Lawrence Livermore National Laboratory

December 2010

Science & Technology REVIEW

Tracking the Carbon Cycle

Also in this issue:

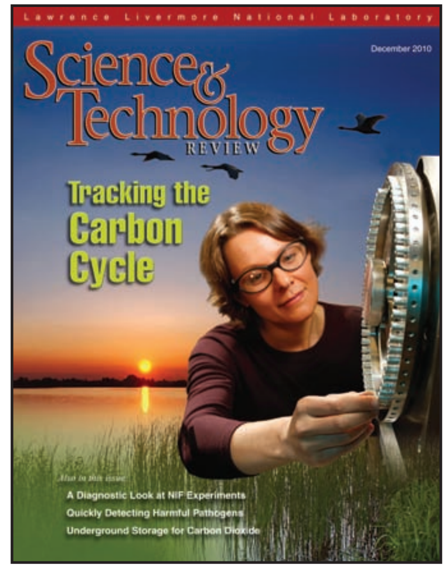
A Diagnostic Look at NIF Experiments

Quickly Detecting Harmful Pathogens

Underground Storage for Carbon Dioxide

About the Cover

Climate scientists are using Livermore's Center for Accelerator Mass Spectrometry to examine how carbon dioxide enters and leaves the atmosphere, oceans, and terrestrial biosphere and to reconstruct climate records from centuries past. By analyzing the isotopic composition of samples taken from lake beds, forests, deep-water corals, and other sources, they can study how Earth's carbon cycle is affected by variations in climate and how past ecosystems have reacted to significant climatic changes. The article beginning on p. 4 describes this research, which focuses on enhancing scientific understanding of regional and global climate change. On the cover, Livermore scientist Karis McFarlane loads a sample into the spectrometer.



Cover design: George A. Kitrinos

About *S&TR*

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

The Laboratory is operated by Lawrence Livermore National Security, LLC (LLNS), for the Department of Energy's National Nuclear Security Administration. LLNS is a partnership involving Bechtel National, University of California, Babcock & Wilcox, Washington Division of URS Corporation, and Battelle in affiliation with Texas A&M University. More information about LLNS is available online at www.llnsllc.com.

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NNSA National Nuclear Security Administration

LAWRENCE LIVERMORE NATIONAL SECURITY LLC

Prepared by LLNL under contract DE-AC52-07NA27344

Science & Technology REVIEW

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

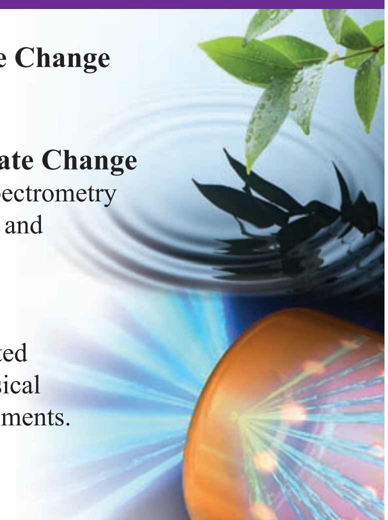
S&TR is available on the Web at str.llnl.gov

Printed in the United States of America

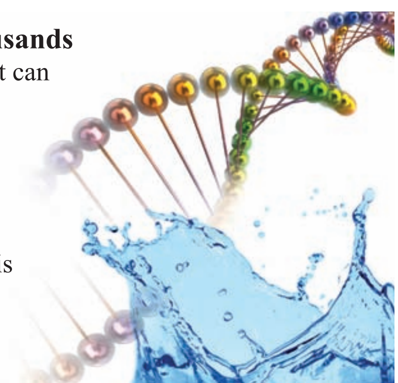
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-10-12
Distribution Category UC-99
December 2010

Features



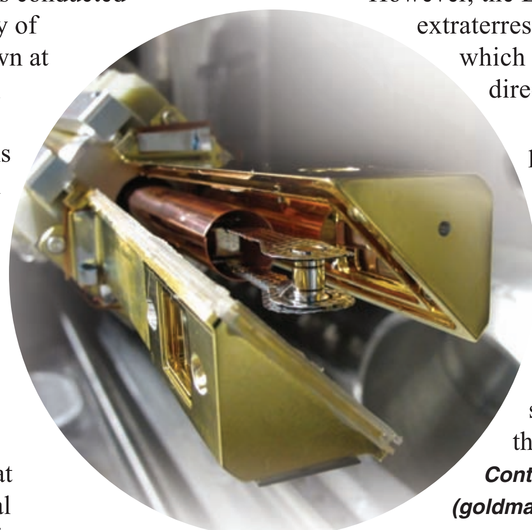
Research Highlights



Departments

NIF Shot Lights the Way to Ignition

In September 2010, the National Ignition Facility (NIF) completed its first integrated ignition experiment. For this shot, the 192-beam laser system fired 1 million joules of laser energy into its first cryogenically layered capsule, raising the drive energy by a factor of 30 over previous experiments conducted with the OMEGA laser at the University of Rochester. The target for this shot (shown at right) was filled with tritium, hydrogen, and deuterium—a mixture tailored to demonstrate that NIF's complex systems can operate in concert to achieve fusion ignition and energy gain. All systems operated successfully, and 26 devices recorded target diagnostic data during the shot.



"From both a system integration and a physics point of view, this experiment was outstanding," says Ed Moses, principal associate director for NIF and Photon Science. "This is a great moment in the 50-year history of inertial confinement fusion. It represents significant progress in our ability to field complex experiments in support of the Laboratory's missions in stockpile stewardship, national security, fundamental science, and energy."

NIF, the world's largest and highest-energy laser, is expected to be the first laser system to demonstrate reliable fusion ignition, the same force that powers the Sun and stars, in a laboratory environment. With the completion of this test, the National Ignition Campaign—a partnership among Lawrence Livermore, Los Alamos, and Sandia national laboratories; the University of Rochester's Laboratory for Laser Energetics; and General Atomics—is beginning its next phase, which will culminate in fusion ignition tests. The National Ignition Campaign is focused on advancing the nation's Stockpile Stewardship Program as well as basic high-energy-density science in such fields as astrophysics, nuclear physics, radiation transport, materials dynamics, and hydrodynamics.

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First Life on Earth May Have Come as a Shock

Research by a team of Livermore scientists shows that comets crashing into Earth millions of years ago could have produced amino acids, which contribute to the process of metabolism and serve as protein building blocks. Using molecular-dynamics simulations, the team studied shock compression to extremely high pressures and temperatures in a prototypical astrophysical ice mixture, similar to a comet crashing into Earth. Results from the simulations, which were published in the September 12, 2010, edition of *Nature Chemistry*, indicated that the sudden compression and heating of these cometary ices could produce complexes resembling the amino acid glycine.

Previous research indicated that cometary impact events were unlikely to produce amino acids because extreme heating from the impact would destroy the potential life-building molecules found in comets, such as water, ammonia, and carbon dioxide. However, the Livermore team studied a scenario in which an extraterrestrial ice impacts a planet with a glancing blow, which could generate much lower temperatures than a direct impact would.

"Under this situation, organic materials could potentially be synthesized within the comet's interior during shock compression and survive the high pressures and temperatures," says Livermore scientist Nir Goldman, who led the project team. "Once the compressed material expands, stable amino acids could survive interactions with the planet's atmosphere or ocean. These processes could result in concentrations of prebiotic organic species 'shock-synthesized' on Earth from materials that originated in the outer regions of space."

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Large Telescope Named a Top Priority

In the report *New Worlds, New Horizons in Astronomy and Astrophysics*, a science committee convened by the National Research Council for the National Academy of Sciences recommended building the Large Synoptic Survey Telescope (LSST) with a goal of achieving first light by 2020. Lawrence Livermore is one of 34 institutions in the public–private partnership working on the LSST project, which receives funding from the National Science Foundation and the Department of Energy's Office of Science.

The 8.4-meter-diameter telescope will be constructed on Cerro Pachón, a mountain in northern Chile. Scheduled to begin full operation six years after construction begins, LSST will be equipped with the world's largest digital camera (3.2 billion pixels) and will survey the entire visible sky to very faint detection limits. LSST will produce 30 trillion bytes of data per night, yielding a total database of 30 quadrillion bytes.

With this massive data set, researchers will, for the first time, construct a color "movie" of the sky, allowing them to study objects that move or change in brightness, from potentially hazardous near-Earth asteroids to exploding massive stars (supernovae) in the distant universe. Because of the light-bending gravity of dark matter, the data collected over a 10-year period will also be used to chart the history of the expanding universe and to probe the mysterious nature of dark energy. The LSST data will be open to the public and scientists around the world. Anyone with a Web browser will have access to the images and other data produced.

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Commentary by Tomás Díaz de la Rubia

More Insight to Better Understand Climate Change

ONE of the most daunting scientific challenges of our time involves determining the role of human activities in global climate change and predicting how that change will likely progress over the coming decades. As detailed in the article beginning on p. 4, a group of Livermore researchers and their collaborators is enhancing our scientific understanding of regional and global climate change. They are obtaining samples, many of them thousands of years old, from lake beds, forests, deep-water corals, and other sources and precisely dating them at Livermore's Center for Accelerator Mass Spectrometry (CAMS).

For more than two decades, researchers have depended on CAMS for extraordinarily accurate analyses of the isotopic composition of materials. Hundreds of scientists have used the facility for a broad range of efforts, including those devoted to climate change, biomedicine, and materials science for new energy technologies.

Data supplied by CAMS help reduce uncertainty in our modeling results and thereby increase confidence in climate change predictions. Simulations using the most advanced models offer a glimpse into Earth's climate future and help us develop the means to mitigate potential environmental and economic damage. These simulations require very high-capability computing, such as the massively parallel supercomputers at Livermore and other national laboratories. The simulations must also be based on realistic descriptions of the physics driving atmospheric processes, careful environmental observations, and accurate records of climate change from hundreds and even thousands of years ago.

Livermore's study of climate began in the late 1950s, when Laboratory cofounder Edward Teller encouraged researchers to develop the first global general circulation model simulating the growth, movement, and decay of large weather systems. The effort took advantage of the early—and by today's standards, primitive—computers installed at Livermore. In the late 1960s, Laboratory researchers became interested in the effects of human activities on the environment. Because the Livermore Valley was experiencing an increase in the number of excess ozone days, our researchers developed a model for predicting air quality in the San Francisco Bay Area, which became widely used. A broader range of activities followed in the 1970s to assess the effects of ozone, pollutants such as chlorofluorocarbons, and greenhouse gases on the climate.

These efforts blossomed into the National Atmospheric Release Advisory Center, which started as a research project in 1973 and has long served as an emergency response service for the federal government, and the Program for Climate Model Diagnosis and Intercomparison, which was formally established in 1989. Through this internationally recognized program, Livermore scientists develop methods to diagnose, validate, and compare the global climate models produced by organizations worldwide.

Today, we are focused on better understanding to what extent the growing concentration of atmospheric carbon dioxide and other greenhouse gases is driving climate change, and we are exploring what mitigation measures would be viable. Atmospheric carbon dioxide emissions from the burning of fossil fuels affect the carbon content of both terrestrial and oceanic systems, which have a profound effect on climate. The flow of carbon dioxide through the atmosphere and the terrestrial and marine ecosystems—referred to as the carbon cycle—is fiendishly complex. But as the article reports, we are slowly uncovering its mechanisms.

In our quest to reduce uncertainties about climate change, we are tapping the field of uncertainty quantification and error analysis. In 2009, we launched a three-year initiative dedicated to identifying sources of uncertainty to improve the predictive capability of climate-change models. This effort, which combines Livermore expertise in software, mathematics, statistics, and physics, is an offshoot of the methodology used to assess the performance of nuclear weapon systems without underground nuclear testing.

In the near future, we will begin work on a new Department of Energy effort called "Climate Science for a Sustainable Future," whose goal is to develop a climate model two generations beyond current capabilities. This multilaboratory effort is aimed at addressing climate-science questions critical to the nation's energy security. The research will encompass several related activities, such as developing flexible and comprehensive model components that enable climate predictions at regional scales and achieving greater fidelity in understanding feedbacks in the climate system. By achieving increased scientific understanding of climate change, researchers will provide policy makers with more complete data with which to make decisions about how society can successfully adapt to our changing planet.

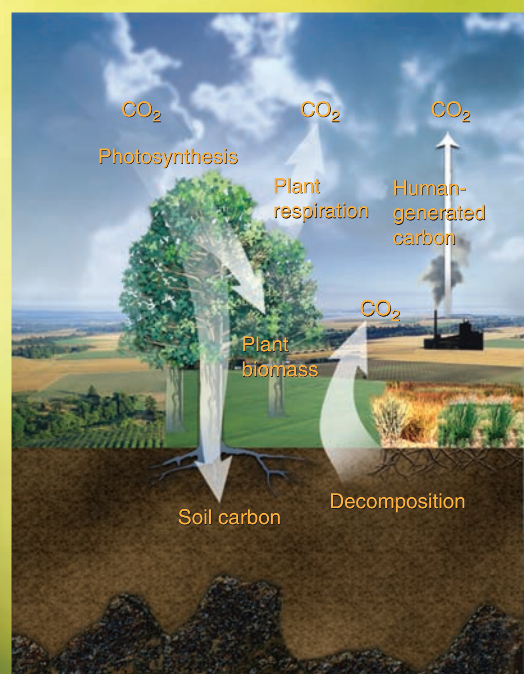
■ Tomás Díaz de la Rubia is deputy director for Science and Technology.

Strengthening Our Understanding of Climate Change

At the Center for Accelerator Mass Spectrometry, researchers are examining how climate variations affect Earth's carbon cycle.

FROM ice ages to long warming periods, Earth's climate has changed, often drastically, during the planet's history. Human activities associated with burning fossil fuels for transportation, manufacturing, and energy production have dramatically altered the composition of the atmosphere, which ultimately may modify long-term climactic trends.

For more than two decades, Lawrence Livermore has been a leader in advancing scientific understanding of the causes and consequences of climate change, developing strategies to mitigate the risks, and strengthening computational tools used to predict future patterns. Accurate



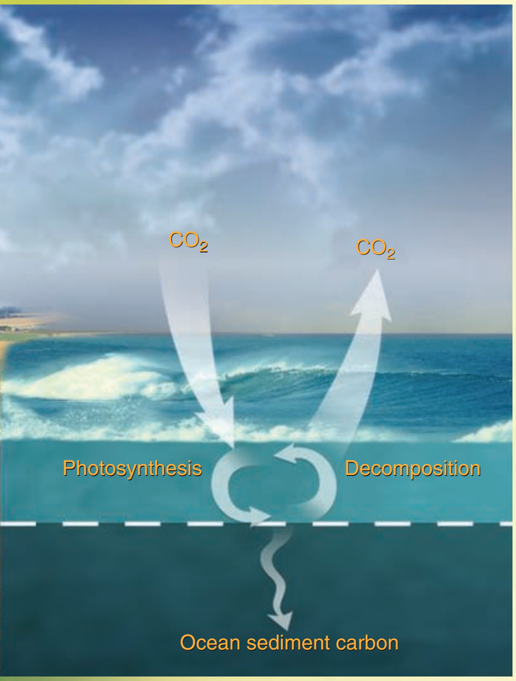
predictions are essential because long-term climate changes have the potential to significantly affect human health, crop yields, pest management, fire danger, water quality and supply, and many other factors related to socioeconomic well-being.

Livermore's Center for Accelerator Mass Spectrometry (CAMS) has become a valuable resource for climate scientists by providing high-fidelity historical data to improve long-term predictions. In particular, CAMS is revealing details about Earth's carbon cycle, the flow of carbon atoms through the planet's living organisms, oceans, atmosphere, and soil. At CAMS, researchers can precisely measure the ratio of radiocarbon (the unstable carbon-14 isotope) to stable carbon (carbon-12). Radiocarbon is naturally produced by the interaction of cosmic rays and air and is present at low levels in the atmosphere and food. By dating samples and characterizing their material components, scientists can examine how climate variations affected the carbon cycle and how past ecosystems reacted to significant changes. (See the box on p. 7.)

Climate change is a variation in the statistical distribution of weather patterns over periods ranging from tens to millions of years. "It can be a change in the average weather or a change in the distribution of weather events around an average," says CAMS Director Graham Bench. "Climate change may be limited to a specific region, or it may occur across the whole Earth." Accurate predictions help policy makers evaluate potential responses to projected scenarios. Predicting a long-term increase in precipitation, for example, tells only part of the story. Precipitation falling as rain instead of snow could be disastrous for a state such as California, which depends on its snowpack for water storage. Likewise, precipitation that falls evenly over several months usually causes much less havoc than a few potentially flood-causing storms, even when the total rainfall is equal.

Climate change research at CAMS is led by the Natural Carbon Group, headed by Livermore geochemist Tom Guilderson. Members of the group and its dozens of collaborators worldwide use radiocarbon measurements as an easily identifiable tracer to measure geologic time and to follow the path of carbon flow.

The group's research focuses both on understanding how carbon dioxide (CO_2) enters and leaves the atmosphere, oceans, and terrestrial biosphere and on acquiring climate records from the past to examine the processes governing current and future climate patterns. Research activities include studying corals to document changes in ocean circulation, determining the uptake and storage of carbon in soils, mapping the decades- to centuries-long droughts in California, studying the exchange of CO_2 between the atmosphere and oceans, and calculating carbon uptake by different ecosystems. The group works closely with the international scientific community and with the Department of Energy's Program for Climate Model Diagnosis and Intercomparison, which was established in 1989 at Lawrence Livermore to analyze current climate models.



In Earth's carbon cycle, photosynthesis removes carbon dioxide (CO_2) from the atmosphere. Respiration from plants and soil microbes and the decomposition of biological material returns CO_2 to the atmosphere, as do human activities, mainly from burning fossil fuels. Oceans absorb and release carbon primarily via diffusion across the air–ocean interface. Phytoplankton photosynthesis converts CO_2 into organic carbon that is largely returned to ocean water as CO_2 via microbial respiration and decomposition. A small amount of organic carbon sinks to the ocean floor. (Courtesy of the Department of Energy Office of Science.)

Warming May Not Increase Fires

One major concern for climate scientists is that rising temperatures could make many regions drier and hence elevate the risk of forest fires. Research by Livermore scientist Tom Brown and colleagues is showing that nature's response to higher temperatures may instead counteract the heat effects and reduce the projected fire risks. To study climate effects on fire frequency, Brown worked with Philip Higuera of Montana State University and colleagues at the University of Washington and the University of Illinois to analyze sediment cores extracted from lake bottoms in the Brooks Range of northern Alaska.

The scientists recorded the types and abundance of preserved plant parts, such as microscopic pollen grains, from 15,000 years ago to the present. At CAMS, they radiocarbon-dated organic deposits in the sediment. They also looked for charcoal particles in the samples to determine how frequently forest fires occurred. Next, they compared the fire frequency data to the kinds of vegetation that were dominant during various periods and considered those findings in terms of what is known about past climate patterns in northern Alaska. Results indicated that, contrary to conventional thinking, the number of fires decreased during warmer periods. In fact, the researchers found that historically, fire frequency coincided more with the type of vegetation than with temperature.

For example, about 10,500 years ago, northern Alaska's climate changed from cool and dry to warm and dry, which would suggest a higher incidence of fires. However, sediment cores revealed that during this period vegetation changed from flammable shrubs to fire-resistant deciduous trees. As a result, the frequency of fires declined sharply. About 5,000 years ago, the area became cooler and wetter, conditions that would suggest a decrease in fires. However, the scientists found evidence of more frequent fires, which they attributed to the growth of highly flammable spruce forests in the region.

According to Brown, many climate models show that warmer temperatures decrease moisture and increase ignition rates. However, the CAMS results indicate that the type of vegetation can significantly alter the direct link between climate and fire. "Vegetation can have a profound impact on fire occurrences, independent of climate's influence," says Brown. "Models that consider rising temperatures while ignoring vegetation will not accurately predict the likelihood of wildfires in a particular region. We have to look at the whole picture."

In the south-central region of the Brooks Range, Alaska, researchers are determining the historical relationship between climate, vegetation, and the incidence of fires. (Courtesy of Philip Higuera.)

Researchers collect sediment cores from a lake in the Brooks Range of Alaska. (Courtesy of Philip Higuera.)

In an earlier study, Brown measured carbon storage in the 6.2-million-square-kilometer Amazon River Basin, where each year, vegetation and soil absorb millions of tons of CO_2 through the process of photosynthesis. Determining how long an ecosystem such as a tropical rain forest stores atmospheric CO_2 is important because some scientists have suggested that such ecosystems might serve as long-term storage sites of atmospheric CO_2. However, radiocarbon measurements showed that the basin stores carbon for only about five years before returning it to the atmosphere as CO_2. (See *S&TR*, March 2006, pp. 17–19.)

Using the Radiocarbon Pulse

In recent decades, scientists have studied the growing amount of CO_2 emitted to the atmosphere from human activities and its relationship to the slow but steady rise in average planetary temperature. Globally, more carbon (contained in many different organic compounds) is stored as soil organic matter than in vegetation and the atmosphere combined. Despite their importance to climate, soils are a poorly understood aspect of the terrestrial carbon cycle.

Because trees capture so much of the atmosphere's CO_2, predicting the amount of carbon that might be retained by forests provides important information. A significant portion of this carbon is sequestered for decades to centuries in the trunks and large branches of trees. Much of the carbon consumed as CO_2 is later shed in leaves, twigs, and small roots. As these components decompose, they release carbon to the soil and eventually back to the atmosphere.

Determining the rates of carbon transfer between plants and soil and back to the atmosphere is important for improving carbon cycle models and determining if CO_2 produced by human activities can be sequestered in terrestrial ecosystems, such as forests. To better understand this cycle, environmental scientist Karis McFarlane has been taking advantage of a large, unplanned release of innocuous radiocarbon-labeled CO_2 from incinerators near Oak Ridge, Tennessee, in 1999. Trees in a nearby hardwood forest incorporated the released CO_2 into leaf, stem, and root tissue, which eventually became leaf and root litter. This "pulse" of a rare isotope

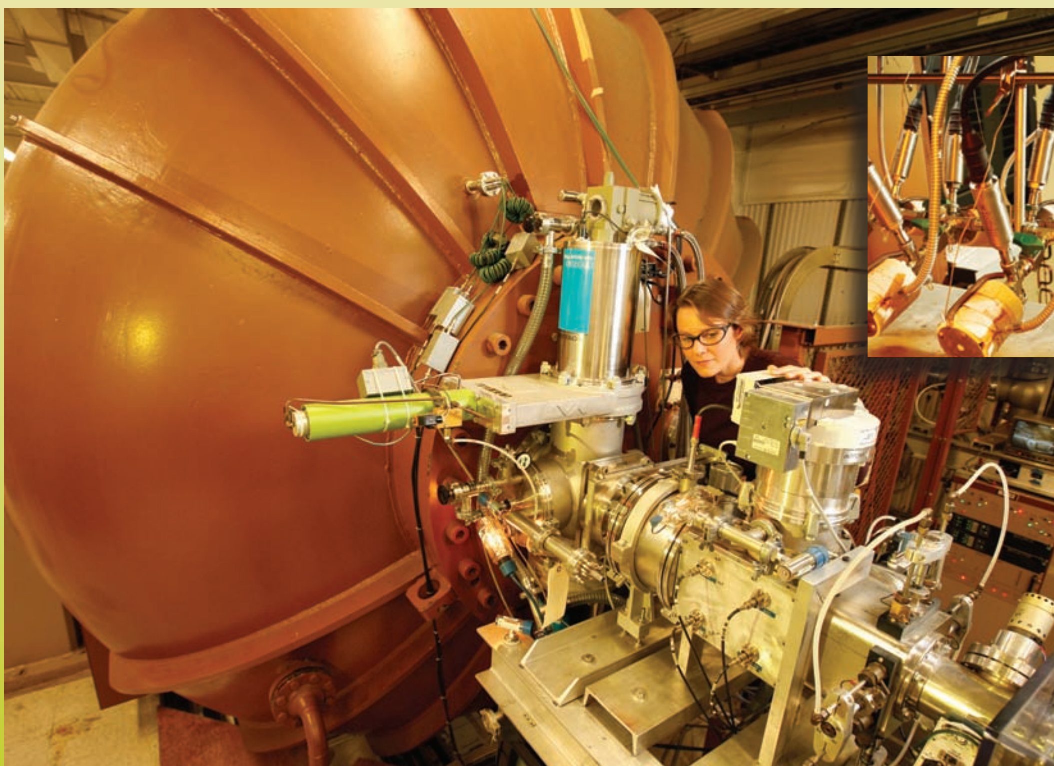
Center for Accelerator Mass Spectrometry Serves Scientists Worldwide

Established at Livermore in 1989, the Center for Accelerator Mass Spectrometry (CAMS) allows researchers to accurately measure extremely small samples (weighing less than 1 milligram) containing minute quantities of isotopes of interest in materials ranging from archaeological artifacts to biological tissues. Scientists use CAMS to measure isotopes of carbon, calcium, beryllium, aluminum, strontium, plutonium, uranium, chlorine, iodine, and hydrogen.

CAMS contributes to research in earth and environmental sciences, climate change, carbon sequestration, and national security applications. The center is also a leader in biomedical applications of accelerator mass spectrometry (AMS) for studying the metabolism of chemicals, toxic compounds, and nutrients. "AMS facilities tend to specialize in a few isotopes," notes CAMS Director Graham Bench. "CAMS is truly unique in the gamut of disciplines that use the facility and the range of isotopes the facility can detect." CAMS currently features close to 150 scientific collaborations throughout the world. In addition, the center has been essential to the successful completion of more than 200 graduate theses.

Running around-the-clock, CAMS performs more than 15,000 measurements per year. Many measurements involve radiocarbon (carbon-14), an unstable isotope for dating samples back to 50,000 years. With its half-life of 5,700 years, radiocarbon is frequently used in the fields of archaeology, anthropology, biology, geology, and ocean sciences. One carbon atom out of a trillion is radiocarbon.

The concentration of radiocarbon in atmospheric carbon dioxide remained fairly constant for thousands of years. However, between 1954 and 1963, when atmospheric tests of nuclear devices were conducted, the amount of radiocarbon in the atmosphere doubled. After the tests were halted, the elevated concentrations quickly dispersed around the globe, diffusing into Earth's biosphere. This spike in radiocarbon has been particularly useful in biomedical research. (See *S&TR*, April/May 2010, pp. 15–17.)



Livermore scientist Karis McFarlane is analyzing thousands of soil samples at the Center for Accelerator Mass Spectrometry as part of a project to improve models showing how organic and mineral soils accumulate and disperse carbon so researchers can better understand the carbon cycle in deciduous forests.

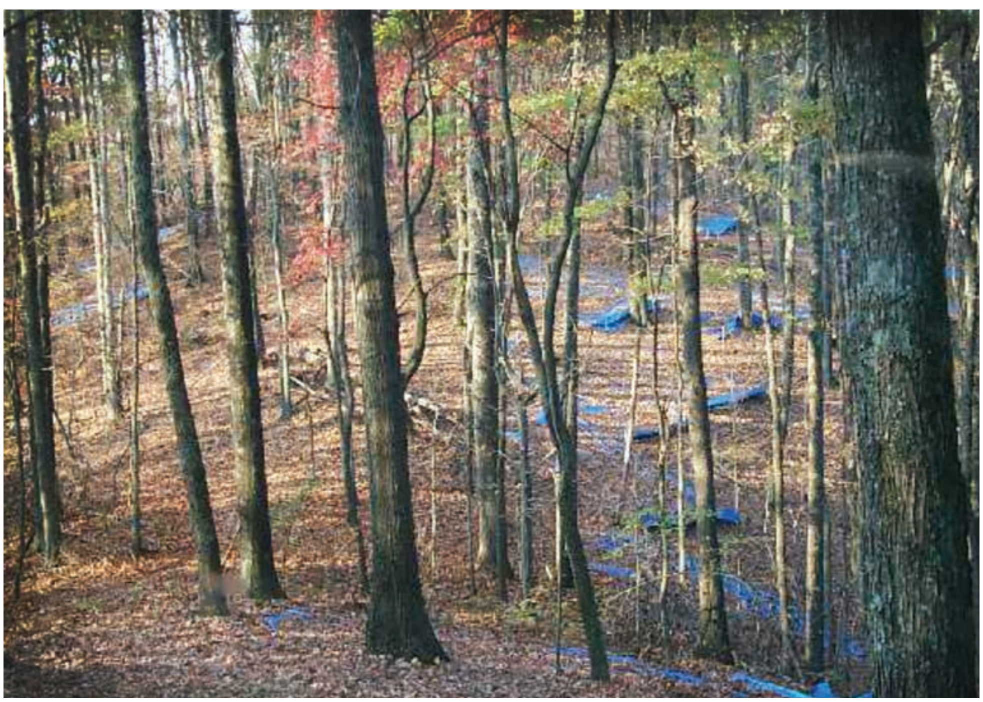
in an ecosystem presented a unique opportunity for studying how carbon is incorporated into the soil of a temperate forest, how long it resides there, and what causes it to reemerge into the atmosphere.

The research, which has involved analyzing thousands of soil samples at CAMS, is part of the Department of Energy's Enriched Background Isotope Study. This project is aimed at improving the ability to model the accumulation and fate of carbon within organic and mineral soils and thus better understand the carbon cycle in the deciduous forests that comprise 46,000 to 60,000 square kilometers of North America east of the Mississippi River. The radiocarbon-pulse study includes researchers from Oak Ridge, Argonne, and Lawrence Berkeley national laboratories; the U.S. Forest Service; and the University of California.

As part of the isotope study, scientists collected leaf litter and dug up small roots from radiocarbon-enriched trees at Oak Ridge and transferred them to four research forests in New Hampshire, Massachusetts, northern Michigan, and Missouri. Every year, McFarlane takes samples from each of the four forests and measures the radiocarbon levels to study the contribution of leaf versus root litter to the carbon accumulation in soil and the transport rate of carbon into mineral soil storage. She first separates the soil organic matter into three different fractions based on their density: light-density plant organic matter; physically protected soil organic matter; and heavy, mineral-rich fractions. She then measures the radiocarbon concentration of each fraction.

Results from the first six years of the Oak Ridge study show that carbon in the top, leaf-litter layer is respired as CO_2 by microbes and is not being transported into the mineral soil where it might be protected and sequestered for decades or centuries. "New carbon from leaves makes it only into the top couple of centimeters in soil over several years," says McFarlane. "Below this level, tree roots are providing new carbon to soil, meaning that roots are more important sources for carbon in soil than previously realized."

Data from the four forests provided new information as well. "We know that carbon stays around longer in cold climates because microbial activity is limited," says McFarlane. "We are finding that soil characteristics also affect carbon storage. They are an important consideration for developing carbon models that can improve our ability to predict future climate."



In 1999, trees in a hardwood forest near Oak Ridge, Tennessee, incorporated a pulse of radiocarbon-labeled CO_2, which eventually became leaf and root litter. By analyzing soil organic matter from this forest, researchers are determining how carbon is incorporated into the soil of temperate forests, how long it resides there, and what causes it to reemerge into the atmosphere. (Courtesy of Paul Hanson, Oak Ridge National Laboratory.)

Ocean Currents Key to CO_2 Levels

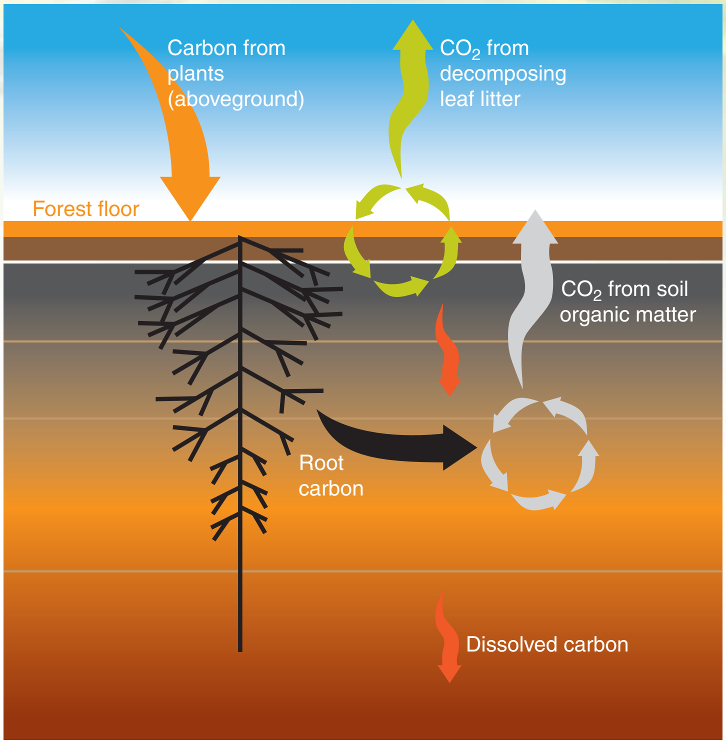
Studies performed at CAMS have helped pioneer the application of large radiocarbon data sets in determining past ocean circulation patterns. Ocean currents transport enormous quantities of heat and thus play a crucial but poorly documented role in Earth's climate. In addition, ocean circulation controls the sequestration of CO_2 in the deep sea on millennial timescales.

As part of a research collaboration, Guilderson is making radiocarbon measurements at CAMS to trace the pathway of a large amount of CO_2 released from the deep ocean to the atmosphere at the end of the last ice age, about 10,000 years ago. Funded by the National Science Foundation, this project includes researchers from the University of California at Davis and Santa Cruz, Rutgers University, Institut de Ciència i Technologia Ambientals in Spain, University of Auckland in New Zealand, and Woods Hole Oceanographic Institution.

The team took sediment cores from the area surrounding Antarctica and the South Pacific Ocean near New Zealand and dated the samples to between 13,000 and 19,000 years old. The radiocarbon in the cores served as a tracer showing when the large CO_2 release occurred and the ocean pathway by which it escaped. A rapid increase in atmospheric CO_2 concentrations during this period coincided with a reduced amount of radiocarbon in the atmosphere, suggesting that a release of very "old" carbon—or CO_2 with a low ratio of radiocarbon to stable carbon—from the deep ocean to the atmosphere occurred at the end of the last ice age.

Some scientists have wondered whether deeper waters, which are substantially depleted in radiocarbon, were drawn to the upper ocean layers near Antarctica and served as the main source of the CO_2 release that sped up the melting of glaciers. Analysis of cores taken from the ocean floor near New Zealand suggests that if the old, low-radiocarbon water upwelled near Antarctica, it remained at the surface long enough to nearly equilibrate with the atmosphere. However, the expected low-radiocarbon signal that would be transported from the surface back into intermediate-depth waters is absent in the New Zealand data. An alternative interpretation is that the low-radiocarbon signal outcropped elsewhere, with a likely candidate the far northern region of the Pacific Ocean.

Guilderson notes that the CO_2 release from the last ice age is not relevant to recent global warming because the average lifetime of CO_2 in the atmosphere is about 70 to 100 years. "When we radiocarbon-dated CO_2 in the atmosphere," says Guilderson, "the isotopic signature we found indicated that this accumulation is mainly due to the use of fossil fuels."



Radiocarbon studies at the Center for Accelerator Mass Spectrometry show that carbon from fallen leaves at Oak Ridge forests is respired as CO_2 by microbes and is not transported into the deeper mineral soil where it might be sequestered for many years. However, decaying tree roots are providing carbon to deeper soil layers.

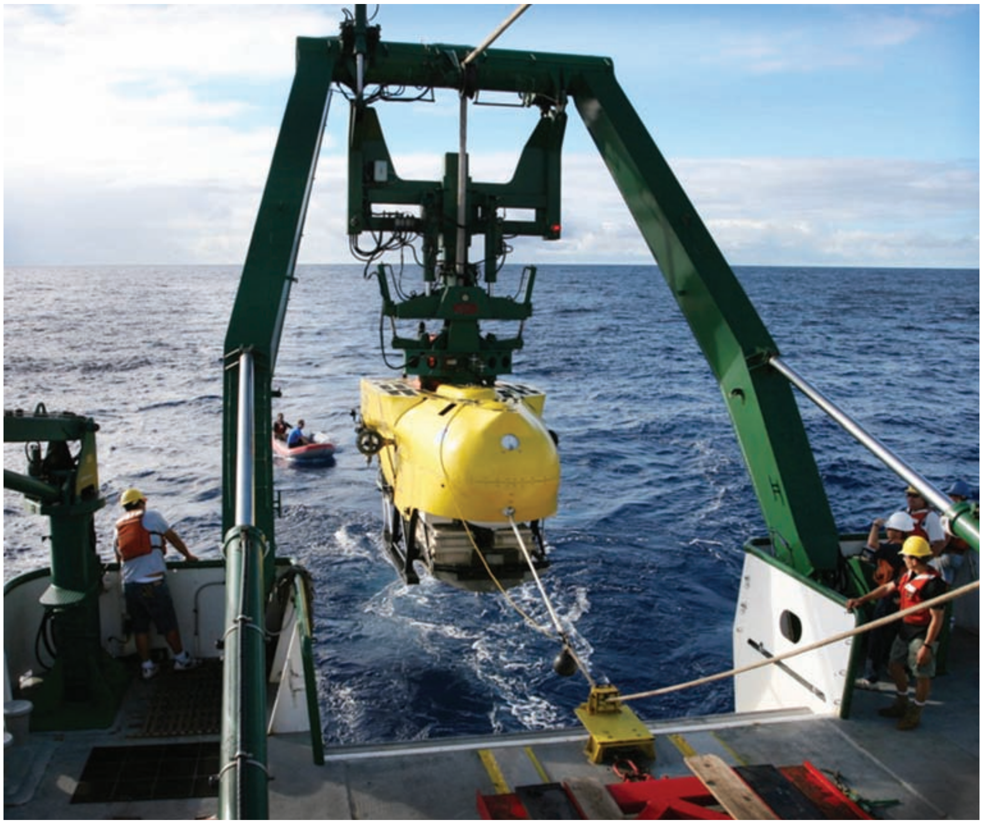
Corals as Data Repositories

Guilderson has also been studying reef-building (surface) and deep-sea corals. Reef-building corals are found in warm, shallow tropical locations. Deep-sea corals grow at depths from 300 to more than 3,000 meters and are ubiquitous throughout the world's oceans. These two types of corals lend themselves to radiocarbon-dating studies because their massive calcium carbonate skeletons are accreted nearly continuously, and the colonies can live for thousands of years. The growth of coral colonies is affected by changes in ocean conditions such as acidity and temperature. "We're using surface corals as our thermometers and rain gauges," says Guilderson. "Reef-building corals are repositories for a lot of information that can give us a long-term perspective on ocean currents and hence climate variability for locations and times when people weren't making observations."

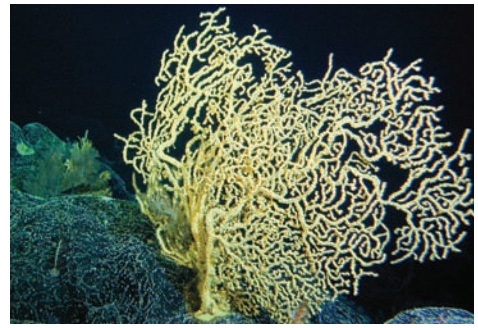
With the help of CAMS, researchers are looking at isotopes of carbon, oxygen, and nitrogen to obtain water temperature, salinity, and CO_2 variations over the past several centuries. As a by-product, the researchers are determining growth rates and longevity of these organisms, important information for establishing conservation and marine policy.

Guilderson and former Livermore colleague Stewart Fallon, together with researchers from Stanford University and the University of California, have been studying deep-sea corals off the coast of Hawaii and elsewhere in the Pacific. For this project, the team deployed human-operated deep-sea research submersibles and remote-operated vehicles to collect samples from the deep ocean. Using radiocarbon dating at CAMS, the researchers determined the ages of deep-sea corals *Geradia sp.*, colloquially known as gold coral, and *Leiopathes sp.,* a deep-water black coral. The longest-lived in each species was 2,740 years and 4,270 years, respectively. At more than 4,000 years old, the deep-water black coral is the oldest known living skeletal-accreting marine organism.

Other dating methods indicated that the *Geradia* coral was much younger. "The ages established at CAMS far exceed previous estimates," Guilderson says. "Individual polyps appear to live only a few years, but they have been continuously replaced for up to thousands of years while accreting their underlying skeleton."



A deep-sea research submersible is used to retrieve coral samples off the coast of Hawaii. (Courtesy of Robert Dunbar, Stanford University.)



Long-living *Leiopathes sp.*, or deep-water black coral (top), and *Geradia sp.*, or gold coral (bottom), provide a storehouse of knowledge on changes in ocean conditions and climate. (Courtesy of National Oceanic and Atmospheric Administration Hawaii Undersea Research Laboratory.)

Prior to the research, some scientists thought the corals might feed on resuspended sediment (which could be old) rather than on recently photosynthesized carbon falling through the water. They also conjectured that corals might stop growing after reaching a certain size. The CAMS research showed that coral polyps eat material that descends from the surface. As a result, says Guilderson, "Deep-water ecosystems are tightly tied to what happens in surface waters because that's where those ecosystems get their food. In addition, because of the close relationship between deep-sea corals and ocean surfaces, corals can be affected by natural and human-made changes in surface ocean conditions, including ocean acidification and warming."

Guilderson notes that long-lived coral communities provide critical habitat for fish and invertebrates, but their survival is threatened by activities such as commercial fishing, trawling, and pipe laying, and in some areas, by the precious coral jewelry industry. By better understanding the ecology of deep-sea corals, researchers can help guide effective conservation strategies. The recent massive oil spill in the Gulf of Mexico has brought attention to the deep-sea coral communities and ecosystems in that region, which were discovered less than a decade ago.

Past Drought Patterns in California

Current global and regional climate models typically incorporate data from only the past 100 to 150 years. As a result, they may not reflect climate's variability when predictions are extended to hundreds or thousands of years. For example, tree-ring records indicate that over the last century, the western U.S. has been relatively wet compared with conditions for the past few hundred years. Without additional long-term data from periods of prolonged drought, current models may be biased toward wet conditions. By analyzing sediments up to 2,000 years old, geochemist Susan Zimmerman is helping to refine regional climate models and thereby improve the accuracy of climate change predictions.

"We want to use the geologic records of climate conditions together with climate models to better understand what caused climate change in the past and gain insight into present and future variations," Zimmerman says. Through a project funded by Livermore's Laboratory Directed Research and Development Program, she is developing lake-sediment records of the natural changes in California's climate, with the focus on tracking the number of

This photograph shows the effects of the 1976 drought on Folsom Lake in California, a state with a long history of prolonged droughts. For the past 100 years, however, California has experienced a relatively wet climate, which could lead to an inaccurate interpretation of results unless climate models incorporate precipitation data from thousands of years ago. (Courtesy of California Department of Water Resources.)

Susan Zimmerman takes samples from lake beds and escarpments in California. By radiocarbon-dating the samples, researchers are reconstructing the state's climate pattern for the last 2,000 years.

droughts through the centuries. "We're taking time slices of California climate for the last 2,000 years to help us reconstruct historical patterns," she says.

Accurately predicting the timing, amount, and patterns of precipitation is especially critical in California, with its growing population, enormous agricultural industry, and propensity for droughts. In particular, state agencies responsible for meeting future water demands must depend on scientific estimates for precipitation over the next few decades.

Zimmerman is working with researchers across California to analyze sediments taken from Zaca, Klamath, Big Bear, Mono, and Big Soda lake beds, among others. "Lakes are long-lived, wet areas where materials are continually deposited over time," Zimmerman says. The lake-sediment data complement annual tree-ring records of precipitation, which are mainly available from 1400 AD to the present. The lake-sediment records provide similar information but span much longer periods than the tree-ring data.

The researchers date samples from the lake cores by measuring the ratio of radiocarbon to the stable isotope carbon-13. CAMS is ideal for this task because it can measure hundreds of samples per month and produces highly precise results. The researchers examine two different sources of radiocarbon: organic carbon such as pine needles, twigs, and other macrofossils; and inorganic carbon, such as the calcium carbonate found in gastropods, ostracodes (millimeter-scale crustaceans indicative of wet periods), and other types of shells.

Zimmerman is also working with geochemist Sidney Hemming at Columbia University's Lamont-Doherty Earth Observatory to date samples from the bottom of California's Mono Lake and its escarpments. She found high levels of ostracodes in Mono Lake sediments dating from the last ice age. "We're very interested in the timing of the last big rise and subsequent drop in water levels at Mono Lake," says Zimmerman, "and to what extent those changes in water depth are consistent with the drastic climate changes recorded in Greenland at the end of the last ice age."

The ultimate goal of the CAMS projects is to determine what forces are driving climate changes. "We don't have enough historical observations," she says. "We need more extensive paleoclimate records to help us determine to what extent current climate change is human activity and how much is natural variation."

—*Arnie Heller*

Key Words: black coral, carbon-12, carbon-14, carbon dioxide (CO_2), Center for Accelerator Mass Spectrometry (CAMS), climate change, *Geradia sp*., gold coral, *Leiopathes sp.,* photosynthesis, Program for Climate Model Diagnosis and Intercomparison, radiocarbon dating.

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Precision Diagnostics Tell All

Robust, high-resolution instruments at the National Ignition Facility reveal the physics behind creating fusion in a laboratory.

Technicians install a static x-ray imager in the target chamber at the National Ignition Facility (NIF). This device helps scientists determine the positioning of NIF beamlines within the hohlraum.

THE ability to capture data from high-energy-density experiments has always been of great importance to the Laboratory and its missions. During the years of underground nuclear testing, Livermore scientists developed advanced diagnostics such as specialized oscilloscopes, streak cameras, and detectors to measure key physical properties of nuclear blasts, including reaction time histories and the overall yield of an explosion. In the absence of underground testing, these sophisticated instruments are still crucial for national security research, especially for the novel experiments conducted at the National Ignition Facility (NIF).

Built to generate up to 1.8 megajoules of ultraviolet light at a peak power of 500 terawatts, NIF is the world's largest, most energetic laser. With its one-of-a-kind capabilities, NIF enables researchers to explore new frontiers in high-energy-density science, from understanding the intricacies of astrophysics, hydrodynamics, and radiation transport to ensuring the continued safety and reliability of the nation's nuclear weapons stockpile. In September 2010, NIF completed its first integrated ignition experiment, demonstrating that all of the facility's complex systems function together as designed. (See the news brief on p. 2.) This experiment was a key milestone in the National Ignition Campaign (NIC), a multi-institutional effort focused on achieving fusion ignition and energy gain.

In an ignition experiment, all of NIF's 192 laser beams will be fired into a cylindrical case called a hohlraum, which contains a BB-sized capsule filled with deuterium–tritium (DT) fuel. Gathering data from ignition experiments requires an extensive suite of reliable, robust diagnostics that can image an experiment faster and in more detail than ever before. These devices detect and measure visible light, x rays, gamma rays, and nuclear products such as neutrons generated during an experiment. By studying the collected data, scientists and engineers can evaluate the performance characteristics of the laser, hohlraum, and target capsule. With this better understanding of the system's performance, they can determine how to manipulate the laser and the target design to produce the precise conditions for initiating fusion burn that produces more energy than was used to create it.

NIF diagnostics are designed to withstand the harsh environment of the target chamber—conditions that would destroy traditional electronics—and to record micrometer-scale details within tens of picoseconds (trillionths of a second). Since 2005, an international team of scientists and engineers has been working to improve established diagnostic systems and build new devices that can meet these stringent requirements. (See the box on p. 16.) Says Livermore scientist Bob Kauffman, "As a result of this collaboration, we have designed and built over 30 diagnostics specifically for NIF, and the number keeps growing."

Each diagnostic is being installed, calibrated, and tested in one of three stages. The first stage, completed in fall 2009, focused on instruments designed to measure the laser's operational capabilities. (See *S&TR*, April/May 2010, pp. 4–11.) Diagnostics tested in the second stage analyzed hohlraum energetics and how well the laser energy coupled to surrogate targets. (See *S&TR*, June 2010, pp. 17–19.) In 2011, the remaining diagnostics needed to evaluate the capsule implosion and neutron yield will be integrated into the target chamber.

Shock to the Heart

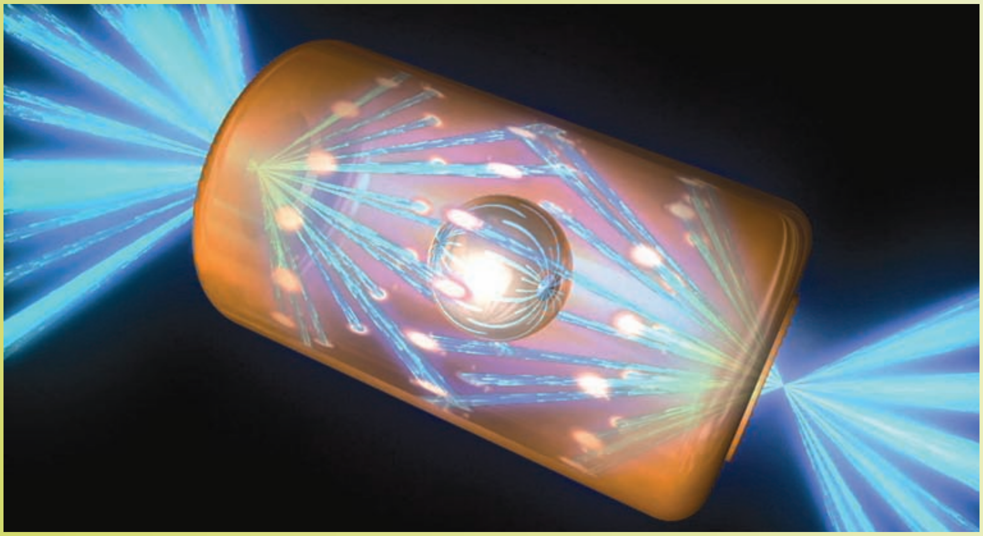
Inertial confinement fusion is the process by which a laser imparts enough energy into a capsule filled with hydrogen isotopes to heat and compress the fuel, creating fusion reactions. During an ignition experiment, 192 beams enter the hohlraum via holes at either end of the target. When these beams hit the hohlraum's interior walls, they generate x rays that heat and vaporize the fuel capsule's surface. The vaporizing outer (ablator) surface produces an inward force that compresses the fuel. This compression generates a series of shock waves that heat the capsule's inner core. The ignition "hot spot" created in the core starts the fusion burn. The velocity of the implosion, x-ray temperature of the hohlraum, shape and size of the hot spot, and neutron yield are all factors that determine whether ignition will be achieved.

Optical diagnostics designed to detect visible light help determine the energy balance of an experiment as well as the implosion velocity of the fuel capsule, laser–plasma interactions, and instabilities that affect the target performance. In a perfect world, the amount of energy fired into the hohlraum would be transferred to the target with minimal loss. However, two types of optical effects—Raman and Brillouin scattering—can cause the light to scatter out of the hohlraum. Because scattered light can adversely affect the drive of an implosion, researchers have designed optical devices to measure the light's power, spectrum, and angular distribution.

One such instrument is the full-aperture backscatter station. When light bounces off the hohlraum, some of it is reflected back through the laser's final focusing lens and into the beamline. There, a turning mirror diverts it into the backscatter station, which combines time-resolved imaging, spectrometry, and calorimetry to accurately characterize the reflected light.

A near backscatter imager, on the other hand, uses specially coated plates inside the target chamber to measure light scattered outside the aperture of the focusing lens. Says Kauffman, "We need these data to calculate the total energy absorbed from the incident beam, which is important for determining energy balance." A gated, intensified charge-coupled-device camera within the near backscatter imager provides time-resolved images recorded inside the hohlraum for analysis.

Another optical diagnostic is VISAR, the Velocity Interferometer for Any Reflector, which measures the speed of shock waves compressing the DT fuel. NIF can deliver pulses in a variety of shapes and lengths depending on the demands of a given experiment. For ignition, the laser produces four shocks that are timed to collapse the capsule in a specific sequence. If the shocks are too close together, they will coalesce in the ice layer that surrounds



During an ignition experiment, NIF's 192 beamlines will be fired into a hohlraum containing a deuterium–tritium fuel capsule. Within 20-billionths of a second, the capsule will be compressed and heated to create an energy-producing fusion reaction.

the DT gas. If they are too far apart, the ice will decompress between shocks.

VISAR is a time-resolved Doppler velocity camera that detects and images light reflected from the fuel capsule's ablator surface. Two interferometers combine the reflected beam with a reference beam to create an interference pattern. When a shock hits the fuel capsule, the interference pattern changes, indicating a phase difference between the beams that is proportional to the shock velocity. A streak camera records the pattern, providing the information needed to optimize the target design and its overall performance.

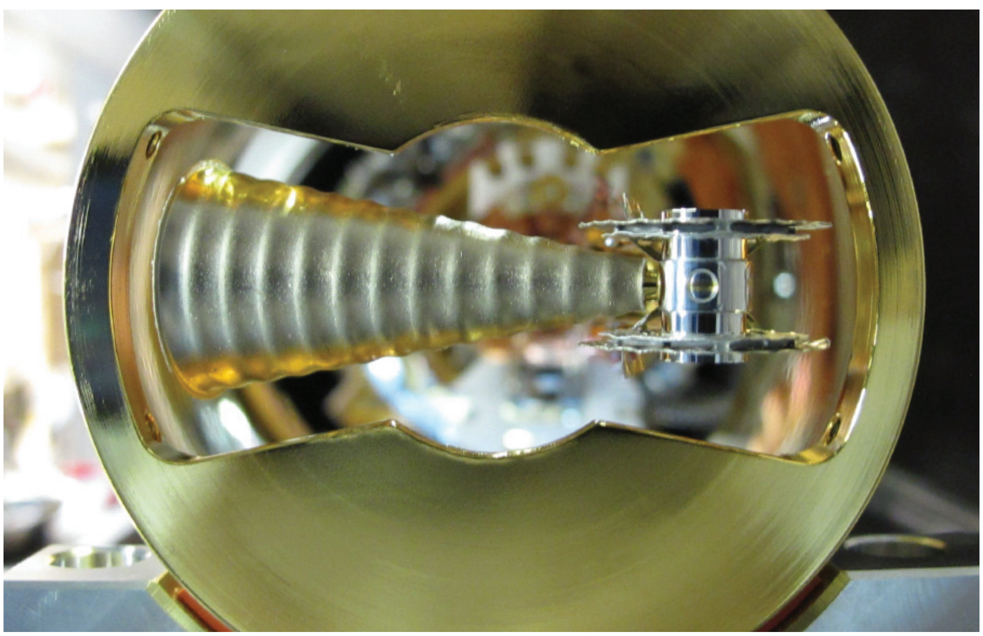
Feeling Hot, Hot, Hot

Diagnostic techniques that can detect hard and soft x-ray emissions also help researchers evaluate laser, hohlraum, and target performance. Among their many capabilities, these instruments measure beam alignment, hohlraum temperature, and implosion symmetry. Static x-ray imagers located near the laser entrance holes of the hohlraum, for example, reveal whether all 192 beamlines are hitting the hohlraum's interior walls at the designated points for generating a uniform x-ray bath.

Beamlines that miss the entrance holes produce an x-ray emission spot outside the hohlraum. A static x-ray imager is a filtered pinhole camera designed to record such emissions. These cameras typically measure x rays in the 2- to 3-kiloelectronvolt range. However, filters made from different materials can be placed in the imager to broaden the detection range. Time-integrated images show the x-ray emission from each laser beam as it irradiates the target, allowing shot controllers to verify beam positioning.

X-ray diagnostics also help measure the radiation temperature within the hohlraum, providing details on the time history and symmetry of the x-ray drive needed to implode the fuel capsule. A broadband, time-resolved x-ray spectrometer called Dante measures the x-ray flux emitted by the target throughout an experiment. "Dante is the workhorse diagnostic for measuring hohlraum temperature," says Joe Kilkenny, diagnostic chief scientist and the NIC program leader at General Atomics. "Using data from Dante, we can determine the radiation temperature from the distribution of x-ray energies as a function of time." Dante includes an array of filters and diodes for measuring radiation flux. Depending on the requirements for an experiment, filters made from various materials can be placed within the 18-channel instrument to detect a broad range of x-ray spectra emitted at the foot and peak of the laser pulse.

Without x-ray diagnostics, obtaining a clear picture of the physical processes occurring inside the hohlraum would be nearly impossible. Additional devices such as gated x-ray cameras capture details on the shape and velocity of the implosion. Streak x-ray cameras continually record a target as it evolves over trillionths of a second, producing time-resolved images that show the x-ray emissions of beams focused on the target. And an x-ray fluorescer characterizes broadband high-energy x rays that can preheat the capsule and degrade the quality of the implosion.

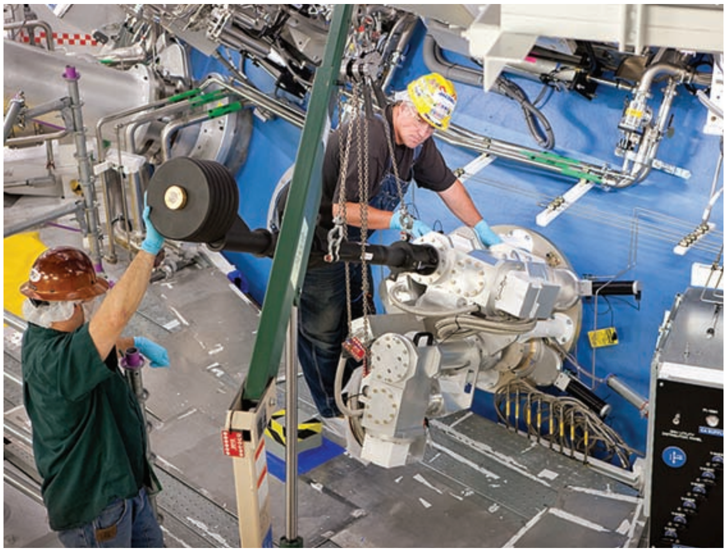


This target is used with the Velocity Interferometer for Any Reflector (VISAR) diagnostic. VISAR data help optimize the laser pulse and NIF target design.

Are We There Yet?

The ultimate signature for ignition will be the presence of high-energy neutrons, which are generated along with alpha particles during DT fusion. The positively charged alpha particles extend the fusion burn as they deposit their energy in the compressed fuel layers, one layer at a time. However, neutrons, which carry no electric charge, escape the fuel, retaining their energy. As the burn wave propagates outward, the fuel becomes hotter and burns more rapidly, releasing more alpha particles and neutrons. The process continues until the pressure is so high that the fuel is no longer inertially confined and fusion ceases.

"NIF experiments will produce about 10^{19} neutrons in a few tens of picoseconds," says Trish Baisden, the deputy director for NIC Operations. "Nuclear diagnostics will allow us to measure physical properties

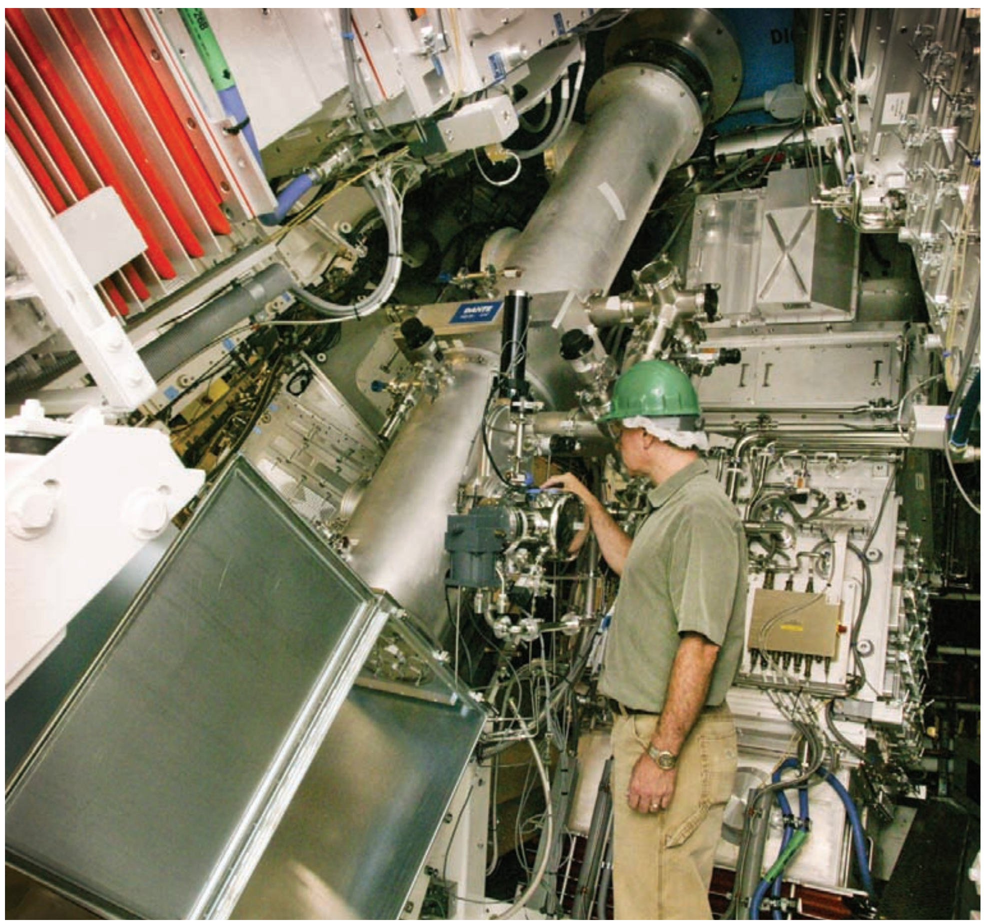


More than 30 diagnostic instruments have been installed at NIF, such as the gamma reaction history device (left) and the gated x-ray imager (above).

such as neutron yield, ion temperature, bang time, core temperature, and reaction history to understand how well the experiment performed and how much energy was produced."

One such diagnostic device is the neutron time-of-flight detector. Made with plastic scintillator and photomultiplier tubes or diamond photoconductors, this detector measures the total neutron yield and the energy broadening of the neutron signal from the time neutrons originate in the target to when they arrive at the detector. The signal's travel time depends on the kinetic energy spread, which is a function of ion temperature. "Ion temperature is directly related to how fast the core implodes," says David Meyerhofer, the director of the Experiment Division at the University of Rochester's Laboratory for Laser Energetics. "Without the right temperature, ignition will not occur."

The number of neutrons generated in an experiment depends on the combined thickness and density of the fuel shell. Known as the areal density, this characteristic is a function of how much energy is absorbed by the material, the accuracy of target conditions during implosion, and the attenuation of particles through the material. By detecting the



A technician inspects a Dante diagnostic device, which measures the x-ray flux emitted by the target—data that are used to determine hohlraum temperature.

It Takes a Team to Achieve Ignition

Developing diagnostics that can meet the stringent requirements for the National Ignition Facility (NIF) is an international endeavor. Since 2005, a multidisciplinary team of scientists and engineers from institutions in the U.S. and abroad has been hard at work designing, building, and calibrating more than 30 diagnostics for the National Ignition Campaign (NIC)—the program dedicated to achieving thermonuclear burn and energy gain through inertial confinement fusion. Collectively, team members offer a wealth of expertise in areas such as optics, electronics, imaging, and data acquisition and analysis, to name a few.

The advanced instruments created by this collaboration allow researchers to gather key physics data from experiments under the most extreme conditions. "What one has to realize is that the NIF environment is uncharted territory," says Trish Baisden, deputy director for NIC Operations. Inside the target chamber, the high radiation, intense electromagnetic pulses, and considerable debris from experiments are too much for traditional equipment and electronics to survive. "To build diagnostics that can handle this harsh environment, we need as much brainpower as possible solving the difficult challenges associated with the task."

Work on the diagnostics suite involves researchers from Lawrence Livermore, Lawrence Berkeley, Los Alamos, Brookhaven, and Sandia national laboratories; National Security Technologies, LLC; the Laboratory for Laser Energetics (LLE) at the University of Rochester; Massachusetts Institute of Technology (MIT); Duke University; Atomic Weapons Establishment in the United Kingdom; and Commissariat à L'Énergie Atomique in France. Several sites are dedicated to the entire diagnostic development cycle, from drawing up the initial specifications to testing prototypes. Others such as Lawrence Berkeley, National Security Technologies, and Duke University are also responsible for calibrating devices. Each site's assignment is based on its expertise in a given area. As an example, MIT has a history of research and development in new types of nuclear diagnostics. That knowledge was valuable for building the magnetic recoil spectrometer to detect neutron time of flight.

Before a device is installed at NIF, it is tested on the OMEGA laser at LLE. "LLE is a key partner in our diagnostic effort," says Baisden. Although the OMEGA laser operates at lower energy than NIF, it provides a valuable test bed for each diagnostic. "At LLE, we cannot achieve the neutron flux that NIF will produce," says David Meyerhofer, director of LLE's Experiment Division. "Instead, we increase the number of neutrons that diagnostics are exposed to by moving the diagnostics closer to the target." In what Meyerhofer and colleagues whimsically refer to as "neutron derbies," LLE hosts Diagnostic Development Days where they invite scientists from across the country to conduct experiments on the OMEGA laser, with the goal of achieving the highest neutron yields possible. These events are useful not only for testing diagnostics but also for stimulating new ideas to measure data from high-energy-density experiments.

In the past two years, Livermore has hosted several workshops geared toward expanding the diagnostic effort. "Through these workshops, we engage with the broader scientific community to overcome the complex physics challenges posed by NIF," says Doug Larson, lead engineer for NIC Diagnostics. Thanks to the help of a dedicated multidisciplinary team, an array of advanced diagnostics will provide a wealth of information about laser, hohlraum, and capsule performance. "From the beginning, it has been a team effort to make ignition happen at NIF," says Meyerhofer. "All of us want to see the facility succeed. It's essential to the future of fusion research."

In May 2010, Livermore hosted the fourth diagnostic workshop for the National Ignition Facility, with participants from the U.S. and abroad.

dispersion and spread of neutrons, scientists can calculate a target's areal density, which is essential for determining whether the capsule has enough mass to sustain the fusion reaction. "The temperature and shape of the implosion at peak compression and the areal density of the material are the most critical components for ensuring that we are on track to ignition," says Meyerhofer.

The neutron time-of-flight detectors work in conjunction with neutron-based reaction history diagnostics to determine the burn time of the imploding capsule. Neutron imaging and spectroscopy devices further detail the compressed capsule's shape and size.

To test these diagnostics, researchers are conducting experiments with dudded targets, in which hydrogen is added to the DT fuel mix. "The dudded targets allow us to study all the necessary experimental parameters for ignition in an environment with very low neutron yield," says Baisden.

A Balanced View

NIF diagnostics are designed to be redundant and complementary. For example, NIF has two Dante devices, one in the upper half of the target chamber and the other in the lower half. From these two locations, the "Dantes" can measure the soft x-ray emission from either side of the hohlraum, increasing the fidelity of the captured data. During an experiment, multiple diagnostics work in concert to gather sets of data that together help scientists compare and verify experimental results. "No diagnostic makes a perfect measurement," says Kilkenny. "We need complementary and redundant devices to truly understand what is going on."

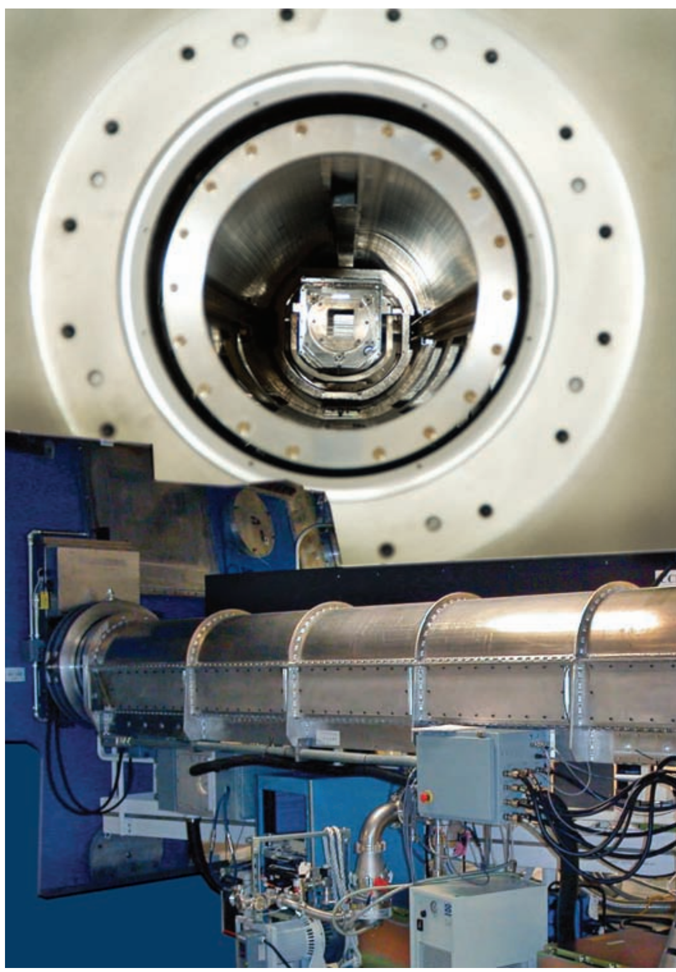
The variety of diagnostic techniques provides a more complete picture of what is happening with the laser, hohlraum, and target. "During hohlraum energetics experiments, we simultaneously measured laser light entering the target, light backscattered from the target, and hohlraum temperature," says Alex Hamza, a target fabrication manager at NIF. "We evaluated all three pieces of recorded data together. If the results had not matched, we would have needed to investigate the discrepancies."

More than 20 devices can be installed for an experiment using diagnostic instrument manipulators. These vacuum-sealed tubes are attached to the target chamber and house specialized carts that can accommodate up to five diagnostics at a time. "The manipulators are like the Swiss Army knives of NIF," says the facility's operations manager Bruno Van Wonterghem. "With this equipment, we can tailor diagnostics to fit the requirements of a particular experiment."

Diagnostic instrument manipulators allow the same diagnostic to view an experiment from different lines of sight, improving the operational availability and reliability of the detectors. In addition, they provide flexibility to quickly reconfigure and relocate instruments between shots.

Going beyond the Standard

Many NIF diagnostics are variations of time-tested technologies used in high-energy-density research. Dante and the two backscatter devices, for example, have all been fielded on other lasers, such as Nova, the predecessor laser to NIF, and the University of Rochester's OMEGA laser. "We know how well certain diagnostics work based on past experience," says Kauffman. "Our primary objective has been to adapt technologies so they can survive the harsh, often destructive conditions of the NIF target chamber." Diagnostic development teams have designed special shielding to protect instruments from electromagnetic pulses,



A diagnostic instrument manipulator (top) has a specialized cart that can house multiple devices. Shown from the outside (below), attached to the target chamber, the manipulator allows several diagnostics to simultaneously record data during an experiment.

The magnetic recoil spectrometer provides a novel approach to measuring neutron time of flight by converting neutrons to protons, which have a higher interaction probability within the detector.

high-energy neutrons, and debris. In addition, devices are modified to function at greater distances from the target than they do at other laser facilities.

Radiochemical techniques are also being adapted for NIF research. During an underground nuclear test, tracer elements incorporated into materials were activated by neutrons generated in the explosion, as one material transmuted into another. Researchers analyzed the resulting isotopes to determine whether the experiment achieved the desired conditions.

Using the same principles for NIF, scientists are adding tracer elements to target materials. "A big difference between applying these techniques for laser research as opposed to underground testing is that we can collect a signal within hours instead of weeks," says Hamza. Future diagnostics may collect solid elements from an experiment by using a device that acts like a catcher's mitt.

Some NIF diagnostics are new additions to inertial fusion research. For example, the magnetic recoil spectrometer, developed at the Massachusetts Institute of Technology, is a novel approach for measuring the neutron energy spectrum. Because neutrons cannot be dispersed according to energy by a magnet, they are first converted to protons. A diagnostic instrument manipulator places a plastic foil about 1 meter from the target. Neutrons from the experiment collide with atoms in the foil, causing protons to recoil. This process converts the neutron energy to protons, which are dispersed by a magnet onto a detector that measures the proton energy spectrum. The probability of detecting a proton is much higher than it is for detecting a neutron, allowing the magnetic recoil spectrometer to capture more information. When fielded on the OMEGA laser during DT experiments, the device proved to be extremely successful.

The most highly anticipated NIF diagnostic is the advanced radiographic capability. This high-energy, short-pulse x-ray backlighter uses one of the NIF beamlines to x ray a target during an experiment. Each pulse of x-ray energy lasts just a few picoseconds. Coupled with a backlighter, the device provides high-resolution images of the capsule as it implodes.

A Future Filled with Possibilities

Over the next decade, scientists will use NIF to delve into unexplored areas of high-energy-density science. "At Livermore, we already have some of the world's fastest supercomputers providing us with unprecedented predictive capabilities," says Livermore physicist Richard Fortner, one of the pioneers in developing NIF diagnostics. "With NIF, we'll be able to perform the most complex high-energy-density experiments ever attempted and compare those results to our simulations. The data provided by the two methods won't always agree, but that's what helps us to learn. Science on NIF is going to be very exciting."

The full suite of NIF diagnostics will be essential to making ignition a success. "Because of the hard work and ingenuity of scientists and engineers all over the country and abroad designing and building instruments that can help us characterize the laser, hohlraum, and capsule, we are closer to achieving ignition than ever before," says Ed Moses, principal associate director for NIF and Photon Science. As anticipation builds for the first ignition shot, scientists look forward to analyzing the impressive data these precision diagnostics will reveal.

—Caryn Meissner

Key Words: advanced radiographic capability, Dante spectrometer, diagnostic instrument manipulator, full aperture backscatter station, high-energy-density science, hohlraum, ignition, inertial confinement fusion, laser, magnetic recoil spectrometer, National Ignition Campaign (NIC), National Ignition Facility (NIF), near backscatter imager, neutron, OMEGA laser, target, Velocity Interferometer for Any Reflector (VISAR).

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Quick Detection of Pathogens by the Thousands

Biologist Crystal Jaing holds the Lawrence Livermore Microbial Detection Array (LLMDA), which can detect or identify pathogens from known viruses and bacteria within 24 hours.

MEDICAL professionals diagnosing diseases, law-enforcement authorities dealing with an apparent bioterrorism attack, and regulatory agencies testing product safety may have a new detection tool to add to their arsenal—the Lawrence Livermore Microbial Detection Array (LLMDA). Designed by a team of Livermore biologists and informatics specialists, LLMDA can simultaneously identify thousands of known viruses and bacteria within 24 hours.

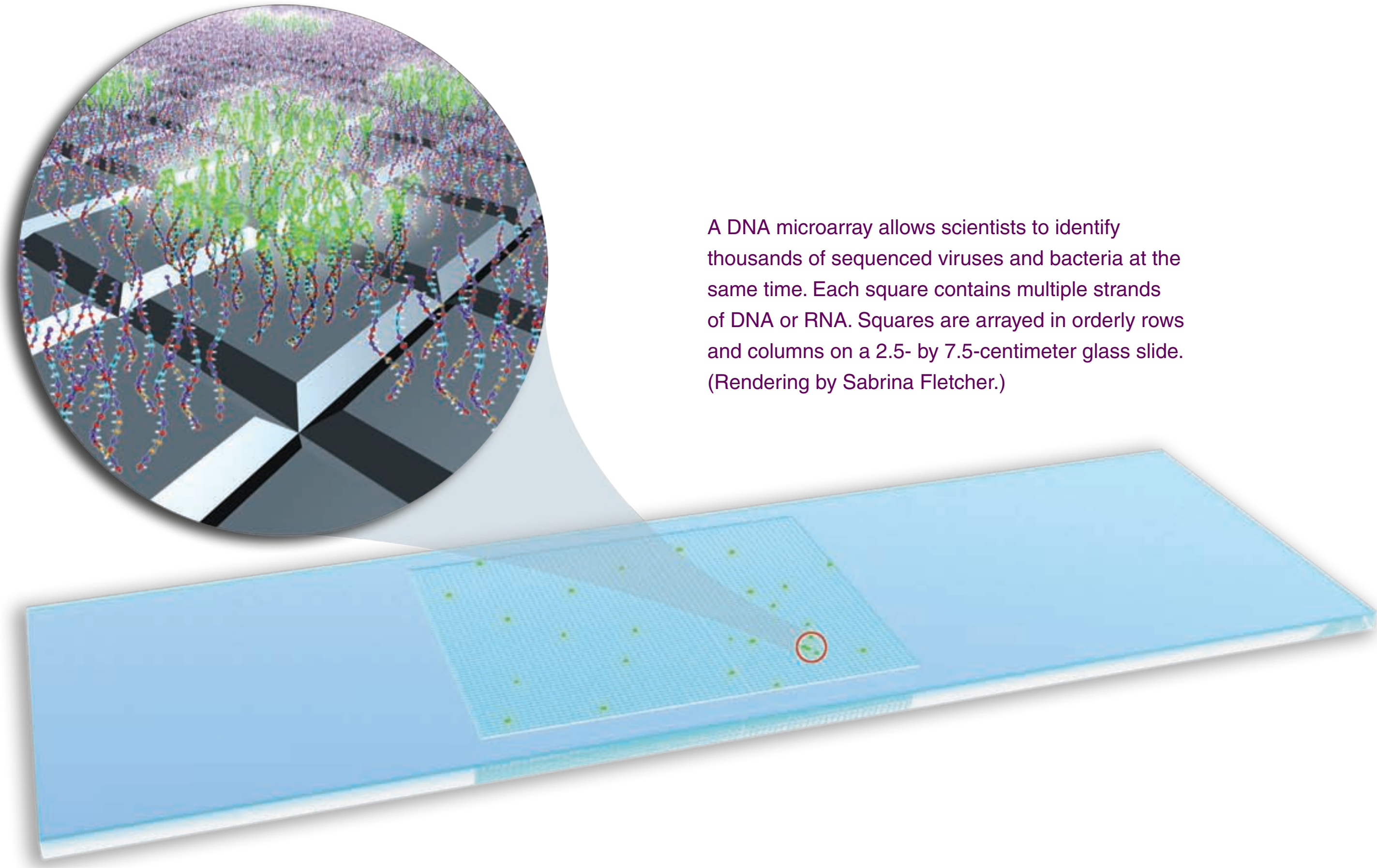
Current detection systems, such as polymerase chain reaction (PCR) technologies, focus on small, prioritized sets of high-risk biological pathogens. LLMDA, however, can identify a broad range of organisms, including pathogens on a priority screening list, sequenced bacteria or viruses that might not be anticipated, or even emerging pathogens containing DNA sequences previously identified in other pathogens.

Computer scientist Thomas Slezak, who leads the Laboratory's pathogen bioinformatics team, came up with the idea for LLMDA after working on the biosecurity system deployed by the Department of Homeland Security (DHS) at the 2002 Winter Olympic Games in Salt Lake City, Utah. "The PCR signatures we were building provided diagnostic protection only for the short list of high-risk pathogens that DHS had chosen to focus on," he says. "I realized that new advances in microarray technology would allow us to design a single assay to detect any sequenced bacterium or pathogen."

Work on the first-generation LLMDA began in 2007 as a Laboratory Directed Research and Development project. In designing the microarray, the bioinformatics team collaborated with researchers at institutions worldwide, including the University of California at San Francisco; University of Texas Medical Branch at Galveston; National Institute for Public Health and the Environment in Bilthoven, Netherlands; Statens Serum Institut in Copenhagen, Denmark; Imigene in St. Petersburg, Florida; and U.S. Food and Drug Administration. Crystal Jaing, a biologist in Livermore's Physical and Life Sciences Directorate, leads the LLMDA laboratory research, which includes probe designer Shea Gardner, biostatistician Kevin McLoughlin, and biologist James Thissen.

Pathogens Exposed

The LLMDA process begins by purifying DNA or RNA from a blood or stool sample. The purified DNA or RNA is labeled with a fluorescent dye and then squirted onto the microarray, which sits on top of an incubator heated to 42°C. The microarray contains nearly 400,000 probes arranged in a checkerboard pattern on a 2.5- by 7.5-centimeter glass slide. Scientists examine these probes using a fluorescent scanner and analysis software. "If a DNA sequence from the sample matches a sequence on the microarray, the target DNA will bind to the microarray, and that spot will fluoresce, or light up," says Jaing. "By looking at the sequences that light up, we can identify the virus or bacterium, sometimes down to the strain level."



A DNA microarray allows scientists to identify thousands of sequenced viruses and bacteria at the same time. Each square contains multiple strands of DNA or RNA. Squares are arrayed in orderly rows and columns on a 2.5- by 7.5-centimeter glass slide. (Rendering by Sabrina Fletcher.)

LLMDA is designed to improve on two pathogen identification techniques: PCR analysis and sequencing. PCR analysis is relatively inexpensive and fast. It also has a high sensitivity for known organisms, but it can process no more than 50 DNA signatures at one time. The likelihood of discovering new species is also low with PCR analysis. Sequencing is a highly effective approach—in fact, it may provide the most comprehensive information about biological pathogens, both known and unknown. The process, however, is costly and can take several days to produce results.

LLMDA is less expensive than sequencing and more inclusive than PCR analysis. It can identify any sequenced virus and bacterium. The microarray's checkerboard has several dozen squares for each of the thousands of organisms sequenced to date, so it can simultaneously examine multiple regions from each organism.

The Livermore team is testing a next-generation LLMDA that contains 2.1 million probes representing about 178,000 sequences from 5,700 viruses and 785,000 sequences from thousands of bacteria. The latest version also includes about 237,000 sequences from hundreds of fungi and about 202,000 sequences from 75 protozoa. "We are designing the next-generation array to be the most comprehensive in the world," says Jaing. "Our goal is to develop a cost-effective technology that can detect both known and unknown pathogens within 24 hours."

Wide-Ranging Potential

Jaing foresees many potential applications for the microarray technology. For example, LLMDA could perform routine quality-control checks during a manufacturing process to ensure that no harmful pathogens are present in consumer products. A collaboration with the Blood Systems Research Institute in San Francisco, California, demonstrated how useful the technology can be.

In January 2010, while using a DNA sequencing technology to analyze several vaccines, a scientist at the institute found a contaminant in one of the products being tested. Results showed that a vaccine to prevent rotavirus—a disease that causes severe diarrhea in children—contained a benign pig virus, porcine circovirus-1. Tests of the vaccine with LLMDA confirmed the institute's results. The manufacturer's quality-control tests did not detect the pig virus because it was not listed as a known contaminant for the rotavirus vaccine. According to Jaing, technologies such as LLMDA would allow a manufacturer to identify every biological material that is present in quantities large enough to be of concern.

LLMDA could also help law-enforcement officials. The National Biodefense Analysis and Countermeasures Center in Frederick, Maryland, is evaluating the technology as a bioforensic tool. The DHS center analyzes biological samples related to criminal cases under investigation by the Federal Bureau of Investigation. It is considering LLMDA for two scenarios: to perform the initial forensic characterization of a substance, which is typically done by PCR analysis, or to provide an independent identification of the organisms present. Another potential law-enforcement application is characterizing an unknown substance, such as a package of "white powder," to determine whether it is a dangerous pathogen.

Doctors also might one day use the LLMDA technology to diagnose human disease. Clinical samples could be analyzed to identify the cause of a patient's symptoms. For example, doctors could easily determine whether flulike symptoms are caused by influenza or one of dozens of other viruses or bacteria. "One of our collaborators used the microarray to diagnose a range of bacterial and viral organisms in human samples," says Slezak. "As the cost of the array is reduced, the technology could improve public health diagnostics because it can detect multiple bacteria and viruses in a single test." He cautions, however, that further work is needed, including approval from the Food and Drug Administration for clinical trials to measure the technology's efficacy in diagnosing human disease.

Scientists from Lawrence Livermore and the Marine Mammal Center in Sausalito, California, are evaluating LLMDA as a potential tool for diagnosing disease outbreaks in sea lions and harbor seals.

A Friend to Animals

Jaing is working with the Marine Mammal Center in Sausalito, California, to diagnose diseases that have struck California sea lions and harbor seals. In June 2009, about 20 harbor seals died in northern California from brain lesions caused by the premature death of living cells. In addition, cancer has killed about 17 percent of the adult sea lions at the center.

The Livermore researchers have used LLMDA to analyze frozen tissue samples from two dead sea lions. One sample contained calicivirus, which does not cause cancer. No virus or bacteria could be positively identified in the other sample. Frozen tissue samples from four sea lions and four harbor seals are being analyzed.

"This research has the potential to be very helpful because the genetic makeup of sea lions and harbor seals has not been well studied," Jaing says. "LLMDA gives us the potential to identify novel viruses or bacteria that can cause cancer in other marine animals."

In addition, says Slezak, "The work on marine mammals provides excellent training for emergency response should the nation experience a disease outbreak from an unknown human pathogen. It is only through these sorts of collaborations that the Livermore team can continually improve our microarray probe design and analysis software and our sample preparation techniques to be ready for a day that we hope never comes."

Looking Ahead

The team will update the array annually to include new viral and bacterial sequences. "We don't know how many sequences are available worldwide," says Jaing. "Different outbreaks occur every year, and there could be undiscovered viruses and bacteria that we have yet to access."

LLMDA has great potential for improving processes used by medical professionals, law-enforcement personnel, and product manufacturers. "Each proposed application will require various levels of validation and approvals before it can be deployed," says Slezak. "That process could take several years." Deploying LLMDA in these different applications could better prepare the nation when the next outbreak from an unknown pathogen hits.

—Kristen Light

Key Words: bacteria, bacterial sequences, Lawrence Livermore Microbial Detection Array (LLMDA), microarray, pathogen detection technology, viral sequence, virus.

For further information contact Crystal Jaing (925) 424-6574 (jaing2@llnl.gov).

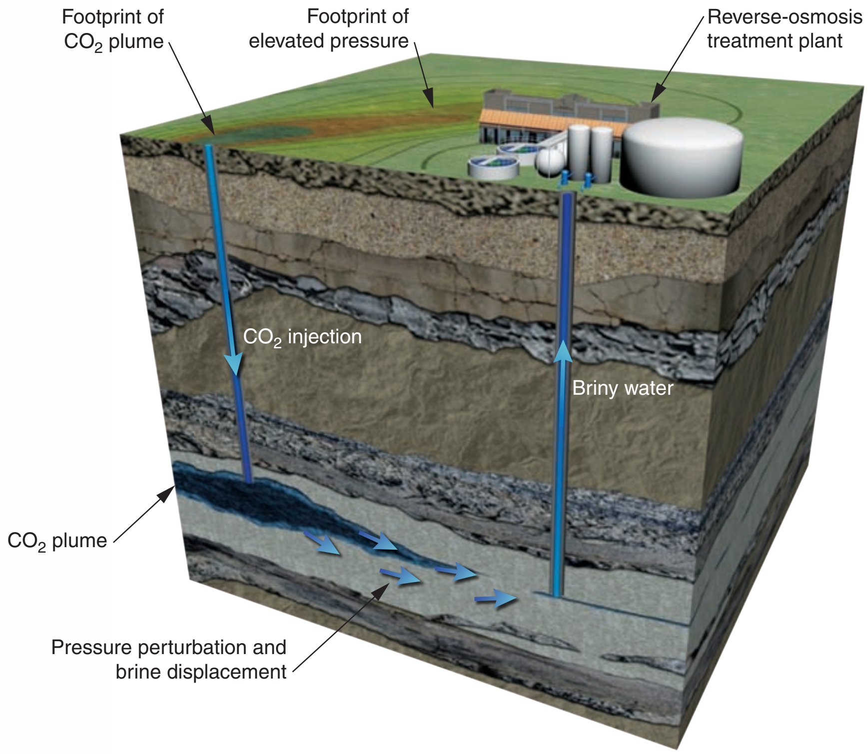
Carbon Dioxide into the Briny Deep

WITH every passing year, the amount of carbon dioxide (CO_2) in the atmosphere increases. Because of the way this gas absorbs and emits infrared radiation, excessive quantities can cause the warming of Earth's atmosphere. Natural sources of atmospheric CO_2 such as volcanic outgassing, the combustion of organic matter, and the respiration processes of living aerobic organisms are nearly balanced by physical and biological processes that remove the gas from the atmosphere. For example, some CO_2 dissolves in seawater, and plants remove some by photosynthesis.

However, problems arise with the increased amounts of CO_2 from human activities, such as burning fossil fuels for heating, power generation, and transport as well as some industrial processes. Natural processes are too slow to remove these anthropogenic amounts from the atmosphere. In 2008, 8.67 gigatons of carbon (31.8 gigatons of CO_2) were released worldwide from burning fossil fuels, compared with 6.14 gigatons in 1990.

The present level of atmospheric CO_2 is higher than at any time during the last 800,000 years and likely is higher than it has been in the last 20 million years. Researchers around the world are exploring ways to dispose of this excess. One proposed approach, called carbon capture and sequestration, is to store CO_2 by injecting it deep into the ocean or into rock formations far underground. The G8, an informal group of economic powers including the U.S., has endorsed efforts to demonstrate carbon capture and sequestration. The international forum recommended that work begin on at least 20 industrial-scale CO_2 sequestration projects, with the goal of broadly deploying the technology by 2020.

Several carbon sequestration projects are already under way. One, under the North Sea, is part of an oil drilling operation that separates CO_2 from natural gas and traps it in undersea rock formations. Other projects are using sequestered CO_2 to push oil around underground so that drillers can maximize the quantity of crude oil they remove—a process called enhanced oil recovery.



In active reservoir management, as carbon dioxide (CO_2) is pumped into underground sandstone formations, briny waters are pushed to the surface and treated by reverse osmosis to create freshwater. The recirculating process inherent in active CO_2 reservoir management will naturally generate the pressures needed for reverse osmosis, considerably lowering the cost of desalination. (Rendering by Sabrina Fletcher.)

An alternative approach, being pursued by researchers at Lawrence Livermore and the Department of Energy's National Energy Technology Laboratory, involves putting CO_2 back into the ground while simultaneously producing freshwater. According to Livermore geochemist Roger Aines, who leads the Laboratory's work on this project, vast underground sandstone formations are filled with very salty water, many times saltier than the ocean. The idea is to pump CO_2 into these rock formations, thereby pushing briny water up into a reverse-osmosis water-treatment plant where most of the salt can be removed. The result is to increase volume for storing CO_2 in the underground formation while producing freshwater aboveground.

Although this water might be too salty to drink, it would provide a critical resource for industrial processes that require huge quantities of freshwater. Petroleum refining, for example, consumes 1 to 2 billion gallons of water per day. Even technologies designed to reduce greenhouse gases, such as the biofuels production process, are increasing demands on the world's water resources.

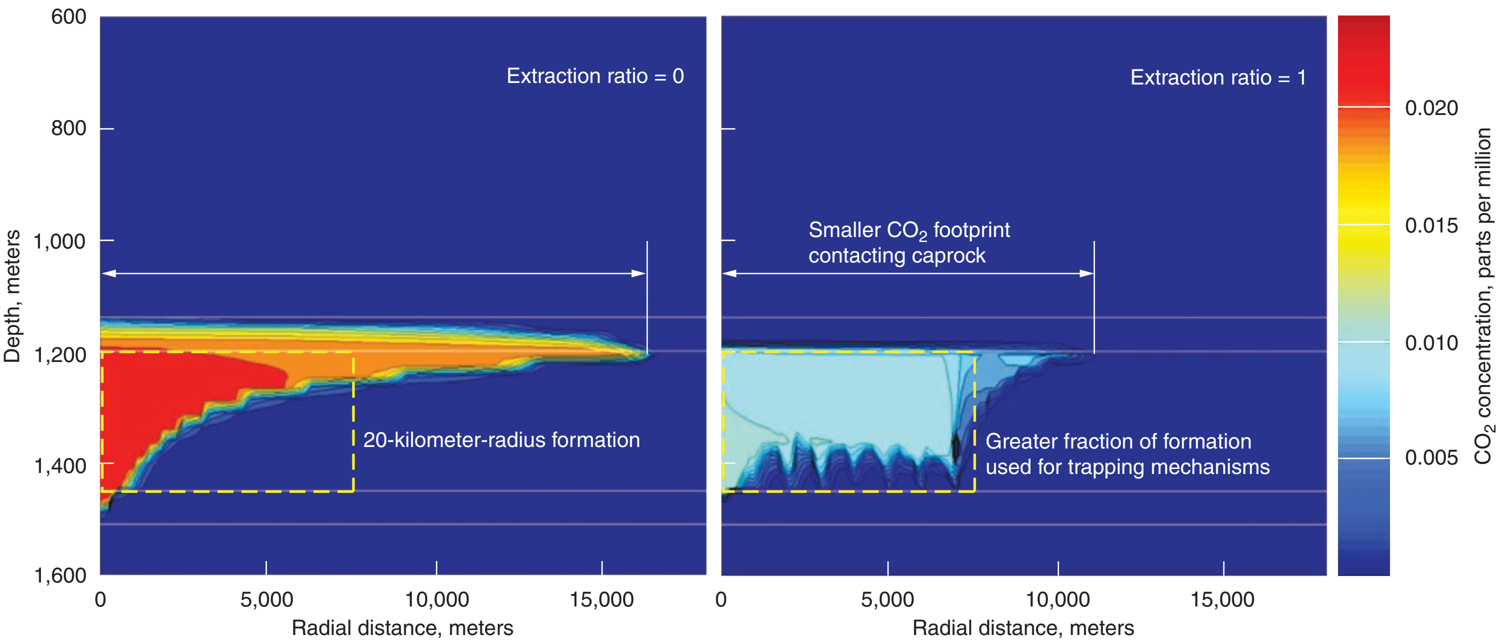
Affordable Freshwater

"Reverse osmosis is typically quite expensive because pressures of over 1,000 pounds per square inch [or nearly 7 megapascals] must be generated to push the salty water through the filters," says Aines. For the Livermore project, however, pumping CO_2 underground would naturally create the pressures needed to force water to the surface and into reverse-osmosis filters, vastly reducing desalination costs.

After treatment by reverse osmosis, a much more concentrated salty brine remains and must be disposed of. Also, when stored underground, the sequestered CO_2 is in a supercritical state, where it is neither a liquid or a gas. But because its properties will be similar to those of a liquid, it will have the potential to move around and disturb other rock formations. According to Aines, the Livermore approach is designed to address both issues. Current plans are to reinject the supersalty brine and use it in the space created by extracting water to keep the injected CO_2 in place. This balancing act is called "active reservoir management." Because the ability to remove water allows engineers to manage the pressure in the storage zone, active reservoir management can be an important way to ensure that CO_2 is stored safely and fills the reservoirs to capacity. "By changing pressures," says Aines, "we should be able to move reinjected brine and CO_2 around to fill the entire reservoir."

Active reservoir management not only produces freshwater and reduces pressure buildup underground, but it also reduces the ultimate footprint of the underground CO_2 reservoir. Simulations indicate that the radius of an unmanaged underground reservoir is about twice that of an actively managed one.

"We have worked through the economics of active reservoir management with industrial partner PerLorica," says Aines, "and the results look good." A small, private firm in Rough and Ready,



Computer simulations indicate that an actively managed CO_2 reservoir will occupy a much smaller underground footprint (right) than a reservoir that is passively managed (left) because more of the formation can be used to trap the CO_2.

California, PerLorica, Inc., provides water-treatment monitoring and consulting services to customers in the U.S. The company specializes in process control and monitoring using a range of proprietary software and related process management services.

"However, there are several caveats to making this technique work effectively," notes Aines. For one thing, the chemistry is complicated. The reverse-osmosis process will work on brine formations with saline levels up to about 85,000 parts per million (ppm). While ocean salinity is typically about 35,000 ppm, the water salinity in some sandstone formations can be as high as 300,000 ppm. Fortunately, about half of the formations have brine with salt content below the 85,000-ppm range.

CO_2 on the Move

A Laboratory team is using the fluid dynamics code NUFT-C (for Nonisothermal, Unsaturated Flow and Transport with Chemistry) to address some of the other caveats. The original NUFT code was designed almost 20 years ago to simulate the movement of multiple liquids and gas in saturated or unsaturated porous media. The code has been modified over the years to meet the needs of larger projects and to capitalize on the ever-expanding capabilities of large computers. "This project definitely presents a high-performance computing challenge," says Aines.

Researchers have applied NUFT-C in the past, for example, to examine the flow of subsurface pollutants and the behavior of oil and surrounding fluids and rock in individual oil wells. Active reservoir management presents a more complicated scenario. A storage reservoir may be tens of kilometers across and have separate wells for extracting briny water and injecting CO_2 and processed brine into the underground formation. NUFT-C simulations are beginning to reveal how CO_2, the less buoyant briny water, and the denser reinjected brine move through and around rock formations.

The project team is running the initial reservoir simulations on the massively parallel computers at the Laboratory's main site. In the future, simulations may be performed in a supercomputing facility at the proposed Livermore Valley Open Campus. Access requirements for the Open Campus would be more streamlined than those in place now for national security laboratories, thereby facilitating collaboration with partners from government entities, universities, and private companies working with researchers at Lawrence Livermore or Sandia national laboratories.

Aines notes that a National Applied Energy Simulation Center has been proposed for the Open Campus. He adds, "Our project may well be an early user of the center's supercomputers."

—Katie Walter

Key Words: active carbon dioxide (CO_2) reservoir management, carbon capture and sequestration, NUFT-C code.

For further information contact Roger Aines (925) 423-7194 (aines1@llnl.gov).

Patents and Awards

In this section, we list recent patents issued to and 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

System and Method for Ultrafast Optical Signal Detecting via a Synchronously Coupled Anamorphic Light Pulse Encoded Laterally
John E. Heebner
U.S. Patent 7,768,649 B2
August 3, 2010
This method provides for ultrafast optical signal detection. In operation, a first optical input signal propagates through the first layer of a waveguide, and a second signal propagates through the waveguide's second layer. An optical control signal is then applied to the top of the waveguide. The control signal is oriented diagonally relative to the top of the waveguide such that the application influences at least part of the signal propagating through the first waveguiding layer. The combined outputs from the first and second optical input signals are then detected. In another design, a system for ultrafast optical signal recording has a waveguide with several waveguiding layers. The all-optical control source is positioned to propagate a signal toward the waveguide. The signal is oriented diagonally to the top of the waveguide, and at least one optical input source is positioned to input a signal into at least the first and second layers of the waveguide. A detector records the interference pattern output from the waveguide, and at least one of these patterns results from combining the optical input signals into the first and second waveguiding layers. Propagation of the optical control signal influences part of the signal input through the first waveguide layer.

Explosives Tester with Heater
Joel Del Eckels, Peter J. Nunes, Randall L. Simpson, Richard E. Whipple, J. Chance Carter, John G. Reynolds
U.S. Patent 7,771,653 B2
August 10, 2010
An inspection system for testing explosives has a removable swab unit connected to a body with at least one reagent holder and a dispenser that contains an explosives-detecting reagent. The holder and dispenser are positioned to deliver the explosives-detecting reagent to the swab unit. A heater is connected to the body, and the swab unit is adapted to be connected to the heater.

Metal Hydride Fuel Storage and Method Thereof
Jeffrey D. Morse, Alan F. Jankowski, Conrad Yu
U.S. Patent 7,771,887 B2
August 10, 2010
This apparatus has one substrate with a cavity, one or more resistive heaters, and one or more coatings forming a diffusion barrier to hydrogen. A second substrate has an outlet valve with a pressure relief structure and one or more coatings that form a diffusion barrier to hydrogen. The second substrate is coupled to the first to form a sealed volume in the cavity, which contains a metal hydride material. A gas distribution system is then formed by coupling a microfluidic interconnect to the pressure relief structure.

Micro-Electro-Mechanical Systems Phosphoric Acid Fuel Cell
David A. Sopchak, Jeffrey D. Morse, Ravindra S. Upadhye, Jack Kotovsky, Robert T. Graff
U.S. Patent 7,776,479 B2
August 17, 2010
A phosphoric acid fuel-cell system has a porous electrolyte support containing a phosphoric acid electrolyte and cathode and anode electrodes contacting the phosphoric acid electrolyte.

Paint for Detection of Radiological or Chemical Agents
Joseph C. Farmer, James L. Brunk, Sumner Daniel Day
U.S. Patent 7,780,912 B2
August 24, 2010
A paint designed to warn of radiological or chemical substances has an indicator material and a thermo-activation material. In one setup, a surface coated with the paint is monitored for indications of radiological or chemical substances. In another setup, the paint is applied to a vehicle, and the indicator material provides a warning when radiological or chemical substances are present.

Paint for Detection of Corrosion and Warning of Chemical and Radiological Attack
Joseph C. Farmer
U.S. Patent 7,780,913 B2
August 24, 2010
A system for warning of corrosion or the presence of chemical or radiological substances involves coating a surface with a paint that includes an indicator material. The surface is then monitored for indications of corrosion or for chemical or radiological substances.

Safe Biodegradable Fluorescent Particles
Sue I. Martin, David P. Fergenson, Abneesh Srivastava, Michael J. Bogan, Vincent J. Riot, Matthias Frank
U.S. Patent 7,781,224 B2
August 24, 2010
This human-safe fluorescence particle can be used with fluorescence detection instruments or as a safe simulant for mimicking the fluorescence properties of microorganisms. The particle has natural fluorophores encapsulated in a nonbiological carrier. Biodegradable polymer drug-delivery microspheres can be doped with natural or synthetic fluorophores to attain the desired fluorescence. They also can be used to simulate biological organisms without the associated risks and logistical difficulties of working with live microorganisms.

Large Optics Inspection, Tilting, and Washing Stand
Marion Jay Ayers, Shannon Lee Ayers
U.S. Patent 7,782,555 B1
August 24, 2010
A large optics stand provides a risk-free means of safely tilting large optics with ease. The optics are supported in the horizontal position by pads and in the vertical plane by saddles that evenly distribute the optics weight over a large area.

Method for Generation of THz Frequency Radiation and Sensing of Large Amplitude Material Strain Waves in Piezoelectric Materials
Evan J. Reed, Michael R. Armstrong
U.S. Patent 7,788,980 B2
September 7, 2010
Strain waves of terahertz (THz) frequencies can coherently generate radiation when they propagate past an interface between materials with different piezoelectric coefficients. Such radiation is of detectable amplitude and contains sufficient information to determine the strain wave's time-dependence with unprecedented subpicosecond and nearly atomic time and space resolution.

High-Resolution Retinal Imaging Using Adaptive Optics and Fourier-Domain Optical Coherence Tomography
Scot S. Olivier, John S. Werner, Robert J. Zawadzki, Sophie P. Laut, Steven M. Jones
U.S. Patent 7,791,734 B2
September 7, 2010
This device permits retinal images to be acquired at high speed and with unprecedented resolution in three dimensions (4 by 4 by 6 micrometers). The instrument achieves high lateral resolution by applying adaptive optics to correct optical aberrations of the human eye in real time. High axial resolution and high speed are achieved with Fourier-domain optical coherence tomography. With this system, we have demonstrated the ability to image microscopic blood vessels and the cone photoreceptor mosaic.

Rapidly Reconfigurable All-Optical Universal Logic Gate
Lynford L. Goddard, Tiziana C. Bond, Jeffrey S. Kallman
U.S. Patent 7,791,781 B2
September 7, 2010
This all-optical on-chip device is cascadable and can be reconfigured. The gate operates by combining the Vernier effect with the gain-index lever, a novel effect, to help shift the dominant lasing mode so that laser light is output in a different facet. Because the laser remains above threshold, the speed of the gate for both logic operations and reprogramming the gate's function is primarily limited to the small signal optical modulation of the laser, which can be up to about tens of gigahertz. The gate can be rapidly and repeatedly reprogrammed to perform any of the basic digital logic operations by using an appropriate analog optical or electrical signal at the gate selection port. Other all-optical functionality includes wavelength conversion, signal duplication, threshold switching, analog-to-digital and digital-to-analog conversion, signal routing, and environmental sensing. Each gate can perform different operations, so the functionality of such a cascaded circuit grows exponentially.

Multiplex Detection of Agricultural Pathogens
Mary Teresa McBride, Thomas Richard Slezak, Sharon Lee Messenger
U.S. Patent 7,794,938 B2
September 14, 2010
These kits can detect seven agricultural pathogens (bovine papular stomatitis virus, bovine herpesvirus, bovine viral diarrhea, foot-and-mouth disease, bluetongue virus, swine vesicular disease, and vesicular exanthema of swine virus) in one sample. Genomic sequence information from the agricultural pathogens was analyzed to identify signature sequences, such as polynucleotide sequences useful for confirming the presence or absence of a pathogen in a sample. Primer and probe sets are optimized for use in a polymerase-chain-reaction-based, multiplexed Luminex assay to identify the presence or absence of pathogens in a sample.

Physics-Based Statistical Model and Simulation Method of RF Propagation in Urban Environments
Hsueh-Yuan Pao, Steven L. Dvorak
U.S. Patent 7,796,983 B2
September 14, 2010
This physics-based statistical model and simulation method shows the electromagnetic wave propagation (wireless communication) in urban environments. In particular, the model is a computationally efficient close-formed parametric model of radio-frequency (rf) propagation in an urban environment, which is extracted from a physics-based statistical wireless channel simulation method and system. The simulation divides the complex environment into a network of interconnected urban canyon waveguides that can be analyzed individually. It uses a database of statistical impedance boundary conditions that incorporate the complexity of building walls to calculate the spectral coefficients of modal fields in the waveguides excited by the propagation. It then determines statistical parameters of the calculated modal fields and a parametric propagation model based on those parameters from which it makes predictions of communications capability.

Awards

The **Department of Energy**'s **Artificial Retina Team**, which includes researchers from Lawrence Livermore, received a **2010 Breakthrough Award** from ***Popular Mechanics*** for developing the Argus II retinal implant. Breakthrough awards recognize the innovators and products poised to change the world in the fields of technology, medicine, aviation, environmental engineering, and more. "From soccer balls that generate light to cell phones that diagnose medical conditions, our diverse, inspired winners are making the seemingly impossible a reality," says James B. Meigs, editor in chief of *Popular Mechanics*.

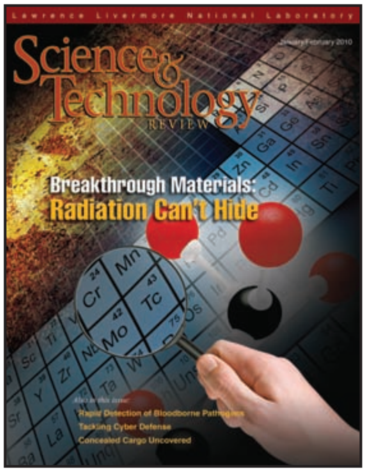
The Argus II retinal implant is designed to restore vision to people who are blind because of such degenerative retinal diseases as macular degeneration and retinitis pigmentosa. The device takes images from an external video camera and sends electric signals to an array implanted in the eye, bypassing damaged photoreceptors to kick-start retinal cells that are still viable.

In addition to Lawrence Livermore, the Artificial Retina Team includes industrial partner Second Sight® Medical Products, Inc.; Doheny Eye Institute, University of Southern California; University of California at Santa Cruz; California Institute of Technology; and Sandia National Laboratories.

Project Management Institute (PMI) awarded its **Project of the Year Award** to the **National Ignition Facility** (NIF). NIF was honored as a facility "pushing beyond the state of the art," bringing together scientists, engineers, construction workers and contractors, vendors, safety technicians, systems managers, administrators, and many more to complete the $3.5 billion project. Sponsored by the Department of Energy's National Nuclear Security Administration, the construction project was led by Lawrence Livermore and involved government, academic, and industrial collaborators, including the University of Rochester's Laboratory for Laser Energetics, Los Alamos and Sandia national laboratories, General Atomics, the United Kingdom's Ministry of Defense, and the French Commissariat à l'Énergie Atomique.

Each year, PMI chooses three finalists from worldwide nominees to recognize each project's accomplishments and the project team for superior performance and execution of exemplary project management. One of these three finalists also receives the PMI Project of the Year Award. In addition to NIF, the 2010 finalists were Cowboys Stadium in Dallas, Texas, and Norton Brownsboro Hospital in Louisville, Kentucky.

Science & Technology Review 2010 Index



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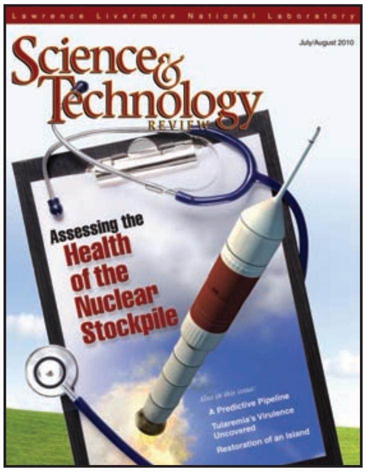

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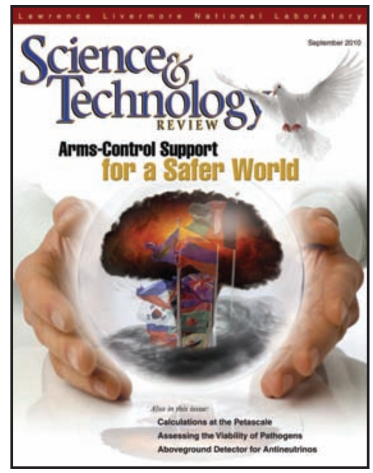

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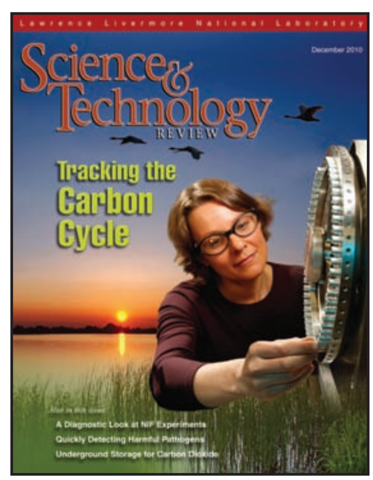


Strengthening Our Understanding of Climate Change

Over the past decade, Lawrence Livermore's Center for Accelerator Mass Spectrometry (CAMS) has become an essential resource for helping scientists to understand climate change, including Earth's carbon cycle. By measuring the ratio of radiocarbon (the unstable carbon-14 isotope) to stable carbon (carbon-12), scientists use CAMS to date samples and determine how the carbon cycle is affected by variations in climate and how past ecosystems have reacted to significant climatic changes. CAMS researchers and their collaborators worldwide take advantage of the dual nature of radiocarbon both to measure geologic time and to serve as an easily identifiable tracer. The center's research focuses on understanding how carbon dioxide enters and leaves the atmosphere, oceans, and terrestrial biosphere and on acquiring climate records from the past to examine the processes governing current and future climate change. Research activities include studying corals to document changes in ocean circulation, determining the uptake and storage of carbon in soils, mapping the decades- to centuries-long droughts in California, studying the exchange of carbon dioxide between atmosphere and oceans, and calculating carbon uptake by different ecosystems.
Contact: Graham Bench (925) 423-5155 (bench1@llnl.gov).

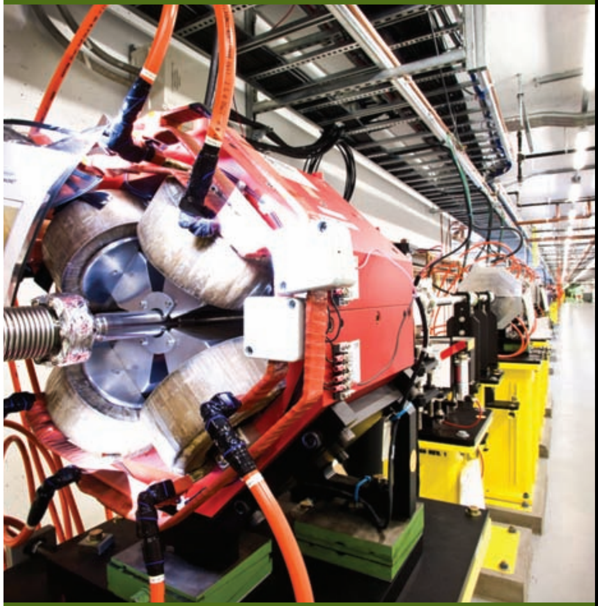
Precision Diagnostics Tell All

The ability to capture data from high-energy-density experiments has always been of great importance to the Laboratory and its missions. Advanced diagnostics initially used to measure the key physical properties of nuclear tests are continuing to be crucial for national security research at the National Ignition Facility (NIF). Gathering data from the various NIF experiments requires an extensive suite of reliable, robust diagnostics that can record micrometer-scale details of an experiment within tens of picoseconds (trillionths of a second). Designed and built by an international team of scientists and engineers, NIF diagnostics can withstand the harsh environment of the target chamber to detect and measure visible light, x rays, gamma rays, and nuclear products such as neutrons generated during an experiment. By studying the collected data, scientists and engineers can evaluate the performance characteristics of the laser, hohlraum, and target capsule and determine how to manipulate the laser and design targets to produce the precise conditions for ignition.
Contact: Robert L. Kauffman (925) 422-0419 (kauffman2@llnl.gov).

U.S. Government Printing Office: 2010/770-075-50001

Coming Next Issue

Experiments Reveal Atoms in Motion



Livermore researchers are conducting some of the first experiments on the Linac Coherent Light Source, which generates x-ray pulses more than a billion times brighter than ever before produced.

Also in January/February

• A novel combination of imaging techniques is being used to understand the three-dimensional architecture of plant cell walls.

• Onboard the Solar Dynamics Observatory, Livermore-developed multilayer mirrors are enabling unprecedented high-resolution images of the Sun.

• Control system enhancements at the National Ignition Facility bolster experimental data understanding and keep the system performing at its peak.

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