isotope decay, continuing CO_2 emissions, radiocarbon exchanges into the oceans and atmosphere, and estimates of future biomass. Nuclear test radiocarbon inventory in 1975, as well as data on both natural and bomb radiocarbon collected through GEOSECS (Geochemical Ocean Sections Study, an ocean data collection

Figure 4. Bands on an archived salmon scale (about 5 millimeters wide) give age and radiocarbon content with the help of Livermore's Center for Accelerator Mass Spectrometry.

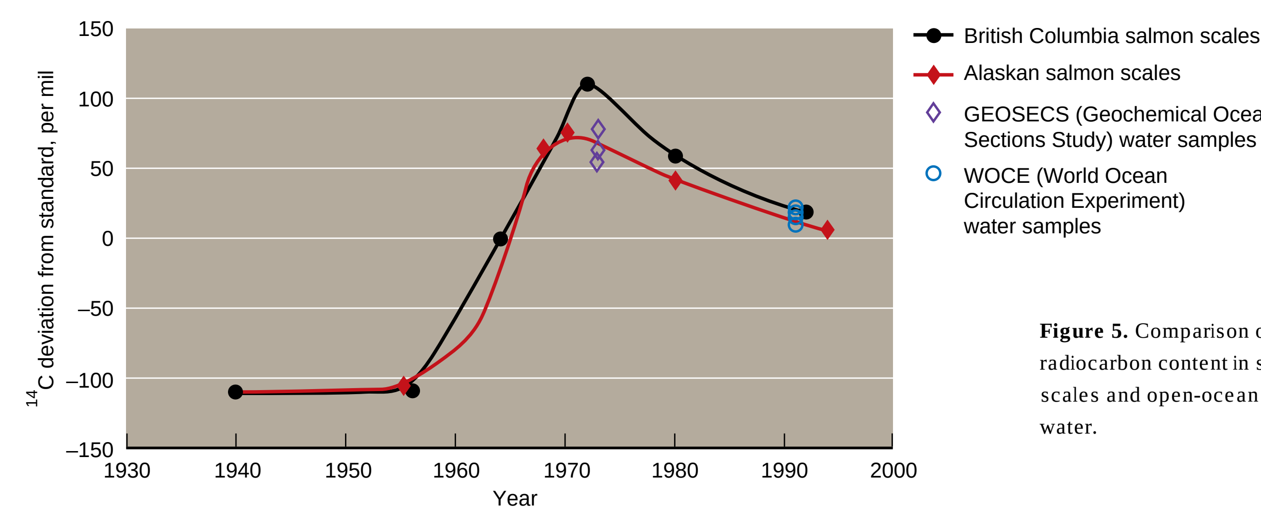


Figure 5. Comparison of measured radiocarbon content in salmon scales and open-ocean surface water.

program), were used as reference points for adjusting model parameters.

Simulations were performed to separately assess the changes caused by (1) land clearing and fossil-fuel burning, (2) land clearing only, (3) fossil-fuel burning only, and (4) both plus observed atmospheric data until 1990, which includes nuclear-testing ^{14}C levels. The last simulation indicates the model's ability to portray past trends and predict future ^{14}C fluxes.

The simulations indicate what percentages of increases in atmospheric CO_2 can be attributed to deforestation and fossil-fuel burning. The data indicate that, prior to about 1910, most of the carbon entering the ocean resulted from deforestation; since that date, the carbon flux has been dominated by the effects of fossil-fuel burning.

The modelers' interpretation of the trends led them to the unexpected prediction that ^{14}C levels in the atmosphere will begin to increase as a result of fossil-fuel burning. The modelers explain it this way: When atmospheric CO_2 content increases, the ocean's absorption of it increases. In the case of fossil-fuel-caused increases, because fossil fuel contains no radiocarbon, the ocean is absorbing CO_2 that consists primarily of ^{12}C, a weak acid. A more acidic ocean tends to reject carbon in all its isotopic forms. So the ^{14}C component of ocean CO_2 is rejected along with the other carbon isotopes, adding to the atmospheric ^{14}C content and reversing the decline that began in the 1960s after the end of atmospheric testing. The model indicates that ^{14}C levels will begin increasing as early as 1998 and, by 2015, the fossil-fuel-induced radiocarbon flux out of the ocean will exceed the nuclear-explosion radiocarbon flux into the ocean, so the ocean's ^{14}C mass will then begin to diminish.

The Caldeira, Duffy, and Rau model is noteworthy because the prediction that the ^{14}C flux into the ocean will be reversed early in the next century indicates that human impacts on the global carbon cycle are significant on geologic, not just human, time scales.

Closing In on Global Climate

The growing consensus that fossil-fuel use is causing climate change and the recent effort to formulate international treaties to limit greenhouse-gas emissions lend urgency to understanding how carbon moves within the climate system. If indeed humans have been responsible for changing the climate, climate models must accurately and conclusively portray this cause and effect. Then we will have the understanding needed to begin mitigating the effects and assuring a better future for the environment.

—Gloria Wilt

Key Words: carbon cycle, carbon dioxide (CO_2), climate change, climate model, fossil-fuel burning, global warming, greenhouse gas, marine biology, mass spectrometry, ocean carbon cycle, ocean convection, proxy data, radiocarbon (^{14}C).

For further information contact Philip B. Duffy (925) 422-3722 duffy2@llnl.gov or Ken Caldeira (925) 423-4191 kenc@llnl.gov.

About the Scientists

PHILIP B. DUFFY is a physicist at the Laboratory, where he is group leader for the Climate System Modeling Group in the Atmospheric Science Division. Duffy worked in strategic defense systems when he joined the Laboratory in 1986. Prior to that, he received his Ph.D. and M.S. in astrophysics in 1986 and 1981 from Stanford University and an A.B. in astronomy and astrophysics in 1979 from Harvard University. Duffy has published research on astronomy, atomic physics, and numerical modeling of ocean circulation.

KENNETH G. CALDEIRA joined the Laboratory's Atmospheric Chemistry Group as a physicist in 1993 and has been an environmental scientist in the Climate System Modeling Group since 1995. He received his Ph.D. and M.S. in atmospheric science from New York University in 1991 and 1988 and his B.A. in philosophy from Rutgers University in 1978. He also served as a postdoc at Pennsylvania State University's Earth System Science Center. Caldeira has published many papers, for example, on climate stability of early Earth and the global carbon cycle as it has been affected by human activity over millions of years.

Reliable Software for Protection Systems

A patient undergoing radiation therapy for cancer wants to be sure that the radiation being delivered is just the amount prescribed and no more. Nuclear power plants must have systems installed to ensure that radiation leaks and accidents do not occur. Today, controlling these protection systems flawlessly depends upon computer software, which occasionally contains unforeseen "bugs." Software bugs on your computer at home are annoying, but at a nuclear power plant or during radiation therapy they can be life-threatening.

At Lawrence Livermore, Gary Johnson's Computer Safety and Reliability Group—part of the Fission Energy and Systems Safety Program—has been working with the Nuclear Regulatory Commission for several years to avoid software problems in safety systems at nuclear power plants. Livermore brings to this job decades of systems engineering experience as well as a regulatory perspective from years of working with the NRC and other regulators.

Johnson's group and the NRC developed software and computer system design guidance that the NRC uses to evaluate the design of safety-critical systems for U.S. plant retrofits. Overseas, where new nuclear power plants are being built, regulators and designers are using this state-of-the-art guidance to help assure plant safety. For the last few years, representatives from Hungary, the Czech Republic, Ukraine, Korea, Taiwan, and Japan have been calling upon Johnson and his group for assistance in setting criteria for their nuclear power plant control systems.

This software design guidance is also applicable to other computer-controlled systems that could endanger human life if they are poorly designed—medical radiation machines, aircraft flight control systems, and railroad signals, for example.

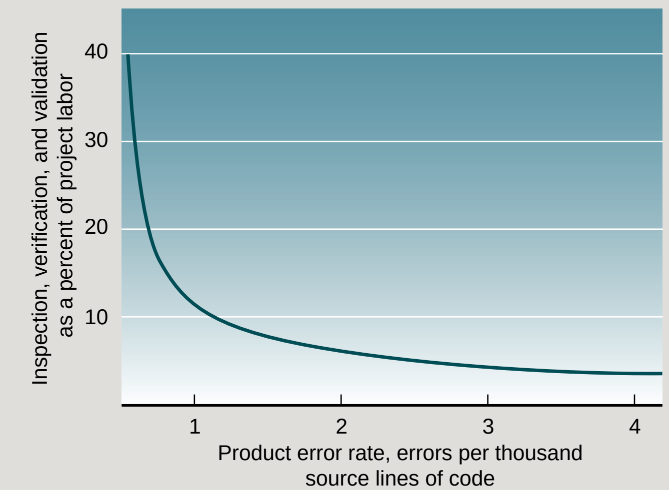


Figure 1. Data from IBM's Federal Systems Division indicate that when more effort is spent up front for inspection, verification, and validation, the product error rate decreases.

When Software Fails

Perhaps the best-documented example of the harm resulting from poorly designed software involved the Therac-25, an accelerator used in medical radiation therapy. The *IEEE Computer Applications in Power* reported, "Between June 1985 and January 1987, six known accidents involved massive overdoses by the Therac-25—with resultant deaths and serious injuries" at treatment centers around the U.S. and in Canada.[1] Between the patient and the Therac-25's radiation beam was a turntable that could position a window or an x-ray-mode target between the accelerator and patient, depending on which of two modes of operation was being used. If the window was positioned in the beam's path with the machine set to deliver radiation through the x-ray-mode target, disaster could result because software errors allowed the machine to operate in this configuration.

Engineering Reliable Software

Conditions such as these, where software was assigned sole responsibility for safety systems and where a single software error or software-engineering error could have catastrophic results, are precisely what Johnson's group aimed to avoid when it helped to prepare the portion of the NRC's recently published *Standard Review Plan*[2] regarding computer-based safety systems. Their process requires that software for nuclear power plant protection systems be written in accordance with good engineering practices. That is, software should follow a step-by-step approach of planning, defining requirements for worst-case scenarios, designing the software, and following a detailed inspection and testing program—

known as verification and validation—during each step of development and installation. This process avoids the pitfalls that can occur when software designers are expected to begin writing code before the design is complete, a process akin to pouring concrete footings for a building before knowing how tall the building will be.

Good engineering practices make for better software. But it is axiomatic in the safety-systems business that software can never be perfect. Figure 1, showing IBM's experience from the Space Shuttle program, illustrates the futility of attempting to produce perfect software for every need. The point of diminishing returns is reached well before perfection can be guaranteed.

When the consequences of failure are very high, safety-critical systems should always incorporate "defense-in-depth and diversity," which can be accomplished by incorporating different kinds of hardware, different design approaches, or different software programming languages. The idea is to have different kinds of systems available to accomplish the same goal; for example, a digital system is often backed up with a tried-and-true analog system. Then, if one system fails, a different system is in place to carry on. Simple redundancy, having two versions of the same system, is not enough because both could fail simultaneously as a result of the same flaw (Figure 2).

Many kinds of diversity are possible. Although only some scientific basis dictates what kinds of diversity are the best or how much diversity is enough, experience has shown an effective combination of protections to be the use of different hardware and software acting on different measurements to initiate different protective actions. Based on that experience, the NRC's *Standard Review Plan* requires that at least two independent systems, incorporating multiple types of diversity, protect against each worst-case scenario.

Making the Systems Better

The Institute of Electrical and Electronics Engineers has defined good engineering processes for the design of computer software, but there is little agreement on such specifics as notation, the preparation of specifications, or design and analysis methods. Testing is another challenge. As yet, although methodologies are available, there are no

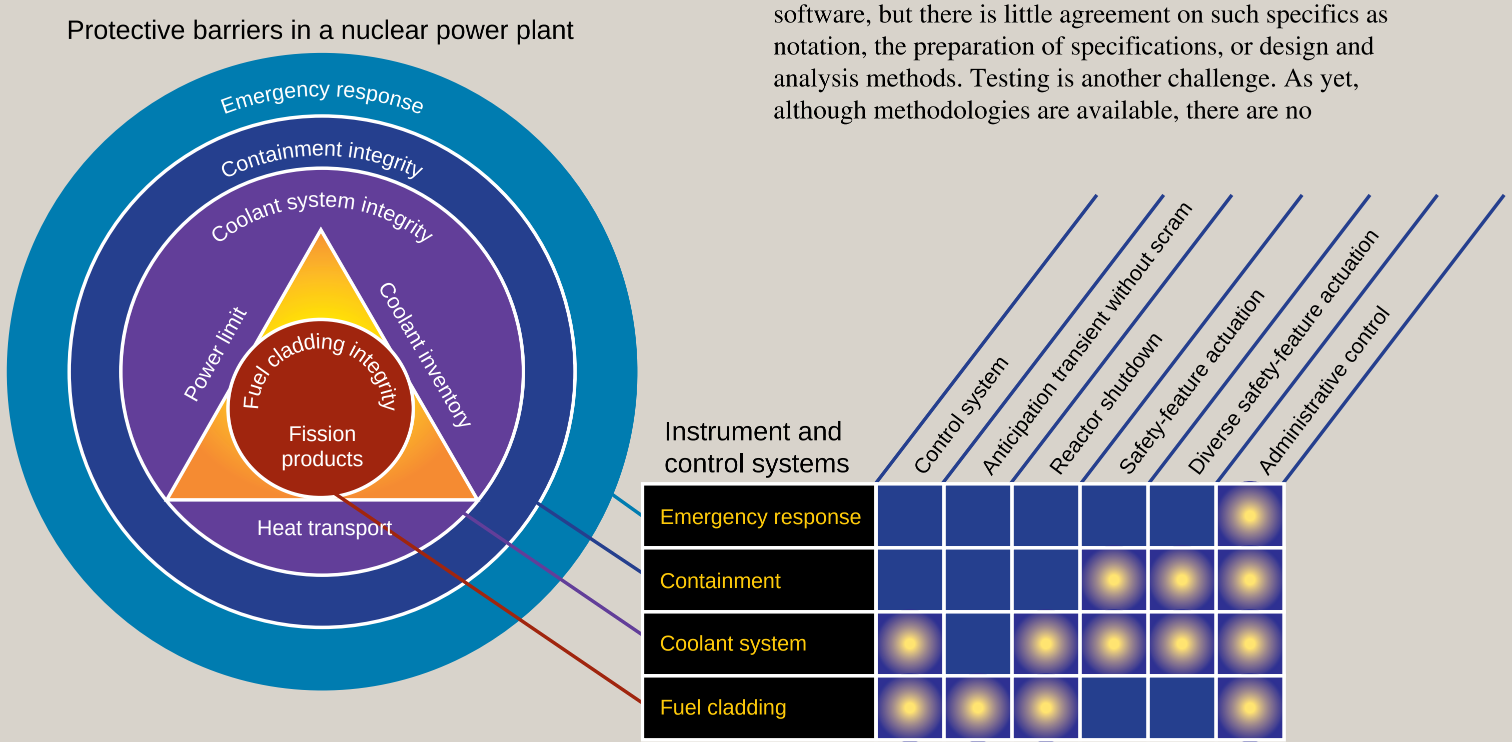


Figure 2. A diverse combination of software and hardware systems ensures that the overall safety of a nuclear power plant is not jeopardized by a single system failure. The large dots indicate various systems that protect the integrity of nuclear power plants.

mathematical equations or models that can be used to evaluate a software program to determine whether it is dependable or whether it contains errors and may fail.

Johnson's group has three projects under way that tackle the software quality issue head on—developing a method for determining the reliability of high-integrity safety systems, developing techniques to test commercial software, and developing methods for establishing the requirements to which software is written.

The first project is related to the current move toward "risk-based regulation," which uses assessments of risk to determine how to regulate. Livermore is developing a methodology for determining software reliability (and conversely, the failure probability of software). Information about software reliability will be integrated with hardware reliability measurements to form a measure of overall system reliability. The result will be used in NRC probabilistic risk assessment analyses.

In the second project, the group is looking for ways to "qualify" software that has not been through a rigorous development process, such as software that is frequently embedded in commercial instrumentation and control components. Demonstrating the dependability of such software is a challenge because thoroughly testing the large numbers of program states and combinations of input conditions is virtually impossible. The group is identifying techniques that limit the inputs and conditions that must be tested to qualify a software design. Considerable research has been done on software integrity, but this particular approach has not been tried before. If this project is successful, the process of introducing new control systems into nuclear power plants will be simplified.

The aim of the third project is to clarify the project goals, or requirements, that are developed before software programs for protection systems are written. Requirements must be carefully specified, but it is almost impossible to anticipate every situation. Livermore engineers are working with Sandia National Laboratories, Albuquerque, to adapt techniques used to design control systems for the defense industry. In the process, they are developing methods for determining the fundamental goals of a computerized control system.

As computers become more powerful and software more complex, projects such as these will go far to increase confidence in the reliability of systems designed to protect workers and the public.

– Katie Walter

Key Words: instrumentation and control systems, nuclear power plants, safety-critical systems, software engineering.

References

1. "An Investigation of the Therac-25 Accidents," *IEEE Computer Applications in Power*, July 1993, pp. 18–41.
2. U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, "Instrumentation and Controls," Chapter 7, *Standard Review Plan*, NUREG-0800, Rev. 4, June 1997.

For further information contact Gary Johnson (925) 423-8834 (johnson27@llnl.gov). Publications from Livermore's Computer Safety and Reliability Center are available at http://nssc.llnl.gov/FESSP/CSRC/refs.html.

Keeping the "More" in Moore's Law

THE number of transistors that can be put on a computer chip tends to double about every two years, just as Intel Corp.'s co-founder Gordon Moore predicted more than 20 years ago. But lately, experts have been worried that Mr. Moore's law might falter as the laws of physics catch up with the ability to cram more and more on a chip. That's why Lawrence Livermore—with its skills in optics, precision machining, multilayer coatings, miniaturization, and a host of other capabilities developed in its weapons work—teamed up with fellow DOE laboratories Lawrence Berkeley and Sandia to literally shed new light on the subject. They also teamed up with three of the biggest names in the semiconductor industry—Intel, Motorola, and Advanced Micro Devices. The result is a $250-million project, funded by corporate money, to continue developing extreme ultraviolet (EUV) lithography technology.

The team's strategy has been to focus on specific technologies for EUV lithography, including multilayer coatings, projection optics, optical substrates, mask and optical design, and metrology (Figure 1). Livermore brings expertise in optics, precision engineering, and multilayer coatings; Sandia's part includes the systems engineering, the resists (protective coatings that prevent unwanted etching), and the light source. Berkeley provides its Advanced Light Source to characterize the optics and resists in the EUV range.

Traditionally, advances in optical lithography—a photography-like technique of using light to carve channels on silicon wafers—have relied on using shorter and shorter wavelengths of light, which can produce smaller features much as a razor can make a finer cut than a hacksaw. State-of-the-art techniques use ultraviolet (UV) light, and experts believe that chips will continue to follow Moore's law for another 10 years as even shorter wavelengths are used.

Current systems use UV light with a wavelength of 0.248 micrometer, to image a master pattern through lenses onto a silicon wafer that is covered by a resist. This technology can produce features of just 0.25 micrometer, or about one four-hundredth the width of a human hair.

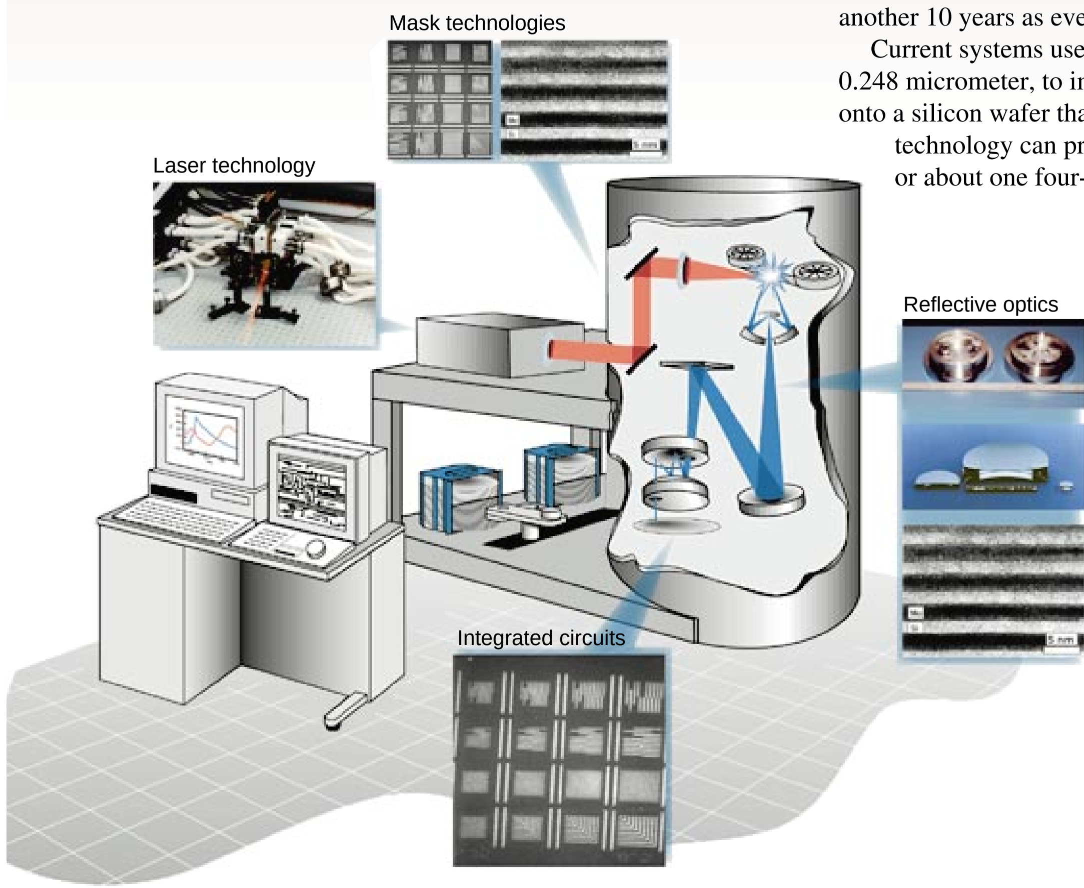


Figure 1. Spin-off and spin-back processes have boosted Livermore technologies for EUV lithography.

In less than 10 years, engineers plan to build chips with features measuring about 0.13 micrometer by using wavelengths of 0.193 micrometer. But beyond that point, physics intervenes and light shorter than that—called extreme ultraviolet light—will be absorbed, rather than refracted, by a conventional quartz lens. The result: no image.

Enter Multilayer Coatings

To solve the absorption problem associated with lenses, Livermore researchers turned to mirrors that reflect and focus the light on the chip. Called extreme ultraviolet lithography, the technique bounces EUV photons off an elaborate setup of mirrors, including a mask made of reflective materials, that ultimately focuses the photons on a resist-coated silicon wafer. By doing so, the Laboratory and its partners have designed an EUV system that can pattern features smaller than 0.05 micrometer.

But this method is not without its own technical challenges. The typical EUV mirror made with coatings of alternating films of silicon and molybdenum can reflect only about 65% of the photons that hit them. Because the photons in the EUV system are reflected nine times before they hit the wafer, the losses mount until only 1 to 2% of the original photons hit the target, which makes for long, costly exposure times. To make the system cost-effective, researchers must boost the reflectivity of the mirrors to at least 72%. However, Don Sweeney, the acting program leader for Advanced Microtechnology, says he thinks that goal can be reached in a few years. "Our researchers have already had some success in making higher-reflectivity mirrors from new combinations of materials."

Boosting EUV Lithography

Another important advance that assists the EUV lithography work is the development of the Ultra Clean Ion Beam Sputter Deposition System, the result of a collaboration between Lawrence Livermore and Veeco Instruments Inc. of Plainview, New York. That work earned an R&D 100 Award for the team in 1997 (see *S&TR*, October 1997, pp. 8–9).

The conventional method for making the reflective masks for EUV lithography is called magnetron sputtering. But the defect rate for the process is about 10,000 defects per square centimeter, far too many for successful EUV lithography. The new process, embodied in Veeco's IBSD-350, produces precise, uniform, highly reflective masks with 81 alternating layers of molybdenum and silicon, each 3 to 4 nanometers thick. As the machine directs a beam of ions at the masks, the ions physically collide with each mask and form a vapor, which is precisely deposited on it at a defect density of less than 0.1 per square centimeter—a 100,000-fold improvement over conventional methods. This process also holds great promise for a number of other applications using virtually any material or combination of materials including metals, semiconductors, and insulators. A near-term possibility is making very-low-defect-density films for ultrahigh-density heads for the magnetic recording industry.

Also boosting the EUV work is another R&D Award-winning Livermore invention—the Absolute Interferometer (see *S&TR*, October 1997, pp. 6–7)—which can measure large

The Incredible Shrinking Chip

Why are smaller computer chips better and faster? It might seem a paradox, but as the size decreases, the chips become more powerful. It's as simple as getting to grandma's house faster if she lives next door rather than across town: the electronic signals zipping around the circuitry to solve computing problems have less distance to travel. Today's chip contains about 3,260 times more transistors than the chip of 1971. Here's a chronology of the shrinking of chips as the semiconductor industry became a $150-billion enterprise.

Year	Microprocessor	Number of Transistors
1971	4004	2,300
1974	8080	6,000
1978	8086	29,000
1982	80286	134,000
1985	Intel 386	275,000
1989	Intel 486	1.2 million
1993	Pentium Processor	3.2 million
1995	Pentium Pro	5.5 million
1997	Pentium II	7.5 million

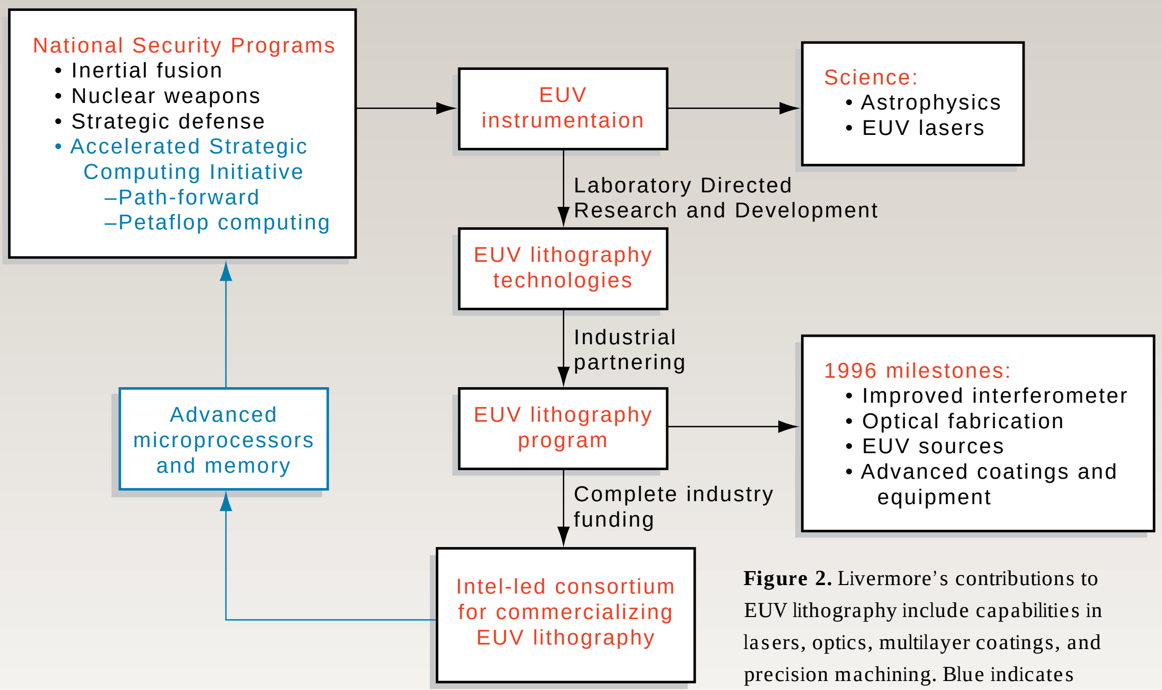


Figure 2. Livermore's contributions to EUV lithography include capabilities in lasers, optics, multilayer coatings, and precision machining. Blue indicates capabilities spun back to the national security programs.

surfaces to an accuracy of less than 1 nanometer, the thickness of a few atoms. This capability is essential to fabricate the nearly perfect mirrors necessary for EUV lithography because the processing requires surface-measurement feedback during the polishing process at a level of accuracy that conventional devices cannot provide.

But any of these technologies would not ensure the longevity of Moore's law by itself. "Intel came to us because we are the world leader in technology for EUV lithography," Sweeney says (Figure 2). "Our work grew out of our national security mission, and our multidisciplinary workforce allows us to integrate the technologies needed for this project. The commercialization of EUV lithography through the consortium is an exciting prospect for everyone who's interested in smaller and faster computing."

—Sam Hunter

Key Words: Absolute Interferometer, Advanced Microtechnology Program, extreme ultraviolet (EUV) lithography, Ultra Clean Ion Beam Sputter Deposition System.

For further information contact Don Sweeney (925) 422-5877 (sweeney4@llnl.gov).

Patents and Awards

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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
William C. Moss	**Thermoacoustic Refrigerator** U.S. Patent 5,673,561 October 7, 1997	A thermoacoustic device having a thermal stack made from a piece of porous material, which provides a desirable ratio of thermoacoustic area to viscous area. The material has a low resistance to flow to minimize acoustic streaming, high specific heat conductivity, and low thermal conductivity. The inexpensive thermal stack can be formed of reticulated vitreous carbon and is easily formed in small sizes. A heat exchanger of heat-conductive, open-cell foam may be included. The thermoacoustic cooling device may be combined with a semiconductor device.
Anthony M. McCarthy	**Silicon on Insulator Achieved Using Electrochemical Etching** U.S. Patent 5,674,758 October 7, 1997	A manufacturing process for forming thin-film crystalline silicon circuits on arbitrary supports. The process includes four basic stages: preparation, bonding, thinning, and silicon region formation. The process takes silicon wafers with completed circuits, bonds the circuit side of the wafer to the support, and thins the wafer to remove excess silicon. Electrochemically enhanced etching is then used to define the circuits and expose the electrical contact regions. This process provides an economical thin-film silicon-on-insulator technique for microelectronics fabrication applications.
Kathleen I. Schaffers Laura D. DeLoach Stephen A. Payne Douglas A. Keszler	**Ytterbium-Doped Borate Fluoride Laser Crystals and Lasers** U.S. Patent 5,677,921 October 14, 1997	Ytterbium-doped borate fluoride host crystals, having a formula of $MM'(BO_3)F$, where M, M' are monovalent, divalent, and trivalent metal cations. The crystals can be used in laser oscillation and amplifiers. A particular composition is Yb-doped $BaCaBO_3F$ (Yb:BCBF). Because BCBF and some related derivative crystals are capable of nonlinear frequency conversion, whereby the fundamental of the laser is converted to a longer or shorter wavelength, these new crystals can simultaneously serve as self-frequency doubling crystals and laser materials within a laser resonator.
Roger D. Aines Robin L. Newmark	**Active Cooling-Based Surface Confinement System for Thermal Soil Treatment** U.S. Patent 5,681,130 October 28, 1997	A process for the use of a thermal barrier to control the ground subsurface pressure by active cooling. This barrier is placed in contact with the ground surface, and a region underneath the barrier is heated for remediation. The cooling capacity of the barrier is controlled so that rising gases and vapors in the soil are condensed and confined beneath the barrier. The subsurface pressure is thereby controlled by controlling the surface temperature. This method is useful for thermal remediation involving steam injection. The thermal barrier prevents steam breakthrough during thermal remediation of shallow underground contaminants.
Thomas E. McEwan	**Pulse Homodyne Field Disturbance Sensor** U.S. Patent 5,682,164 October 28, 1997	An inexpensive field-disturbance sensor that transmits a sequence of transmitted bursts of electromagnetic energy. The transmitter frequency is modulated at an intermediate frequency. The sequence of bursts has a burst repetition rate, and each burst has a burst width and comprises a number of cycles at a transmitter frequency. The sensor includes a receiver that receives electromagnetic energy at the transmitter frequency and a mixer that mixes a transmitted burst with reflections of the same transmitted burst to produce an intermediate-frequency signal. A second range-defining mode transmits two radiofrequency bursts, where the time spacing between the bursts defines the maximum range divided by two.

Awards

Richard W. (Dick) Lee and **Max Tabak** have been elected **Fellows of the American Physical Society** for their outstanding contributions to physics. Among the 179 fellows elected in 1997, they are both members of the society's Plasma Physics Division. Lee, a senior scientist in the Physics and Space Technology Directorate office, was recognized "for technical contributions and outstanding outreach of codes for plasma spectroscopy." A physicist and group leader for inertial confinement fusion in the Defense and Nuclear Technolgoies Directorate, Tabak was cited for "his exceptional inventive and broad contributions to the fields of laser and particle-driven inertial fusion, and in particular for being the principal inventor of the fast ignition concept."

IndustryWeek magazine selected **Charles Alcock** as one of the nation's top 50 R&D "stars" for his research on dark matter, known as MACHOS (Massive Compact Halo Objects).

Kennedy Reed, named the winner of the **International Center for Theoretical Physics Visiting Scholar Award**, traveled to the University of Dakar in Senegal and the University of Cape Coast in Ghana to fulfill duties of the award, which included consulting and leading seminars.

Keeping Laser Development on Target for the National Ignition Facility

The National Ignition Facility (NIF) will be the world's largest laser when it is completed in 2003. The 192-beam facility, costing $1.2 billion, is Lawrence Livermore's largest construction project and permanent facility in its history. The goal is to achieve fusion energy break-even and gain for the first time in a laboratory while focusing on substantial cost savings on all parts of component design, placement, and use. This article discusses the progress of many of the laser technologies that combine to make the NIF laser feasible, including the optical pulse generation system, preamplifier modules, main amplifier modules, flashlamps, power conditioning system, Pockels cells, and deformable mirrors. Also discussed are the contributions of the Beamlet and Amplab experimental facilities.

Contact:
Howard T. Powell (925) 422-6149 (powell4@llnl.gov) or Richard H. Sawicki (925) 423-0963 (sawicki1@llnl.gov).

Tracing the Role of Carbon Dioxide in Global Warming

One important area of work for Lawrence Livermore's Earth and Environmental Sciences Directorate is investigating the carbon cycle. Much of the carbon in our environment exists in the atmosphere in the form of carbon dioxide, the most important greenhouse gas. By tracking carbon as it exchanges from the atmosphere to the terrestrial ecosystem and the oceans, climate scientists are attempting to understand how increased emissions of carbon, as a result of human activities, can perturb global climate. The Climate System Modeling Group, in collaboration with other Laboratory disciplines, investigates better mathematical approximations of physical processes; experiments with different applications of data sets such as past records, collected observations, and proxy indicators for climate-related events; and tests hypotheses on physical and biogeochemical processes.

Contact:
Philip B. Duffy (925) 422-3722 (duffy2@llnl.gov) or Kenneth G. Caldeira (925) 423-4191 (kenc@llnl.gov).

U.S. Government Printing Office: 1998/683-051-60040