Lawrence Livermore National Laboratory

Science & Technology Review

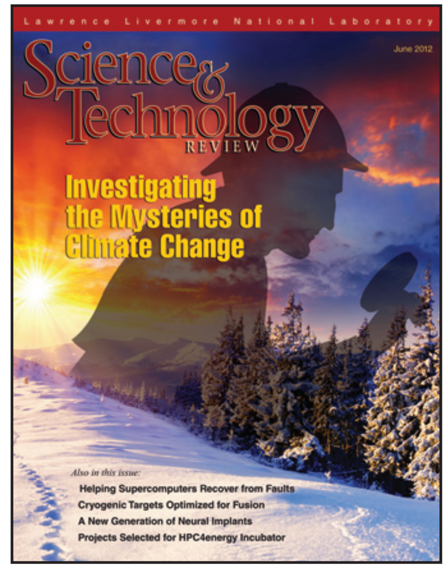
June 2012

Investigating the Mysteries of Climate Change

Also in this issue:

About the Cover

Climate scientists worldwide use sophisticated computer models to project how factors such as rising concentrations of carbon dioxide may affect the global climate. The Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI), established in 1989, supports these efforts by developing methods and tools to evaluate model performance. In comparing historical and present-day climate data with results from computer simulations, PCMDI scientists help researchers understand why the climate has changed and how it might change in the future. The article beginning on p. 4 describes some of the program's current projects, which are focused on improving cloud simulations, examining the forces behind shrinking snowpacks in western U.S. mountain ranges, and determining how increased shrub growth may affect the sub-Arctic boreal regions.



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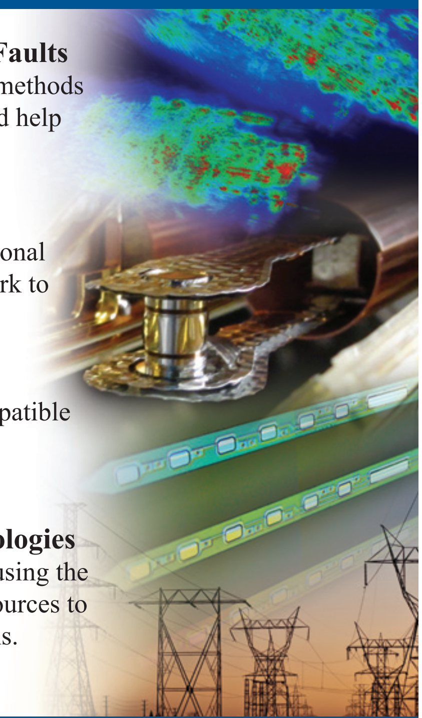
Contents

Feature

Research Highlights



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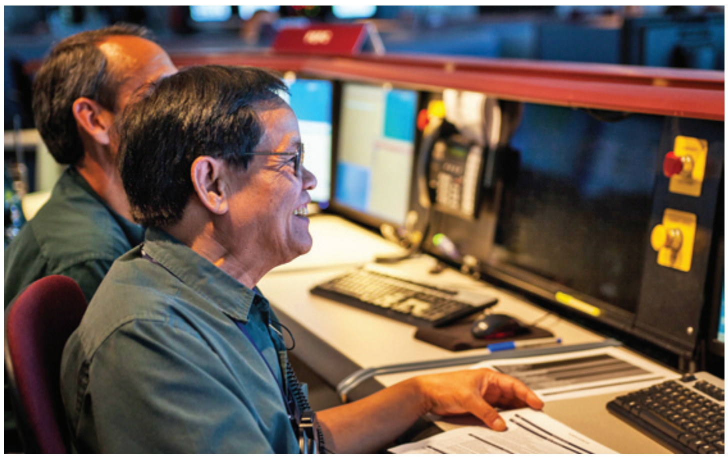
NIF Achieves Record 1.8 Megajoules of Laser Energy

The National Ignition Facility (NIF), the world's most energetic laser, surpassed a critical milestone in its efforts to achieve fusion ignition and energy gain in a laboratory setting. NIF's 192 lasers fired in perfect unison, delivering a record 1.875 megajoules (MJ) of ultraviolet laser light to the facility's target chamber center. In the photo, Dean LaTray (left) and Norris Lao monitor the progress of the record-setting shot from the NIF control room.

This historic laser performance involved a shaped pulse of energy 23-billionths of a second long, generating 411 trillion watts (terawatts) of peak power—1,000 times more than the U.S. uses at any instant in time. The 1.875-MJ shot, fired on March 15, exceeds NIF's original design specification and sets the stage for full-power (500-terawatt) experiments over the coming months. In addition, NIF scientists have plans for shots at even greater energy and power levels.



"This event marks a key milestone in the National Ignition Campaign's drive toward fusion ignition," says Edward Moses, the principal associate director for NIF and Photon Science. "While there have been many demonstrations of similar equivalent energy performance on individual beams or quads during the completion of the NIF project, it is the first time the full complement of 192 beams has operated at this energy level simultaneously. For the NIF team, this accomplishment feels like we've broken the sound barrier for the first time."

Moses notes that the energy produced by NIF, after the initial infrared laser pulse was converted to the final ultraviolet light, was 2.03 MJ before the light passed through the final focusing lens and beam diagnostics. The total energy generated was thus 70 times greater than any other laser in operation.

The historic shot was also one of the most precise ever fired at NIF. The achieved energy was within 1.3 percent of its goal, surpassing the requested energy by that amount. Such precision is vital because the energy distribution among the beams determines the degree of symmetry of the implosion of capsules containing fusion fuel. Symmetric implosion is a critical factor in achieving the pressures and temperatures required for ignition. "NIF's ability to demonstrate this level of precision performance as part of routine operations is a testament to the efforts of multiple teams supporting laser operations, target chamber operations, transport and handling, and optics refurbishment," Moses says.

Laboratory director Parney Albright says, "While congratulations go to all members of the NIF team, this is a collective celebration for our Laboratory. We should all be proud of our colleagues at NIF and of the fact that we all work in a place that does these things."

According to NIF operations manager Bruno Van Wonterghem, the scientific community has regarded the 1.8-MJ milestone as a tremendous technical challenge. "In 2003, we demonstrated this performance level on a single beamline, and in 2008, we repeated the demonstration on a quad of four beams," he says. "To achieve this performance with the same level of precision, quality, and reliability using all 192 beams is unprecedented and very exciting."

Van Wonterghem points in particular to the enormous progress NIF scientists and engineers have made in maintaining the facility's optics system while operating at increasing energy and power levels. For example, he says, "The recycle rate on optics from the 1.875-MJ shot was very close to the rate predicted by computer models, confirming our optics understanding." Two days after the milestone shot, all of the laser beams fired in a successful high-energy test using a target filled with cryogenic deuterium–tritium fuel.

Satisfying this long-standing NIF objective coincides with the third anniversary of the facility's startup in March 2009, when 1-MJ operation was first achieved. Since then, NIF has increased its operational energy, on average, about 1 kilojoule each day for three years. Today, NIF is fully operational around the clock, completing steps toward the goal of ignition and providing experimental access to national and international user communities.

NIF is the premier facility for stockpile stewardship, the National Nuclear Security Administration's program to ensure the safety, security, and reliability of the nation's nuclear weapons stockpile. The laser system also provides unique experimental opportunities to enhance scientific understanding of the universe by replicating in a laboratory setting the same extreme states of matter at the centers of planets, stars, and other celestial objects. Moreover, achieving ignition on NIF will demonstrate the viability of laser fusion as a potential future source for clean energy.

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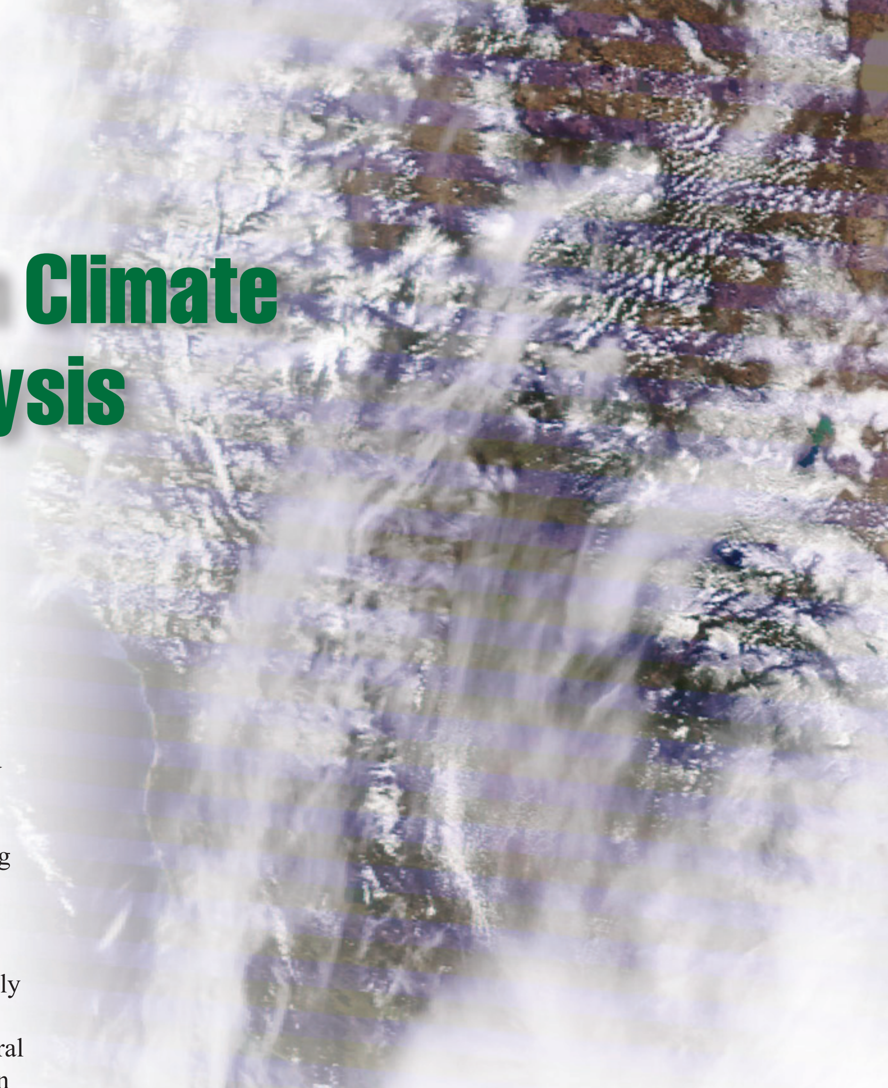
A New Era in Climate System Analysis



IN 2010, the American Meteorological Society presented the Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) with a special award. PCMDI, the society said, had pioneered "a new era in climate system analysis and understanding" and has "really changed the way we do business in climate science."

What is this transformation in climate science that Livermore scientists have led? Through their work, they have revolutionized the openness and ease with which researchers worldwide access and analyze model simulations of climate and climate change. Their work has not only led to a better fundamental understanding of the global climate system, but it has also greatly enhanced the ability of scientists to scrutinize, evaluate—and, thus, improve—climate models.

It is difficult to overstate the importance of this work, especially in light of the debate over the causes and consequences of global warming. The scientific community, policy makers, and the general public all need a means for understanding the differences between climate models and for characterizing these models' uncertainty. PCMDI, which is sponsored by the Office of Biological and Environmental Research at the Department of Energy, is a critical source for this type of information.

PCMDI does not develop or run its own climate model. Because the program does not have a vested interest in the results produced by a particular model, it can maintain a rigid objectivity in its assessment of climate models. PCMDI thus enjoys an international reputation for neutrality. It is a trusted agent for hosting, managing, and presenting climate simulation output without bias. The confidence earned by PCMDI partly explains the international modeling community's willingness to freely share output. This open sharing of results expands the expertise that can be brought to bear in assessing models and thus helps accelerate advances in climate science.

The reliance of the world's climate community on PCMDI is increasing, as these scientists engage in the fifth installment of the Coupled Model Intercomparison Project (CMIP5). The CMIP methodology, which was developed at Livermore, systematically compares and evaluates climate simulations with respect to each other and to climate measurements. Its results have informed the series of reports issued by the United Nations–sponsored Intergovernmental Panel on Climate Change, which is at work on its fifth assessment report.

At the same time, PCMDI is expanding its efforts in response to the need for better methods of evaluating the validity and accuracy of climate models. As part of CMIP5, for example, PCMDI will apply new methods for diagnosing the effects of cloud and carbon cycle changes on climate projections. In a major effort, funded by the Laboratory Directed Research and Development Program, climate scientists at Livermore are seeking to apply the tools of uncertainty quantification, which are used to evaluate the simulations that underlie nuclear stockpile stewardship, to climate modeling. If successfully developed, this approach will revolutionize the ability to quantify scientific confidence in predictions of future climate patterns.

The climate program at Livermore, which is featured in the article beginning on p. 4, exemplifies our defining theme of science in the national interest. Through sustained innovation, excellence, objectivity, and service, PCMDI has earned the trust and recognition summarized in the citation by the American Meteorological Society.

■ William H. Goldstein is associate director for Physical and Life Sciences.

Seeking Clues to Climate

Computer models provide insights to

Change

Earth's climate future.

THE air we breathe, the water we drink, the food we eat—climate affects them all. An atmospheric inversion holds down pollutants in a smoggy city, making it hard to breathe, until a change of weather brings a fresh breeze to blow it all away. A drought dries up water sources, and people and wildlife suffer until it rains and water flows freely again. Unseasonably hot or cold weather plays havoc with crops, ultimately affecting the price and availability of food for all.

Unusual weather patterns and rare strings of meteorological events occur naturally. A changing climate, however, can shift the odds enough so that humankind encounters unprecedented effects. And scientists now know that at least some aspects of Earth's climate are being altered by human activity. Data show that, over the past century, Earth has warmed measurably, and its atmosphere has changed.

At Livermore's Program for Climate Model Diagnosis and Intercomparison (PCMDI), Laboratory scientists are working with colleagues worldwide to better understand why the climate has changed and to improve predictions of the variations to expect in the future. (See the box on p. 6.) Comparing past data records with the results from climate models, PCMDI researchers are developing a clearer picture of the present and future patterns in the clouds above, the ground below, and the air all around.

Code Brings Clouds into Focus

One area of climate research directs the gaze upward, to the clouds. Modeling these masses of condensed water vapor is not straightforward. However, according to Livermore scientist Steve Klein, getting clouds "right" is vital to understanding what is in store for the future of Earth and its climate.

"Clouds modulate temperatures," says Klein. "Everyday experience shows us that cloudy days are cooler and cloudy nights are warmer than when skies are clear." During the daytime, clouds affect the transfer of solar radiation, preventing the Sun's radiative heat from reaching Earth's surface at full intensity. At night, clouds provide a "blanket" over Earth's surface, trapping thermal emission—the radiation emitted by a warmer ground—before it can escape into space. "These mechanisms are affected by sustained variations in climate and the increase in carbon dioxide in the atmosphere," says Klein. "But exactly how clouds will change is up for grabs at this point." Researchers want to determine, for example, whether a region will have more clouds or fewer and how reflective those formations will be.

Clouds also provide precipitation in the form of rain, snow, and ice. Plus they serve as the vehicles that transport water on the global "superhighway" of the atmosphere, with the rate of precipitation varying over time and geography. Some of this water makes its way into rivers, lakes, and groundwater and is used for drinking water and irrigation. "It's important to develop models that accurately predict the precipitation expected from clouds through climate change," says Klein.

Equally important is determining how accurately clouds are represented in climate models. One validation method is to re-create the past by running simulations with historical data and comparing the simulated cloud behavior with observations recorded by satellites since 1979. Much of the data collected for meteorological purposes is available through the International Satellite Cloud Climatology Project. A worldwide collaboration established in 1983, this project focuses on collecting and analyzing satellite radiance measurements to infer the global distribution of clouds; their properties; and their diurnal, seasonal, and interannual variations.

Satellite data come in different "flavors," depending on the types of sensors involved. Passive sensors measure what they "see" in the visible, infrared, and microwave portions of the spectrum. These sensors have limitations, however. For instance, they can provide information on the vertical level of the cloud top but not on a cloud's thickness, the altitude of its base, or the vertical distribution of condensate within it. "It is difficult for a passive sensor to distinguish between a cloud bank and snow on a mountain range," says Klein. "In terms of reflected light, both features look the same."

Active sensors, such as radar and lidar (light detection and ranging), emit signals

Program Addresses Climate Worldwide

The Program for Climate Model Diagnosis and Intercomparison (PCMDI) in Livermore's Physical and Life Sciences Directorate develops methods and tools for evaluating sophisticated climate models. Scientists worldwide rely on these models to project how rising concentrations of carbon dioxide and other factors will change the global climate. Established in 1989, PCMDI is funded primarily by the Regional and Global Climate Modeling Program and the Atmospheric System Research Program, both in the Climate and Environmental Sciences Division of the Department of Energy's Office of Science Biological and Environmental Research Program. PCMDI's mission is to assess climate models and reduce uncertainties in their predictions of future climate. Current activities include coordinating international model intercomparison studies, developing a model parameterization test bed, and devising rigorous statistical methods for detecting climate change and determining its causes.

Nearly two dozen Livermore scientists conduct PCMDI research in a wide range of areas. For example, they have made key contributions to the assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), which planners and policy makers use to prepare for and respond to future climate change. In recognition of its work to build and disseminate knowledge of human-induced climate change, IPCC shared the 2007 Nobel Peace Prize with former Vice President Al Gore.

In addition, PCMDI helped establish and now coordinates an ongoing international effort that facilitates the systematic evaluation of climate models and addresses the question of future climate change. During the third phase of this project, PCMDI and its partners enabled hundreds of researchers worldwide to subject models to unprecedented scrutiny and analysis. For its work, PCMDI was recognized by IPCC in its fourth assessment report, and the program received a special award from the American Meteorological Society.

Today, PCMDI scientists are helping to coordinate an even more ambitious follow-on project, phase five of the Coupled Model Intercomparison Project (CMIP5). CMIP5 calls for a set of coordinated climate model experiments agreed to by the modeling group representatives in the World Climate Research Programme's Working Group on Coupled Modelling. These experiments build on previous CMIP phases but include a more comprehensive set of simulations to enable model evaluation. The suite of simulations is designed to help researchers diagnose the processes responsible for differences in model projections of climate change and should allow them to better understand the uncertainty in the various projections. According to PCMDI director Karl Taylor, the results from CMIP5 will most likely provide the basis for much of the new climate science evaluated in the IPCC's fifth assessment report, planned for publication in late 2013.

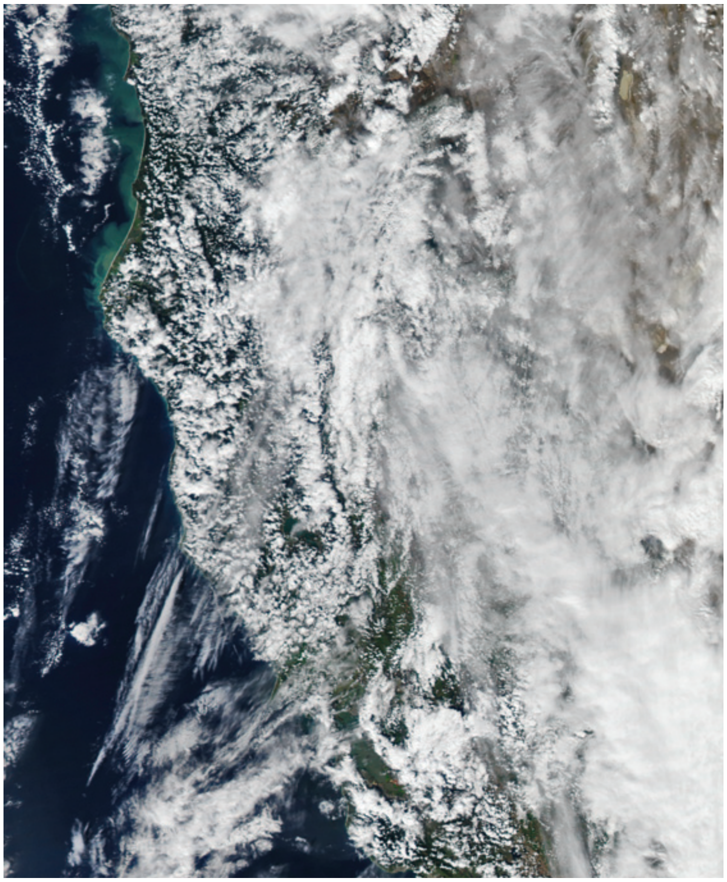
at wavelengths that penetrate clouds to varying degrees. Cloud characteristics determine the fraction of a pulse that is bounced back to the sensor and recorded. Active sensors can provide internal information, including the vertical distribution and density of condensed water inside a cloud mass. In addition, because each satellite has its own orbit, data recorded by different satellites can reveal how often clouds exist at particular points on the globe—the cloud cover, or cloud fraction, for a given region.

However, satellites do not directly measure many of the cloud quantities that interest climate scientists, such as the amount of condensate or the size of cloud particles. Instead, researchers must infer these properties through a retrieval algorithm, which converts observed measurements into the desired information.

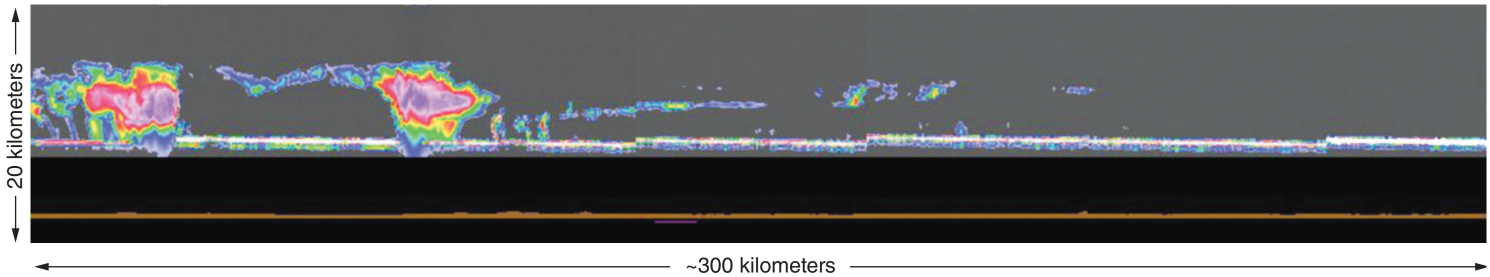
Furthermore, the definition of cloud types differs among observational platforms, and clouds detected by one sensor may not be found by another. A model might predict that clouds will exist at any atmospheric level where condensation occurs, but sensors may not detect a cloud that is overlapped by thick upper-level clouds. A comparison between modeled results and observed data thus requires a consistent definition of cloud types and diagnostic techniques that consider the effects of viewing geometry, sensor sensitivity, and vertical overlap of cloud layers.

To solve this problem, Klein and Livermore scientist Yuying Zhang are collaborating with researchers in Washington, Colorado, France, and the United Kingdom on the Cloud Feedback Model Intercomparison Project (CFMIP) to develop an integrated satellite simulator for use in climate models. The CFMIP Observation Simulator Package (COSP) is a diagnostic code that, when applied to the representation of clouds in a climate model, will emulate the data recorded by five satellites.

COSP mimics the observational process by converting model variables into pseudo-satellite observations. "It's designed to answer the question: What would a satellite see if the atmosphere had the clouds shown in a climate model?" says Klein. "If a model predicts a very thin cloud undetectable by a



Clouds are surprisingly difficult to simulate accurately in climate models.



This image, made from data recorded by the CloudSat satellite, shows the height and moisture content of two cumulus clouds. Colors indicate the amount of ice or liquid particles in the clouds, ranging from high (red) to low (blue).

satellite, for instance, we want the simulator to exclude that cloud from the comparison between model and satellite data. COSP should only count, or include, the model clouds that an actual satellite can record."

By emulating the observational process, COSP allows researchers to compare modeled results with observational data and judge whether models are simulating clouds correctly. "If we want to improve our predictions of how clouds will change in the future," says Klein, "we must accurately model the here and now as well as the patterns observed in the past." Once a climate model can replicate satellite observations, scientists have more confidence in its ability to present an accurate picture of the future.

One area where COSP has been greatly improved is in its ability to deal with cloud resolution. Models and satellites differ in how well they resolve cloud details. Satellite observations typically have a horizontal resolution of about 1 kilometer, whereas models build simulations on coarser grids of about 100 kilometers. "Using a 1-kilometer grid to run global simulations of predicted climate patterns over the next 100 years would be prohibitively expensive in terms of computational time," says Klein. "Working on such a fine scale is just not feasible. As a result, a satellite could easily detect small clouds that a simulation could not predict."

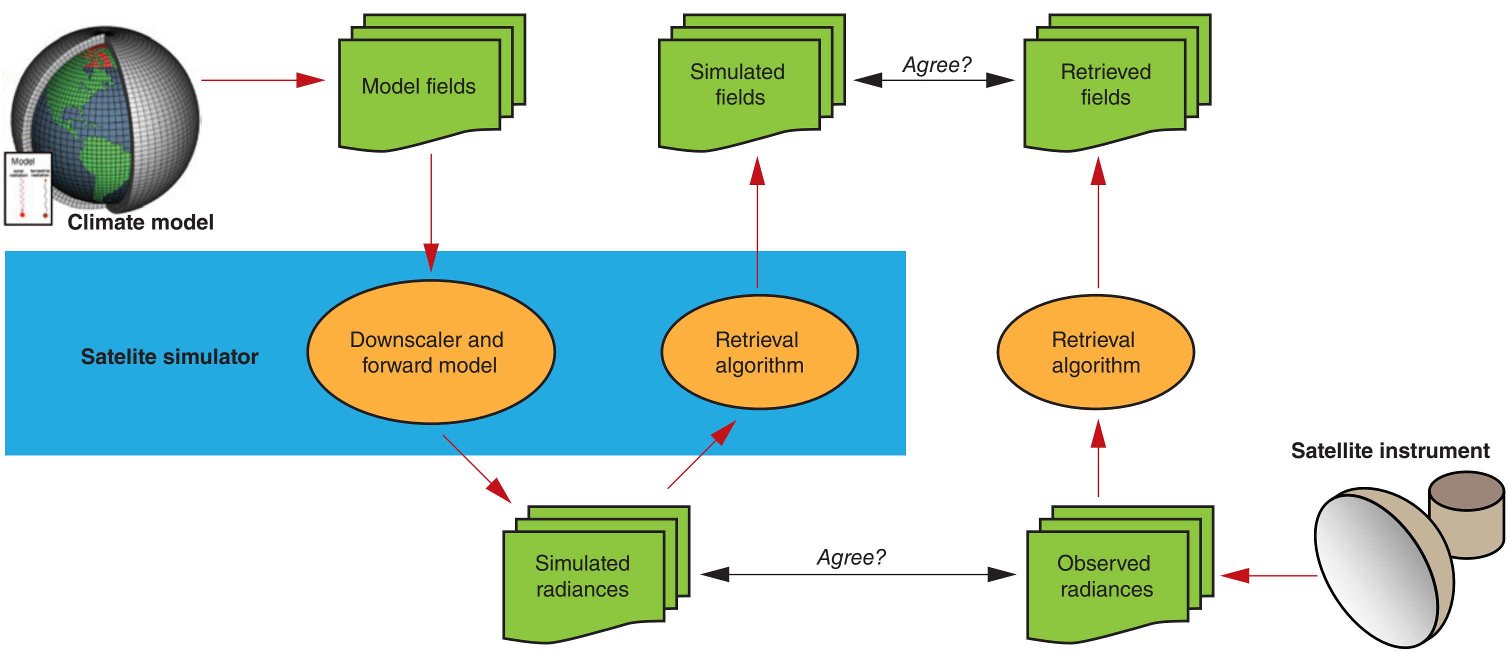
COSP addresses this issue by applying a technique known as downscaling to coarse resolutions. Zhang explains, "In a given simulation, COSP examines each 100-kilometer grid cell to see if that box contains clouds, and if so, what fraction of the box shows cloud cover. A grid cell with clouds is first divided into an equal number of vertical subcolumns. The model then assigns clouds to the columns in a manner consistent with the average amount of stratiform and convective clouds in that cell and with the model's assumptions about cloud overlap."

Next, an algorithm called SCOPS (subgrid cloud overlap profile samples) uses a pseudo-random sampling process to distribute cloud amounts into subcolumns. Zhang developed another algorithm, called PREC_SCOPS, to further distribute precipitation fluxes that are consistent with the distribution provided by SCOPS.

A measure of success in developing the satellite simulator is that most of the climate modeling centers worldwide have now incorporated the free code directly into their models to help scientists determine how accurately different models simulate clouds. The CFMIP team is also creating a standard for model output, so researchers can easily compare their results with those from other climate centers. In addition, the team continues to consolidate and refine COSP to reduce the computational time it consumes and make the code easier to use.

Looking at Regional-Scale Changes

Climate modeling on the global scale is one thing, but modeling the climate for one's regional backyard is something else. At regional scales, the climate change signals are about the same size as those at the global scale, but the background "noise," or natural variability,



To ensure that climate simulations accurately represent clouds, researchers at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) have developed a cloud simulator code called COSP. When incorporated into a climate model, COSP mimics the measurements recorded by satellites, allowing climate scientists to better compare simulated results with observed data.

is often much larger and may completely obscure the signal. Moreover, the local response can be strongly affected by local forcings—those natural or human-induced factors that affect climate—and these forcings are more uncertain at regional scales. Livermore climate scientist Celine Bonfils is leading several studies to investigate whether changes observed in different regions are caused by natural variation or by human activity.

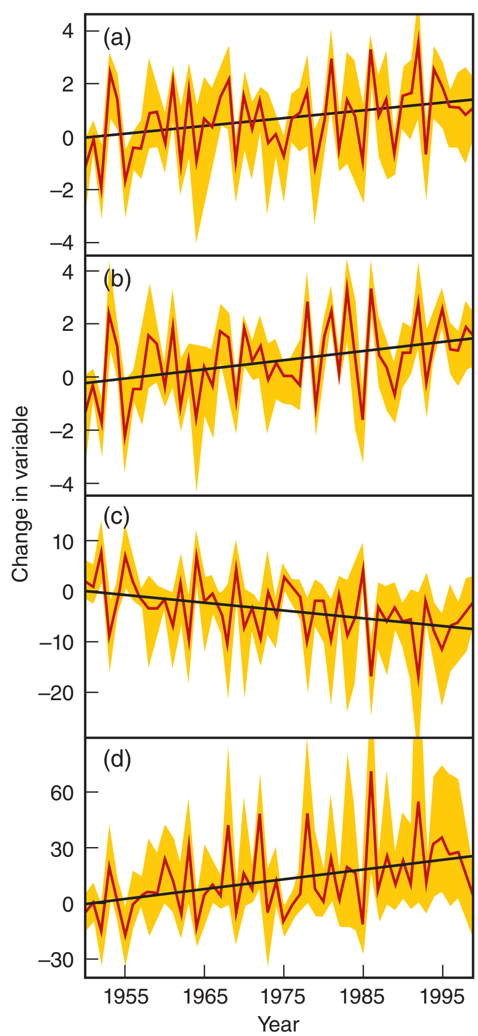
One project is exploring changes in western U.S. hydrology. Measurements show that since the mid-20th century, less snow and more rain are falling in the mountainous regions. In addition, snowpacks are smaller at low and mid elevations, and snowmelt seasons are beginning earlier. Regional warming looked to be the likely culprit, but the exact mechanisms of that warming had not been rigorously studied. Bonfils and colleagues from Lawrence Livermore, Scripps Institution of Oceanography, the U.S. Geological Survey, the University of Washington, and the National Institute for Environmental Studies in Japan conducted a regional detection and attribution study to identify signals that indicate the cause of an observed change. "We wanted to determine not only where the temperatures are changing over the mountainous regions of the western U.S.," says Bonfils, "but also whether those changes are due primarily to natural causes or are human induced."

Finding these signals involves searching past records for a pattern of climate change that has also been predicted by a computer model. Such a pattern could be due solely to natural changes—an increase in the Sun's energy output from a solar flare, for instance, or more volcanic ash in the air from a volcanic eruption—or it could be due to human influences, such as increases in the atmospheric levels of greenhouse gases. Each forcing mechanism has a distinctive signature, or fingerprint, in climate records. Fingerprint techniques allow researchers to examine a change in the climate system and then make rigorous statistical tests of possible explanations for that change. "Having a better understanding of the mechanism behind an observed warming allows us to make realistic projections about the future," says Bonfils. "Once a fingerprint is identified in the data from past records, we can have confidence in moving forward."

Answers are not easy to come by on regional scales. The climate of the western U.S., for example, is affected by strong natural variations, such as El Niño, La Niña, and the Pacific Decadal Oscillation, which in other regions have a smaller effect. In addition, the western U.S. is topographically complex, leading to small-scale climate features that global models may not adequately resolve. Plus, most model simulations often ignore local forcing mechanisms such as the changes associated with agriculture, urbanization, and irrigation. Together, these factors make it difficult to identify the regional manifestations of climate changes that are unambiguous at global scales.

For the fingerprint study, the team used four hydrologically relevant surface-temperature variables: the seasonal averages of daily minimum and maximum temperatures, the number of frost days, and the number of degree-days above 0°C (a variable that defines temperature-driven snowmelt). In the detection phase of the study, the researchers investigated whether the observed changes in the variables could be fully explained by natural internal climate variability. The attribution phase of the study focused on determining whether the observed changes were consistent with climate simulations that included anthropogenic effects such as greenhouse gases, ozone, and aerosols or only solar and volcanic forcings. Downscaling techniques were applied to transform data from three global models to smaller, regional scales.

The team's results indicate that the changes observed since 1950 are consistent with the climate response to anthropogenic forcing and outside the range expected from any natural internal climate variability. Models project an acceleration of warming, with temperatures



A PCMDI study of regional climate forcings examined four variables for nine mountainous regions in the western U.S.: (a) minimum temperature, (b) maximum temperature, (c) number of frost days, and (d) number of degree-days above 0°C for the months January through March. Red lines are results for each variable averaged over nine mountainous regions, all four of which predicted regional warming. Gold shading shows the range of minimum and maximum values for the nine regions. Black lines indicate the least-squares best-fit linear trend.

in California increasing between 1° and 3°C by 2050, and between 2° and 6°C by 2100—important information for decision makers charged with maintaining the region's water infrastructure and ensuring long-term sustainability for the state's water supply.

Warming in the Frozen North

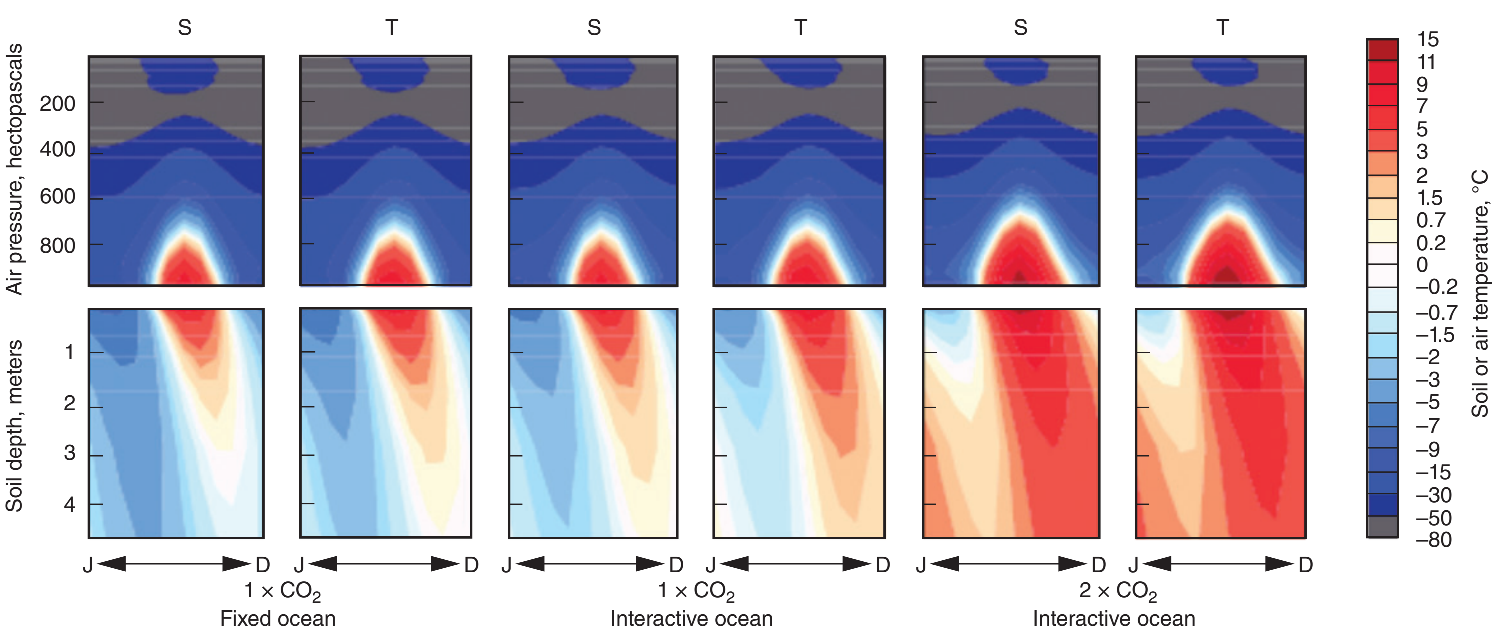
In another study, Bonfils examined a much less vegetated area of the world: the boreal region encircling the Arctic. Permafrost rules in this region, and vegetation consists mostly of short shrubs and tundra. But a warming climate is changing these features as well.

Most boreal studies have focused on what happens as vast areas of tundra convert to forests, a scenario not likely to occur in the 21st century because trees grow and conquer new grounds relatively slowly. However, tundra could convert to shrub-covered areas more quickly. Says Bonfils, "As climate warms and the growing season lengthens, shrub coverage would expand, and the shrubs would grow bigger and taller."

Bonfils is leading a collaboration with the National Center for Atmospheric Research, Lawrence Berkeley National Laboratory, the University of California at Berkeley, and PCMDI researchers to analyze the potential impact of a large-scale tundra-to-shrub conversion. Idealized experiments with the Community Climate System Model used three representations of the area's vegetation: the present-day distribution of short shrubs, a "greener" scenario in which short shrubs cover a wider area than they do now, and a third scenario in which tall shrub coverage expands, instead of short shrubs. Other land-cover types, including different vegetation, glaciers, wetlands, and lakes, were held constant so that the modeled effects came only from shrubs.

In simulations with increased shrub coverage, substantial atmospheric heating resulted from two seasonal land–atmosphere feedback mechanisms. Surface albedo, the fraction of solar energy reflected from Earth's surface, decreased, and the atmospheric moisture content from evapotranspiration increased. "These results show for the first time that the strength and timing of the two mechanisms greatly depend on shrub height and the time at which branches and leaves protrude from the snow," says Bonfils. Taller shrubs reduce the albedo earlier in the spring and transpire more efficiently than shorter shrubs, thereby increasing soil warming and destabilizing the permafrost more efficiently.

In a second part of the study, the team replaced bare ground with tall or short shrubs for three climate scenarios. The first scenario kept the ocean surface temperature unchanged, or fixed. The



In a PCMDI study of the Arctic boreal region, simulations compared the annual air and soil temperature as a function of height and depth in response to short (S) and tall (T) shrub invasions over a calendar year, January (J) to December (D). The model configurations included fixed ocean temperatures, an interactive ocean, and an interactive ocean plus double the amount of atmospheric carbon dioxide (CO_2). Results showed that the active layer thickness (or the thaw depth) deepens with the invasion of shrubs. This layer deepens even further when the ocean is active. The below-freezing season also shortens. When shrub expansion is paired with a warming ocean and increased atmospheric carbon dioxide, refreezing of the soil occurs only in the top meter. Below that, the soil no longer freezes, even in winter, and the heat content of the soil increases overall.

second simulation allowed the ocean and sea ice to interact with the atmosphere. In this scenario, additional warming occurs as sea ice melts. The reduced sea-ice cover lowers the surface albedo further and ocean evaporation increases, adding more water vapor to the atmosphere.

In the third simulation, researchers doubled the carbon dioxide in the atmosphere. This last scenario expanded an underground layer that freezes and thaws. Says Bonfils, "With shrubs in place, this active layer moves deeper, and more of the ground stays unfrozen year-round. Adding shrubs to the tundra landscape changes the activity above and below ground in a significant way."

Bonfils adds that the permafrost layer is a repository of methane, a greenhouse gas about 20 times more damaging than carbon dioxide. When areas that are frozen solid begin to thaw, they may release methane, which could lead to even more changes for the vulnerable, remote region. New simulations would be needed to test this hypothesis.

Different Models, Different Results?

Another concern for climate researchers and policy makers is whether the specific model chosen for a study affects the results. Most detection and attribution studies use a few climate models to produce a fingerprint template that is then matched to historical data. In a 2007 study, a PCMDI team led by climate scientist Ben Santer pooled results from 22 models to determine what caused changes in the atmosphere's moisture content. "We wanted to study the amount of water vapor the air holds because we have a lot of historical data showing how this characteristic has changed over time," says Santer. Routine, satellite-based measurements, which began in 1987, show that atmospheric moisture content has increased significantly.

The model data were taken from simulations performed in support of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC). "We relied on climate model output for estimates of the water-vapor fingerprint in response to human-caused changes in a variety of factors," explains Santer. "We also used the output for estimates of purely natural changes in climate—the background noise we need to take into account while trying to distinguish the fingerprint signal."

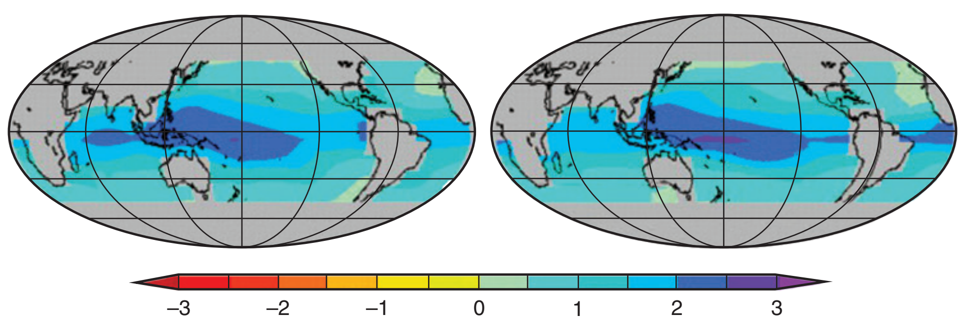
The simulated pattern of human-induced changes in water vapor produced by the 22 models correlated strongly with the data collected by satellites. The fingerprint for this increase was primarily due to the additional greenhouse gases added to the atmosphere by burning fossil fuels.

After these results were published, climate scientists asked whether the study would produce the same findings if, instead of 22 models, the team chose only the better climate models. "It was a reasonable question," says Santer, "so we attempted to identify the top 10 models of the 22 we originally used. We then tried to determine whether these better models showed the same human-caused fingerprint."

The team found that defining what factors makes one model "better" than another is not straightforward. "There isn't just one 'killer variable' that can foretell performance," says Santer. "Each model has strengths and weaknesses, depending on its focus, whether that is seasonal cycle, geographic region, or some other parameter. No single variable rules them all."

To rank the models, the team evaluated 70 performance metrics. One group of metrics examined how well a model captured important features of today's average climate. Another set focused on changes occurring over several seasons in the present-day climate. The largest set provided information on a model's skill in simulating the size and geographic patterns of observed climate variability. "We looked at this variability on different timescales—from month to month, year to year, and decade to decade," says Santer.

The team calculated the metrics for two climate variables, water vapor and sea-surface temperature, over several regions. "We found little relationship between a model's performance in portraying the mean state of these variables and the metrics," says Santer. The researchers then explored the sensitivity of fingerprint results to the procedures chosen for ranking the models. They used the six approaches to identify the 10 best and worst models and then repeated the fingerprint analysis many times.



To determine whether model quality affects simulated results, PCMDI researchers compared fingerprints produced by the top 10 models (left) with those produced by the bottom 10 (right). Fingerprints are based on an empirical orthogonal functions (EOF) analysis, which represents the weight of the signature at each grid point. The fingerprints show distinctive evidence of externally forced changes in water vapor over near-global ocean bands—simulated oceans that exclude areas where observational data and, thus, simulated results are less reliable.

Results indicated that a model's quality had little influence on its ability to identify a human fingerprint in satellite records of water vapor changes. No matter which models were used—the best or the worst—the fingerprint of human impact remained. "It's not terribly surprising because the increase in water vapor is very straightforward physics," says Santer. A warmer ocean surface leads to warmer air above the ocean. Warmer air holds more water, as visitors to a tropical location quickly discover. In addition, the patterns of natural water vapor fluctuation differ significantly from the signature imposed by human effects.

"The human effects lead to a steady overall increase in the amount of water vapor in the atmosphere," says Santer. "The entire panoply of the changing climate shows internal consistency. When we look at the story—the changes in water vapor and ocean temperature—it's like a well-constructed novel with no plot holes or unresolved character issues. In the end, the story does, indeed, make sense."

Looking to the Future

Climate research at the Laboratory continues, with efforts to "pin down" clouds in simulations, explore what changing climates mean on regional levels, and determine the quality of models for various fingerprinting activities. And as humanity searches for what these variations will mean for current and future generations, the Laboratory does its part to help present a more accurate picture of the future climate.

"We bring the best science we can to the challenge of climate science," says PCMDI director Karl Taylor. "The more information we have about the expected future and the more certain we are that that information is accurate, the better off everyone is." Improving scientific understanding of the uncertainty and the consequences of climate warming under various scenarios will help policy makers form an action plan for mitigating the effects and helping humankind adapt to the new environment.

—Ann Parker

Key Words: boreal, climate change, CFMIP Observation Simulator Package (COSP), Cloud Feedback Model Intercomparison Project (CFMIP), cloud simulation, fingerprinting, global warming, permafrost, Program for Climate Model Diagnosis and Intercomparison (PCMDI), regional climate modeling.

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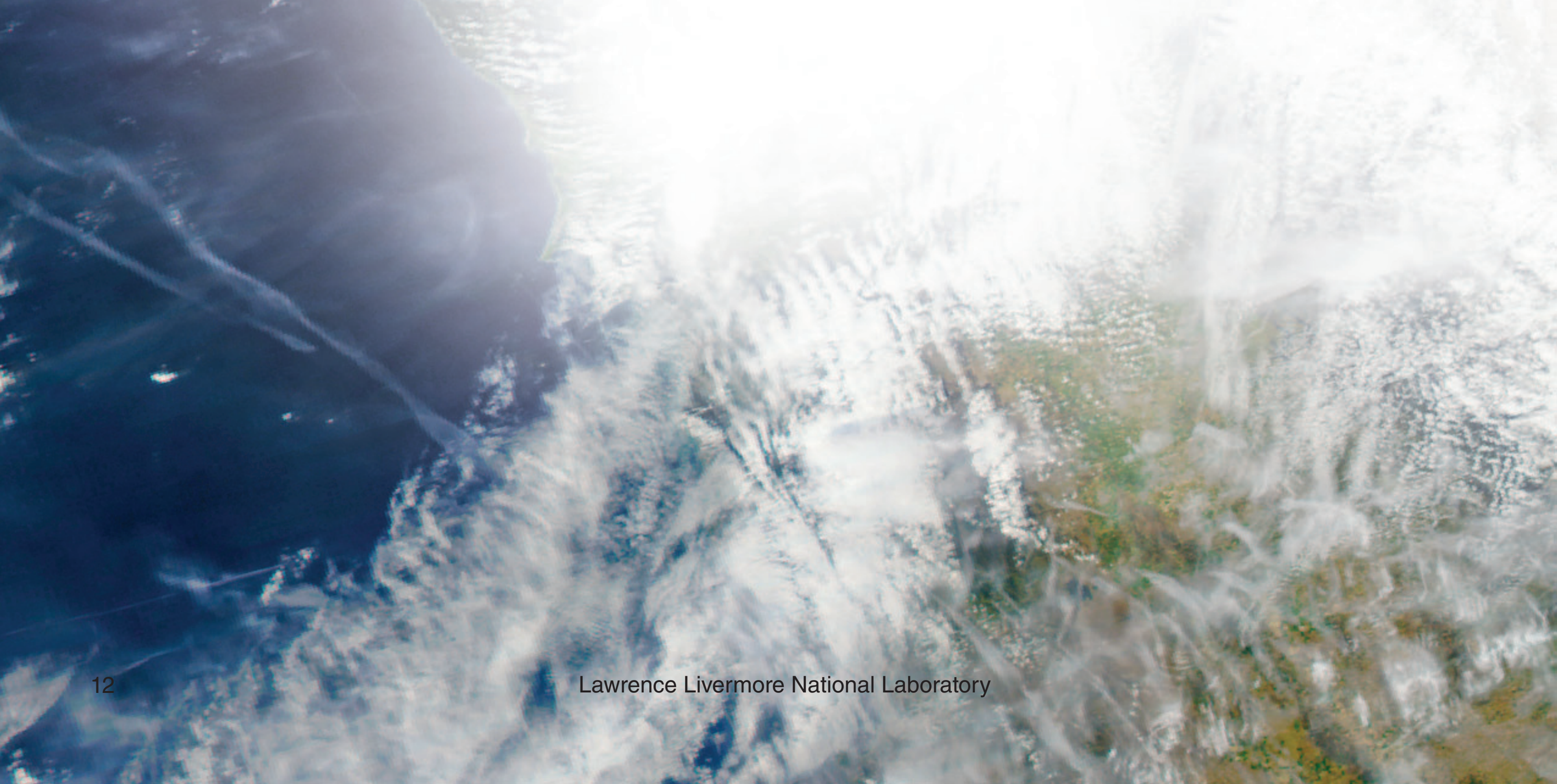
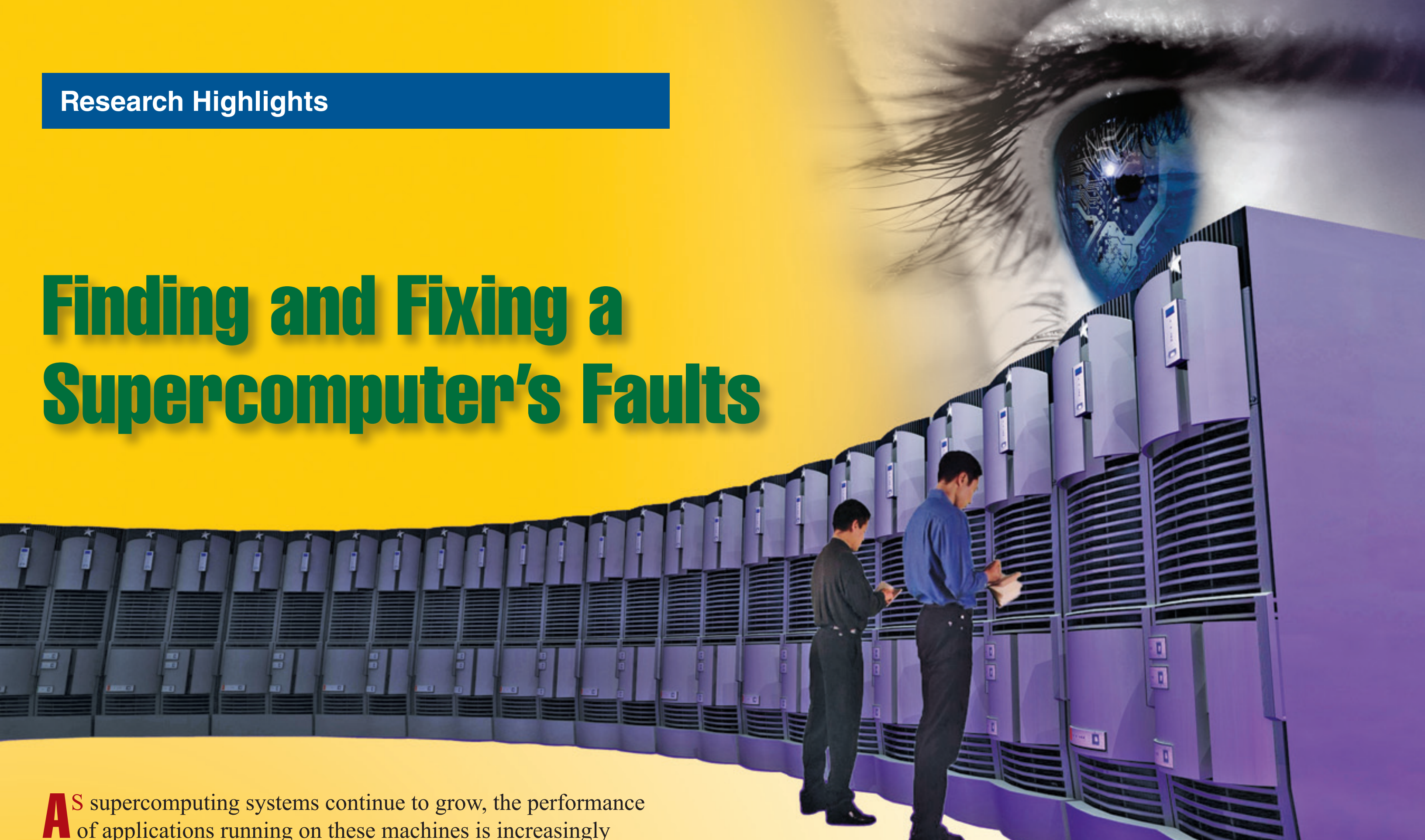


Finding and Fixing a Supercomputer's Faults



As supercomputing systems continue to grow, the performance of applications running on these machines is increasingly threatened by hardware faults. On current petascale machines, the number of processor cores ranges from hundreds of thousands to millions. (A core is the smallest unit of a computer that independently performs calculations.) Operating speeds on petascale systems can exceed 1 quadrillion (10^{15}) floating-point operations per second (flops). By 2020, exascale systems made with hundreds of millions of cores will have 1,000 times the performance of today's petascale systems, running calculations at a rate of 1 quintillion (10^{18}) flops.

The large number of components on a supercomputing system increases the rate of hardware faults, which can cause applications to abort and performance to degrade. More importantly, they may corrupt results. To address this problem, computational scientists, with funding from the Laboratory Directed Research and Development Program, are developing methods to detect faults in supercomputers and help systems recover from errors that do occur, even on exascale systems.

Bronis de Supinski, who leads the Exascale Computing Technologies project in the Laboratory's Center for Applied Scientific Computing, says that the more nodes, components, and memory a system has, the greater its error rate will be. For example, he says, "If you're the only person driving down a road, there is a small chance you could have an accident. But if you're surrounded by 10,000 other cars, your chances of having an accident rise."

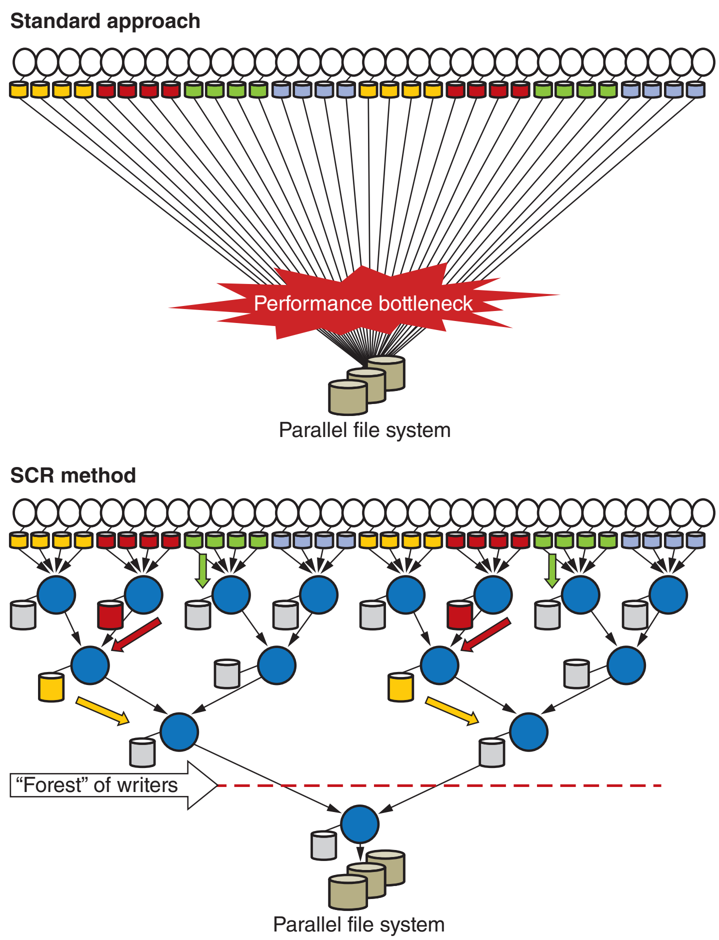
It is the same with computer systems. "We tend to think of computers as infallible," says de Supinski, "but physical processes—such as cosmic-ray strikes—can change the flow of electrons and affect what's on the memory cell."

Computer scientist Greg Bronevetsky adds that a computer is a physical device, not an abstract idea. "The projects at the Laboratory involve such complicated physics, no one can sit down and write out the calculations to solve them," says Bronevetsky, who received a Presidential Early Career Award for Scientists and Engineers in 2011. "The computer is a faster, much more powerful pencil, but like all devices made of parts from different vendors, an interaction between various components can lead to undesired outcomes. Something as simple as one chip dying—a problem we call a hard-stop fault—can cause the entire computation to crash."

Fault Finding

Hard-stop faults are the most common type of error and can stop an entire compute job. They are normally dealt with by writing checkpoints, a method in which the entire state of a job is saved and stored on a parallel file system. If a failure occurs, a program's state can be rolled back, or restored, from the most recent checkpoint, and operation resumed. But writing a single checkpoint to a parallel file system can require tens of minutes on a supercomputer. "Saving information somewhere else so we can bring it back grows expensive," de Supinski says. "If faults happen often, the system spends almost all of its time writing checkpoints and rolling back."

In addition, storage disk speeds are much slower than processor speeds. Their performance has not increased significantly over the years, even though processor performance has accelerated. Because of this bottleneck, an exascale system might spend more time saving and restoring information than performing computations.



The Scalable Checkpoint/Restart (SCR) method improves code performance by writing checkpoints to a compute node's local memory rather than to a parallel file system.

To reduce the time a machine requires to write checkpoints, a team of Livermore scientists led by Adam Moody developed the Scalable Checkpoint/Restart (SCR) approach. The SCR multilevel system can store checkpoints to a compute node's local memory—its random access or flash memory or even its disk—in addition to the parallel file system. Regular checkpoints can be saved quickly to local memory and duplicated on other nodes. If one node fails, its data can be restored from a duplicate. With this technique, the parallel file system is accessed much less frequently.

SCR stores, or caches, only the most recent checkpoints, discarding an older one as each new checkpoint is saved. It can also apply a redundancy scheme to the cache and recover checkpoints after a failure disables a small portion of the system. SCR proved its value when used with the pF3D code, which simulates laser–plasma interactions in support of the National Ignition Facility. In over 5 million node-hours of computation with pF3D, SCR recovered 85 percent of the faults that occurred. "We are also looking into staggering the times at which checkpoints are written," de Supinski says. "Typically, a job computes for a while and then takes a checkpoint. Disk traffic dramatically peaks in bursts because many jobs are writing at once. We found that the higher demand on the file system—this burst of pounding—makes the system less reliable. SCR can help us smooth the input/output traffic."

The team extended SCR to use a technique called Remote Direct Memory Access, which pulls data off the node without involving the processor in data movement. Different nodes can be coordinated to schedule their writing to the file system. Moody and Livermore scientist Kathryn Mohror then worked with several summer students to compress multiple checkpoints into a single file and reduce the number of nodes writing to the file system at one time. This approach led to more reliable performance.

Flipping a Bit

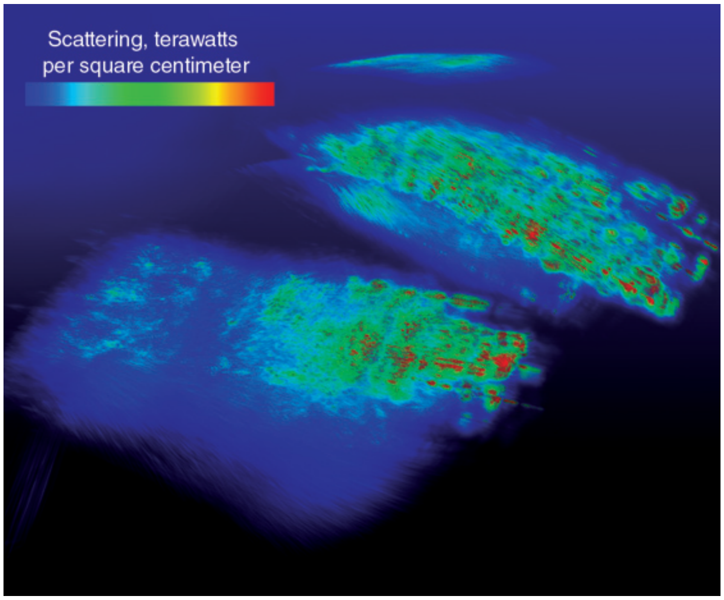
Another type of hardware error is a soft fault. These faults are insidious: Although the job continues to compute, the data are corrupted. "For example," says Bronevetsky, "if a charged particle goes through a transistor, it throws off a little piece of the computation." This error is known as "flipping a bit" because the binary code is switched from 0 to 1 or 1 to 0. When researchers analyzed BlueGene/L, the Laboratory's 108,000-node supercomputer, they found that one data-cache bit flip occurred every four hours. "The machines are expensive, and we want them to do as much productive work as possible," Bronevetsky says. "If an application that takes a week to run encounters a failure every four hours, the odds are that it will never complete."

To make applications more tolerant to bit flips, Livermore computer scientist and postdoctoral researcher Marc Casas Guix adapted the algebraic multigrid (AMG) algorithm, a powerful solver of sparse linear equations. AMG solves linear systems at multiple levels of granularity. The fine-grained solve steps reduce errors that result from inconsistencies between nearby grid cells, and the coarse-grained steps reduce inconsistencies between larger regions of space.

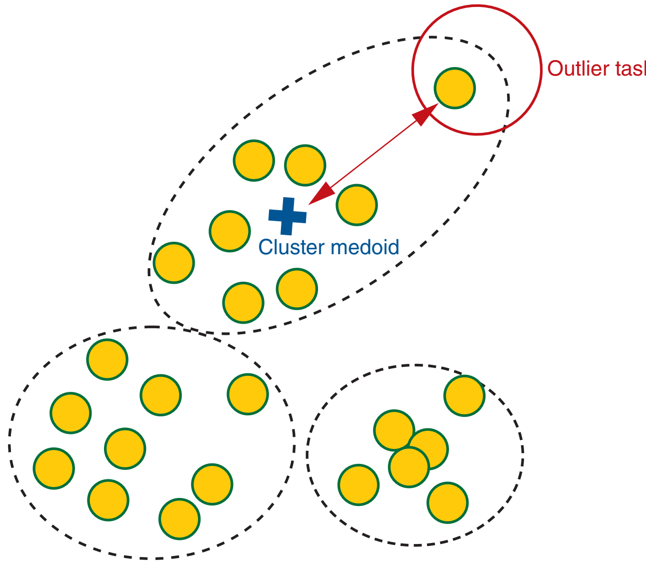
Laboratory researchers then flip bits in AMG to determine the code regions and data structures that are vulnerable to such errors. Based on the consequences, they can choose the most appropriate resilience strategy. To guard against hard failures, they can checkpoint data, automatically recalculate corrupted data structures, or run two copies of the same program simultaneously in case one version becomes corrupted. "AMG is good at overcoming errors by fixing them locally and iteratively," says Bronevetsky. "In practice, it survives faults well."

Clusters to the Rescue

When a supercomputer system computes correctly but the run time lasts much longer than normal, a performance fault is the culprit. Performance faults are challenging to identify because



SCR recovered 85 percent of the faults that occurred in more than 5 million node-hours of computation with the pF3D code, which simulates laser–plasma interactions such as the one shown here.



A clustering algorithm called CAPEK (Clustering Algorithm with Parallel Extended K-Medoids) samples performance data from the various processors on a supercomputing system and locates small clusters with similar characteristics. The clusters quickly reveal outliers whose behavior is suspicious.

they may occur on any of hundreds of thousands of processors in a petascale system. A Livermore team led by computer scientist Todd Gamblin has developed an automated machine-learning technique called CAPEK (Clustering Algorithm with Parallel Extended K-Medoids) that can quickly find faulty processors while a calculation is running.

CAPEK uses a fast sampling method that quickly identifies groups of processors with similar performance characteristics. This analysis gives each processor a general picture of the behavior of the system as a whole. "To know what's abnormal, we must first determine what's normal," says Gamblin, who first studied load imbalance and developed compression techniques while collaborating with Livermore scientists on his dissertation. Once each processor receives a description of "normal" behavior from CAPEK, it can compare this to its own behavior and identify itself as either normal or faulty. Isolating the faulty processors significantly reduces the cost of analyzing an application's performance. "CAPEK has proven to be a good method for determining when node behavior is different or suspicious," says Gamblin. "With that information, we don't have to examine all the nodes, only the ones affected."

CAPEK is used for many types of analysis including statistical trace sampling and scalable detection of performance anomalies. Gamblin has worked with de Supinski, Bronevetsky, and collaborators at Purdue University to incorporate CAPEK with AutomaDeD, which automatically finds performance faults, so the tool can be scaled to next-generation systems. "Most traditional clustering algorithms get slower with large numbers of cores," says Gamblin. "CAPEK doesn't run much slower on 131,072 cores than it does on one. No matter how many cores are in use, it takes less than 1 second to run, which is fast enough for online use in production."

Integrated Support for Laboratory Missions

De Supinski acknowledges that other new techniques are needed to keep predictive simulations running efficiently on exascale supercomputers. But SCR, the modified AMG algorithm, and CAPEK are important advances, making applications more tolerant of hardware faults.

"Ensuring the performance of our petascale and future exascale systems is critical to the success of many Laboratory missions," says de Supinski. These machines provide the computational power researchers need for a wide range of 21st-century efforts, from modeling new materials to studying fusion reactions and predicting the effects of a changing climate.

—Kris Fury

Key Words: algebraic multigrid (AMG) algorithm, checkpoint, Clustering Algorithm with Parallel Extended K-Medoids (CAPEK), compute node, exascale computing, hard fault, performance fault, petascale computing, Scalable Checkpoint/Restart (SCR), soft fault, supercomputing.

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Targeting Ignition

SUCCESSFUL experiments at the world's most energetic laser, the National Ignition Facility (NIF) at Lawrence Livermore, rely on great complexity in a tiny package—an exquisitely designed and meticulously assembled target. Since 2010, researchers at NIF have been conducting experiments as part of the National Ignition Campaign, a collaborative international effort to demonstrate fusion ignition with energy gain in a laboratory setting for the first time. Two recent target improvements, one operational and the other design-oriented, demonstrate the precision that ignition experiments demand and mark important progress toward achieving this grand challenge.

The target for an ignition experiment consists of two components: a hohlraum and a fuel capsule. The hohlraum is a metal object about the size and shape of a pencil eraser with holes at each end for laser beams to enter. Centered within this cylinder is a gas-filled, spherical fuel capsule only 2 millimeters in diameter. During experiments, the hohlraum serves as an oven, focusing laser energy in the form of x rays on the capsule. The x rays heat and compress deuterium–tritium fuel inside the capsule to extremely high pressures and temperatures—conditions matched only by those found in the interior of stars or exploding nuclear weapons.

A Crystallized Layering Process

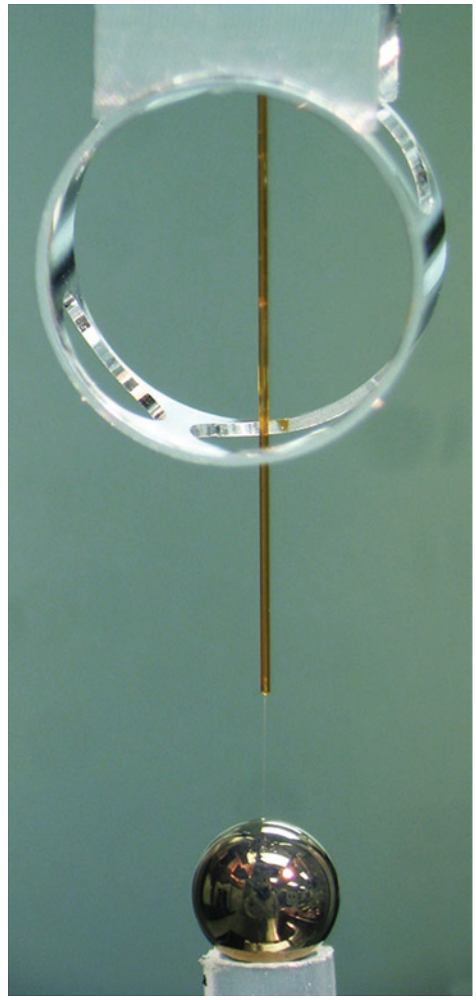
Coating the ignition capsule's interior surface is a thin, frozen layer of hydrogen isotopes. For optimal fuel implosion during an experiment, the ice layer must have a uniform thickness, and its inner surface must be extremely smooth. These characteristics are best achieved if the layer is made from a single crystal. However, no seed can be isolated in the NIF fuel capsule to start the normal crystal growth process.

"In a perfect world, we would use a crystal seed of our own making," says Livermore physicist Evan Mapoles. "But we can't do that for these targets because the layering process begins at room temperature where no seed of solid hydrogen can exist." He adds that crystal seeds will form only when temperatures are cooled to about 20 kelvins (–253°C), close to the triple point of the hydrogen isotope mixture—the temperature at which a substance's solid, liquid, and gas phases can coexist in equilibrium.

The Livermore team has distilled a process that maximizes the probability of growing a layer from a single seed crystal. Before an experiment begins, a target is mounted on the end of the target positioner, which sits in a large vacuum vessel just outside the NIF target chamber. There, a sophisticated system fills the capsule with liquid hydrogen fuel, characterizes the cryogenic fuel layer, and maintains the layer quality. The entire target package is kept below 20 kelvins and is sheltered by shrouds while the layer is formed. The package is then positioned and aligned at the center of the target chamber, ready for the experiment to begin.

The layering process begins by preparing and cooling the target and then adding deuterium–tritium fuel through a slender fill tube attached to the capsule. (See the photo at right.) Technicians can precisely control the fuel volume by adjusting the relative temperature of the capsule and the fuel reservoir. Once the volume is satisfactory for the upcoming experiment, the liquid is rapidly frozen.

Mapoles describes the resulting ice as “a polycrystalline mess.” This initial layer is completely melted, leaving only an ice plug in the fill line to maintain a constant fuel mass in the capsule. Then the capsule is cooled until ice grows out of the fill tube into the capsule. This process requires some supercooling of the liquid. When ice enters the capsule, it grows rapidly, typically leaving just a few ice crystals in the capsule. The capsule is heated again until only the smallest discernible fraction of ice remains. The capsule is cooled and melted again to reveal a crystal seed. It is then cooled slowly for several hours to grow the final ice layer, which is a mere 69 micrometers thick. Scientists use x-ray diagnostics to assess the layer quality and either accept or reject it. If the layer is rejected, the melting and cooling cycle begins again. The layer formation process takes a little less than a day, and achieving a good layer generally requires one to four attempts.



A glass tube smaller than a human hair transfers deuterium–tritium fuel to a 2-millimeter-diameter target capsule for an experiment at the National Ignition Facility (NIF). The design for the NIF fill tubes is the same as that for the tiny needle used to penetrate a single egg during in vitro fertilization.

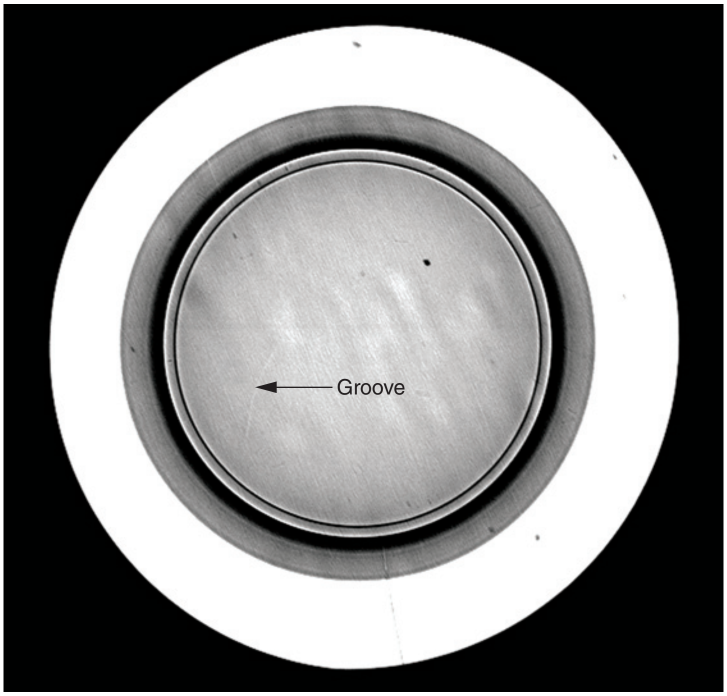
Playing It Smooth

A radiation hydrodynamics code called LASNEX models the full geometry of the hohlraum, capsule, and interacting laser light during an experiment. Simulations allow researchers to observe how factors such as perturbations on the surface of the ice and in the fill tube affect the fuel implosion. Model accuracy is continually enhanced by incorporating data from ignition experiments. Through modeling, Mapoles says, “We know that the ice’s inner surface is a critical factor in target performance.”

As a result, the NIF team has developed a set of target requirements that limit the size and quantity of grooves and the surface roughness allowed on the capsule for an acceptable ice layer. For each experiment, the layer is carefully characterized to locate imperfections in shape and smoothness and for isolated defects. Minor shape issues identified in the fully formed layer can often be corrected with a “shimming” process using small heaters in the target. According to Mapoles, the most common cause for layer failure is natural crystal defects, which tend to cluster and form grooves. Impurities introduced before or during the layering operation can produce occasional imperfections.

In the characterization process, x-ray cameras record the target through slits in the hohlraum walls and the laser entrance holes, producing hundreds of images for a single layering sequence. Within minutes, an automated workflow system processes, combines, and displays the images for analysis. Imaging at both high and low magnification ensures that each target is thoroughly reviewed. High-resolution images taken at three orthogonal views illuminate grooves that are no more than 1 or 2 micrometers deep and are effective at finding defects near the perimeter. Lower-magnification images taken through the hohlraum laser entrance holes offer better contrast, helping analysts identify short, deep grooves across the full ice layer.

Researchers also developed methods to control contamination during the layering process. Before a target is filled, sensitive equipment scans the fuel for pollutants. Improved gas-purging processes and hardware minimize opportunities for undesirable materials to enter the target capsule. Adding a cold trap in the fill tube and keeping this tube and the fuel reservoir below 25 kelvins help isolate the capsule interior from contaminants.



An x-ray image of a NIF target captured through the hohlraum laser entrance holes allows researchers to evaluate the shape and smoothness of the ice layer and to determine whether a groove would enhance or impair experimental results.

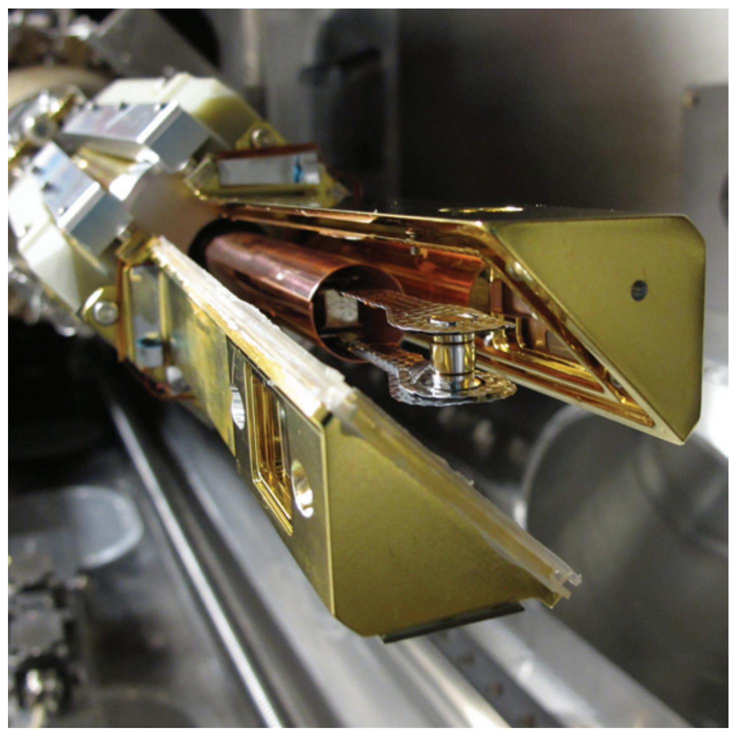
As a result of these improvements, the team is producing high-quality cryogenic layers consistently and efficiently. Researchers are now working to enhance the speed, automation, and reliability of the entire process to accommodate an increased pace of NIF experiments, and more engineers and physicists are being trained to make and characterize the layers.

A Window on Implosion

Producing extremely smooth ice layers was a known challenge for the National Ignition Campaign. More unexpected was finding that ice sometimes formed in the wrong places. In ignition experiments, the laser pulse must be precisely tailored in shape and time to produce four shock waves that compress the hydrogen fuel to the required temperature and density. Early experiments on shock timing produced results at odds with simulations and expectations. Using the VISAR (Velocity Interferometer System for Any Reflector) diagnostic, NIF scientists pinpointed the cause of this inconsistency: the arrival time of the first shock wave.

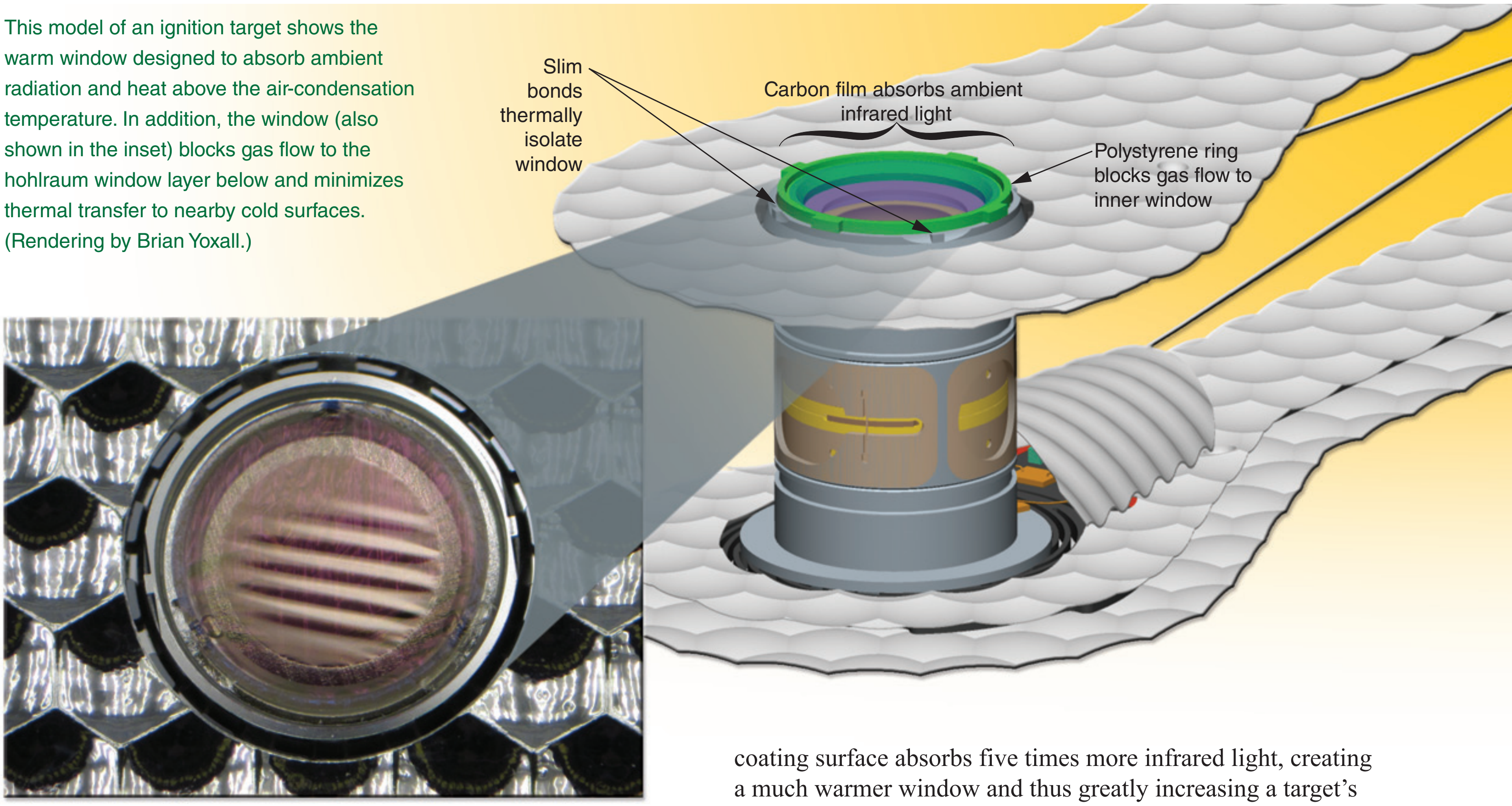
Physicist Harry Robey explains that the four shocks must coalesce inside the gas portion of the capsule. "If the first shock is very slow, the shocks merge early," he says. "As a result, they transfer too much energy to the ice layer, which severely limits how much we can compress the fuel." Ignition hohlraums have thin windows over the laser entrance holes. Although the surrounding shrouds have tight seals, gas would in some instances leak through, allowing a thin coating of frozen oxygen and nitrogen to accumulate on a window. Unfortunately, a condensation layer just 0.1 micrometers thick could delay the laser energy on its way to the target and disrupt the timing required to compress the fuel to the desired density.

Working with colleagues from General Atomics, the NIF researchers designed a second, warmer window to cover the top of each entrance hole, making targets impervious to frost formation. This second window absorbs enough infrared radiation to prevent gases from condensing on the warmed surface. Three tiny feet protruding from the window are attached by low-conductivity bonds to the cold hohlraum below and provide thermal isolation. Initially, gases can flow through the gap between the two windows, but once the system is brought to vacuum, they are blocked from reaching the entrance holes by the polystyrene ring surrounding the warm window.



This cryogenic layered target, shown mounted on the target positioning system, was used in an experiment at the National Ignition Facility in September 2010. The two triangular arms form a shroud around the cold target to protect it until seconds before a shot.

This model of an ignition target shows the warm window designed to absorb ambient radiation and heat above the air-condensation temperature. In addition, the window (also shown in the inset) blocks gas flow to the hohlraum window layer below and minimizes thermal transfer to nearby cold surfaces. (Rendering by Brian Yoxall.)



Warming to a Solution

The Livermore–General Atomics collaboration moved the warm window from idea to prototype in just 10 weeks. The design has a polyimide layer topped with a thinner amorphous carbon layer that together are only 150 nanometers thick. The carbon surface film efficiently uses the ambient thermal radiation from the chamber walls, yet does not interact with laser light so x rays cannot interfere to skew the experimental results. Windows are positioned 500 micrometers above each laser entrance hole. As the carbon film absorbs infrared radiation, it warms the window to above 25 kelvins, the point at which any residual air in the chamber condenses.

When the team tested the first prototype in February 2011, x-ray spectrometer measurements indicated no frost buildup, validating the design. Chemical engineer Jim Fair, who leads the warm window project, says, “Every target that is susceptible to frost is now fitted with a warm window. It is an integral part of the target design.”

Researchers continue to enhance the window’s performance. Instead of applying the carbon coating with a sputtering technique, the team has switched to electron-beam deposition. The new coating surface absorbs five times more infrared light, creating a much warmer window and thus greatly increasing a target’s operating margin before frost is produced. The team is also working on an adhesive-free method to attach the window to the hohlraum and further reduce thermal conductivity.

Mapoles notes that creating and fielding consistently high-quality cryogenic layered targets has been a team effort. “When we look at the integrated technologies going into these targets, we see that we’re pulling from a lot of areas of expertise at the Laboratory,” he says. “We have many success stories.” As they have so many times before, Livermore physicists, chemists, engineers, computer scientists, technicians, and operations specialists are working as part of a multidisciplinary team to create effective solutions in pursuit of a scientific grand challenge—the pioneering effort to achieve ignition.

—Rose Hansen

Key Words: cryogenic target, crystal growth, deuterium–tritium fuel, electron-beam deposition, hohlraum, ignition, laser entrance hole, LASNEX, National Ignition Facility (NIF), shock timing, warm window, x-ray characterization.

For further information on cryogenic layers, contact Evan Mapoles (925) 422-6956 (mapoles1@llnl.gov); on the warm window, contact Jim Fair (925) 424-9826 (fair2@llnl.gov).

Neural Implants Come of Age

THE symbiotic union between man and machine has been a subject of great fascination to scientists and science fiction writers alike for generations. But for researchers such as Satinderpall Pannu of Livermore's Engineering Directorate, integrating nanometer-size devices with biological systems and studying the interface between them is a daily reality. In 2009, he and his team set the stage for a new generation of neural implants with the design and fabrication of an artificial retina. The device—the first high-density, fully implantable neural prosthetic ever produced—restores a sense of vision to people who have lost their sight because of ocular disease. Since then, Pannu and his team have continued to enhance the technology, which promises to dramatically improve the lives of patients with debilitating conditions caused by injury or neurological disease.

Keys to the success of this new class of implants are advances made at Livermore in the area of nano- and microfabrication techniques and in the use of novel materials that make the devices both biocompatible and fully implantable for long-term use. Moreover, the implants promise to do more than just stimulate neural tissue. They will record electrical and even chemical signals for the first time, creating a feedback mechanism that allows the stimulation to be fine-tuned for each patient. "These devices are a real game changer," Pannu says. "Once we understand what fully implantable prosthetics can do, the floodgates to innovation are open."

Neural implants, or prosthetics, are a class of devices that communicate with the nervous system. An electronics package in each device activates an array of tiny electrodes that interface directly with healthy neurons in the body. Signals produced by the electrodes bypass damaged areas of the brain or part of the nervous system to restore function, block pain, or prevent seizures. Someday, these devices may even be used to treat depression and other ailments.

The first widely used neural prosthetic was the cochlear hearing implant in the early 1980s, which provides a sense of sound to people with severe hearing impairment. Since the late 1990s, implants for the brain and spinal cord have been developed with varying degrees of success. Some help prevent seizures in patients with epilepsy and Parkinson's disease. Spine implants are being used for pain control, and other devices stimulate peripheral nerves and muscles. Although these devices have dramatically improved many people's lives, they are limited in terms of performance compared to the promise held by technologies now under development. Except for the artificial retina, today's implants operate with a handful of electrodes and an electronics package the size of a deck of cards, which causes significant complications during and after surgery. Moreover, the lifetime of newer devices is short because the electrodes are made of silicon, a rigid material prone to breaking.

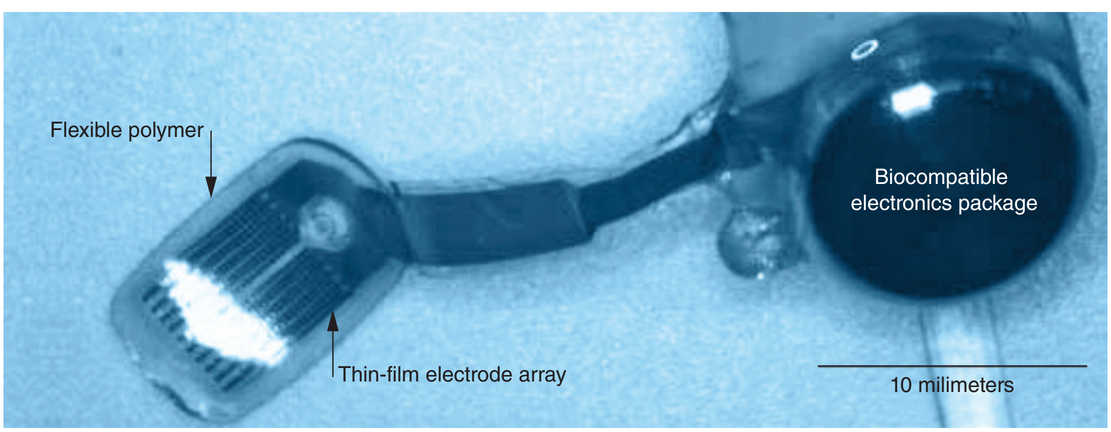
Building a Better Implant

The Livermore researchers wanted to take implant technology to a new level—in particular, by making electrodes smaller and more flexible so that more can be packed in ever-smaller packages. A recent advance by the team seals the components in a self-contained, wireless device that can be placed inside the human body without causing adverse reactions. The package, miniaturized to fit in an area less than 10 millimeters in diameter and 4 millimeters tall, contains a microelectrode array, inductive coils to power the device, and electronics hermetically sealed inside a metal container brazed onto a biocompatible ceramic disk.

The microelectrodes at the heart of this technology are embedded in a flexible polymer, which allows the device to move naturally and conform to the live tissue in which it is implanted, such as the brain. The device can be custom designed to the shape needed for each clinical requirement. Once implanted, the delicate-looking but robust microelectrode array can last for years, possibly even decades, because polymer is more compatible with the human body than silicon. The Livermore technology is the only thin-film electrode array approved for long-term human implantation. According to electrical engineer Angela Tooker, polymers have more commonly been used as insulating materials. "Electronics are made of metal, and getting them to work with polymers is a specialty we've developed at Livermore."

Work on the implant technology is performed at the Center for Micro- and Nanotechnologies in the polymer fabrication laboratory. The center's mission is to invent, develop, and apply micrometer- and nanometer-scale technologies in support of the Laboratory's missions. Specialized equipment available at the facility includes metal deposition systems and machines that etch and pattern electrodes. Other tools can position components within an accuracy of a few micrometers, and wire bonders can electrically connect them. (See the movie at www.llnl.gov/news/video/retina.mov for a look at the artificial retina fabrication process.) Using this equipment, Livermore engineers can design new arrays quickly when the demand arises. "Someone else would have to find a medical device foundry that has these capabilities," says Pannu, who heads the center. "Worldwide, only a couple of such facilities are available."

Equally important is the group's expertise in devising and fabricating such complex devices. Kedar Shah, the mechanical engineer leading the implant assembly, explains the challenge involved in safely integrating implant components into a device the size of a small button. "The electronics package is only 3 millimeters tall," he says. "Within this small unit, we pack a couple electronic chips and dozens of passive components, such as capacitors, resistors, and diodes. But these components are often made of toxic materials, so we have devised methods to seal them off to prevent contact with the body." The body's moisture cannot

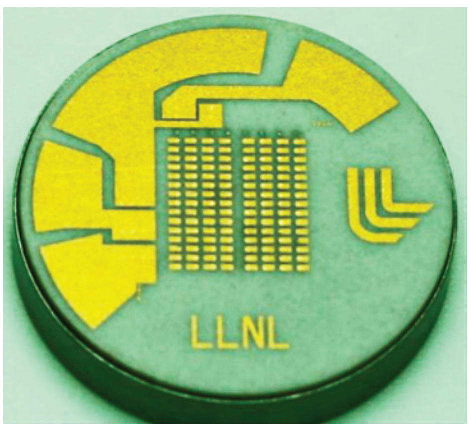


The most recent design of Livermore's artificial retinal implant has an array of 240 thin-film microelectrodes inside a microelectronics package.

touch the electronics either because it would short them out. The package is thus hermetically sealed, and conduits are incorporated to transfer electric signals to the outside without allowing particles to escape.

The artificial retina demonstrated that the Livermore team could meet the design challenge, successfully transitioning the implant from research idea to application. The team received the 2009 Editor's Choice Award in *R&D Magazine*'s annual competition for the top 100 technologies and a 2010 Breakthrough Award for Innovation from *Popular Mechanics*. Since then, the team has continued to improve the technology. Implants now pack hundreds of microelectrodes, compared with 16 and 60 electrodes, respectively, for the first two generations of the artificial retina. The team is now searching for industrial partners with the expertise to run long-term clinical trials—the next step toward obtaining approval from the Food and Drug Administration for the new generation of implants.

"The most recent devices we're developing cannot be put in humans yet, but we design them with this goal in mind," says chemical engineer Vanessa Tolosa. "That's where the collaborators come in. We need to work with neuroscientists and clinicians to determine how they would use the implants and what conditions a device would experience over its lifetime. Then we can design the technology to meet those requirements."

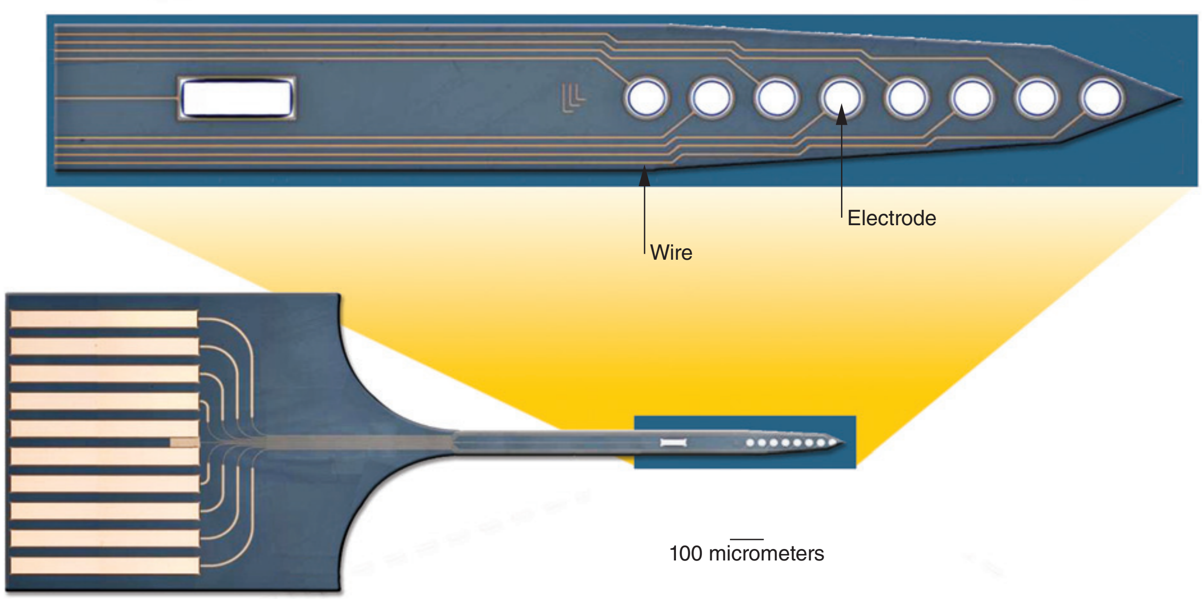


A biocompatible ceramic disk such as the one shown here protects the electronics package for a neural implant from the harsh environment of the body.

Implants under Development

The next application of the neural interface will be an implant to provide bladder control for people with spinal cord injury. This device, which is being developed with funding from the University of California Office of the President, will stimulate nerves in the bladder to contract the appropriate muscles. The system will have about 10 times the number of electrodes in an electronics package 10 times smaller than any previous system. Researchers at the University of California at Santa Cruz are collaborating with the Livermore team to design the wireless electronics. The Huntington Medical Research Institutes in Pasadena, California, will conduct animal trials with the new interface.

The Laboratory is also working with the National Institutes of Health to devise an improved auditory nerve implant. To implant

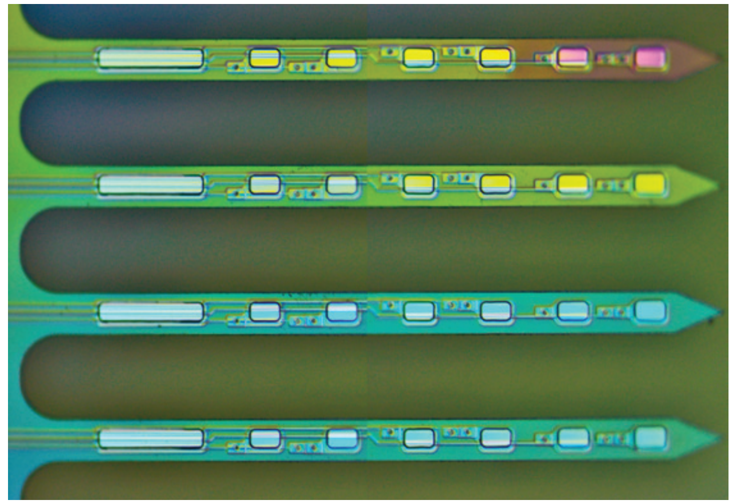


A thin-film electrode array uses complex electronics connections to stimulate and record neural signals.

the commercially available cochlear prosthetic, a surgeon must first remove a small part of a patient's skull and insert the device in the cochlea, a bony membrane inside the ear. The electronics device, however, is placed outside that membrane—not inside the human body—with nerve fibers lying on the opposite side of the bone. As a result, the electric signal's amplitude must be high enough to penetrate the bone and stimulate the neurons on the other side, which causes the current to spread and thus distorts the signal. The fidelity of the device is poor, making it difficult for patients to discern conversations in a noisy environment.

Livermore's auditory device will have hundreds of electrodes, compared with only 19 in the most advanced cochlear implant. "We are designing the implant to go into the auditory nerve directly," Pannu says. "The nerve is approximately 1.5 millimeters long, and we can put hundreds of electrodes along each nerve."

Pannu's team is also working on a Laboratory Directed Research and Development project to design a neural implant that can treat depression with deep brain stimulation. Not only will the device record and stimulate brain signals, but it will also use microfluidic channels for drug delivery.



This multipronged thin-film electrode array records and stimulates brain signals. The device offers a wide range of treatment applications, from Parkinson's disease to seizures or depression.

Offering Hope for Future Treatments

According to Pannu, implants such as the bladder-control device are but a first step toward more advanced technologies. For example, peripheral nerve interfaces could someday give amputees fine motor control over artificial limbs. "Designing such devices is only a matter of adding complexity," he says. The most advanced technologies available today allow people who have lost an arm, for instance, to control a robotic limb by twitching muscles in their chest—a motion that is very unnatural. "What they really need is a peripheral nerve interface," Pannu says, pointing to a video of a veteran who lost her arm in Iraq. "For her, the nervous system is intact except for where the arm was severed. The peripheral nervous system is there; the neurons are there; the brain is sending all the signals. What we need to do is place a microelectrode array in the peripheral nerves to pick up and decode the signal that tells the fingers to move."

Another potential application is to adapt the recording mechanism in electrode arrays to enhance the performance of brain implants for Parkinson's patients. Existing implants are the equivalent of white noise generators for the brain, shocking the brain at all times to prevent occasional seizures. The proposed device would instead monitor electric signals in the hippocampus and pick up abnormal activity to disrupt a seizure before it happens. The highly sensitive device could also track chemical signals, an important feature for brain activity involving neurotransmitters.

This entire field of interfacing human-made devices with neural tissue is still in its infancy. Implementing many of the new technologies will take at least 20 years, Pannu estimates, given the long process of finding research partners and running clinical trials. Scientists will continue to work on better understanding how neural stimulation affects different parts of the body so they can fine-tune the implants for increasingly complex situations. But judging by the progress made since the artificial retina was developed, the possibilities for progress appear to be endless.

"We really believe in the technology," says Tolosa, who is working on the deep brain stimulation project. "We've already seen what it can do in a short period of time, and we think the potential applications on the horizon are not just far-off dreams. We can make them happen provided we have the resources to support this work."

Until then, the researchers take great satisfaction from knowing they are making a difference in people's lives, and—perhaps even more importantly—they are giving many patients a precious gift: hope. "We get e-mails from parents whose children have retinitis pigmentosa," Pannu says. "They know their kids will go blind because no therapies are available to help them. They're desperate. The artificial retina offers hope that there will be a better future for their children."

—Monica Friedlander

Key Words: artificial retina, Center for Micro- and Nanotechnologies, cochlear implant, microelectrode array, neural implant, Parkinson's disease, retinitis pigmentosa.

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Incubator Busy Growing Energy Technologies

LAWRENCE Livermore has selected six projects in which Laboratory researchers will work with an industrial partner to advance innovative energy technologies using high-performance computing (HPC). The collaborations, announced in March 2012, will involve GE Energy Consulting; GE Global Research; ISO New England; Potter Drilling, Inc.; Robert Bosch, LLC; and United Technologies Research Center.

The six projects are part of the hpc4energy incubator, a pilot program designed to leverage HPC resources to shorten the time needed for developing and deploying solutions for urgent energy-related problems. "We aim to establish a model for energy technology innovation by bringing together the computational expertise of the national labs with the specialized knowledge of energy-industry companies to tackle real problems these firms face daily," says Laboratory deputy director Tomás Díaz de la Rubia.

The hpc4energy incubator emerged from the 2011 National Summit on Advancing Clean Energy Technologies, which was sponsored by the Howard Baker Forum, the Bipartisan Policy Center, Lawrence Livermore, and others. In October, the Laboratory sought proposals addressing the critical areas outlined in the summit's report: energy-efficient buildings; carbon capture, utilization, and sequestration; liquid-fuels combustion; nuclear energy; and smart grid, power storage, and renewable energy integration. To be considered, proposals had to address a compelling problem whose solution could be achieved through collaborations that combined HPC resources with the expertise available in industry, energy, and computer science. The following sections highlight the winning projects.

Simulating Complex Power Systems

Planning tools used to simulate electric power systems must now consider networks far larger and more complex than those envisioned just a few years ago, and models must include renewable-energy technologies and pervasive control mechanisms. As a result, planning engineers must incorporate an increasing number of scenarios that represent networks in greater detail—models that demand HPC resources. A Livermore collaboration with GE Energy Consulting will deploy GE Concorda PSLF software on an HPC system to significantly reduce the time required for performing contingency analysis.

Improved Analysis of Fuel-Injector Designs

Stringent emission requirements and increased emphasis on reducing fuel consumption have forced automotive and aviation manufacturers to seek new engine technologies and components that must follow an intensive design optimization cycle. In addition, researchers need more detailed information on the spray breakup that occurs during combustion in fuel-injection engines, including statistics such as drop size distribution, penetration, spray cone angles, and spreading rates. The collaboration between GE Global Research and Livermore is demonstrating that virtual prototyping using HPC can reduce the number of design cycles and thus the cost and time to market for new fuel-injector technologies.

System Reliability Gets a Boost

Ensuring the reliability of a region's electric power system is a critical responsibility for ISO New England. Although renewable resources can provide low-emission energy, the variability and uncertainty of these resources pose challenges for reliable power generation and transmission. In this project, a team from ISO New England is tapping Livermore's HPC expertise to enhance operating procedures for the region's electric power system and to develop effective risk-management methods that incorporate renewable energy resources.

Drilling Down to the Details

The thermal spallation drilling systems developed by Potter Drilling, Inc., rely on the thermal expansion of a superheated liquid to eject earth particles and thus drill boreholes more efficiently. These systems can increase well performance while reducing drilling costs and investment risk. However, much of the knowledge surrounding thermal spallation drilling is empirical, making system design and optimization difficult. By leveraging Livermore's HPC capability, together with its GEODYN and PSUADE codes, Potter Drilling can examine the thermal spallation process in much greater detail than it could with its own computational resources.

Reduced Emissions and Fuel Consumption

Promising developments such as hybrid fuel systems and advanced batteries for electric vehicles are increasing the use of electric power trains. Nevertheless, liquid-fueled internal combustion engines are expected to remain the mainstream power source of vehicles for the coming decades. As a result, optimizing these engines is the quickest way to reduce national energy consumption while lowering emissions. Engineers from Robert Bosch, LLC, and Livermore experts in multiscale modeling are conducting simulations to better understand the physical processes occurring in advanced combustion engines.

A New Look at Building Efficiency

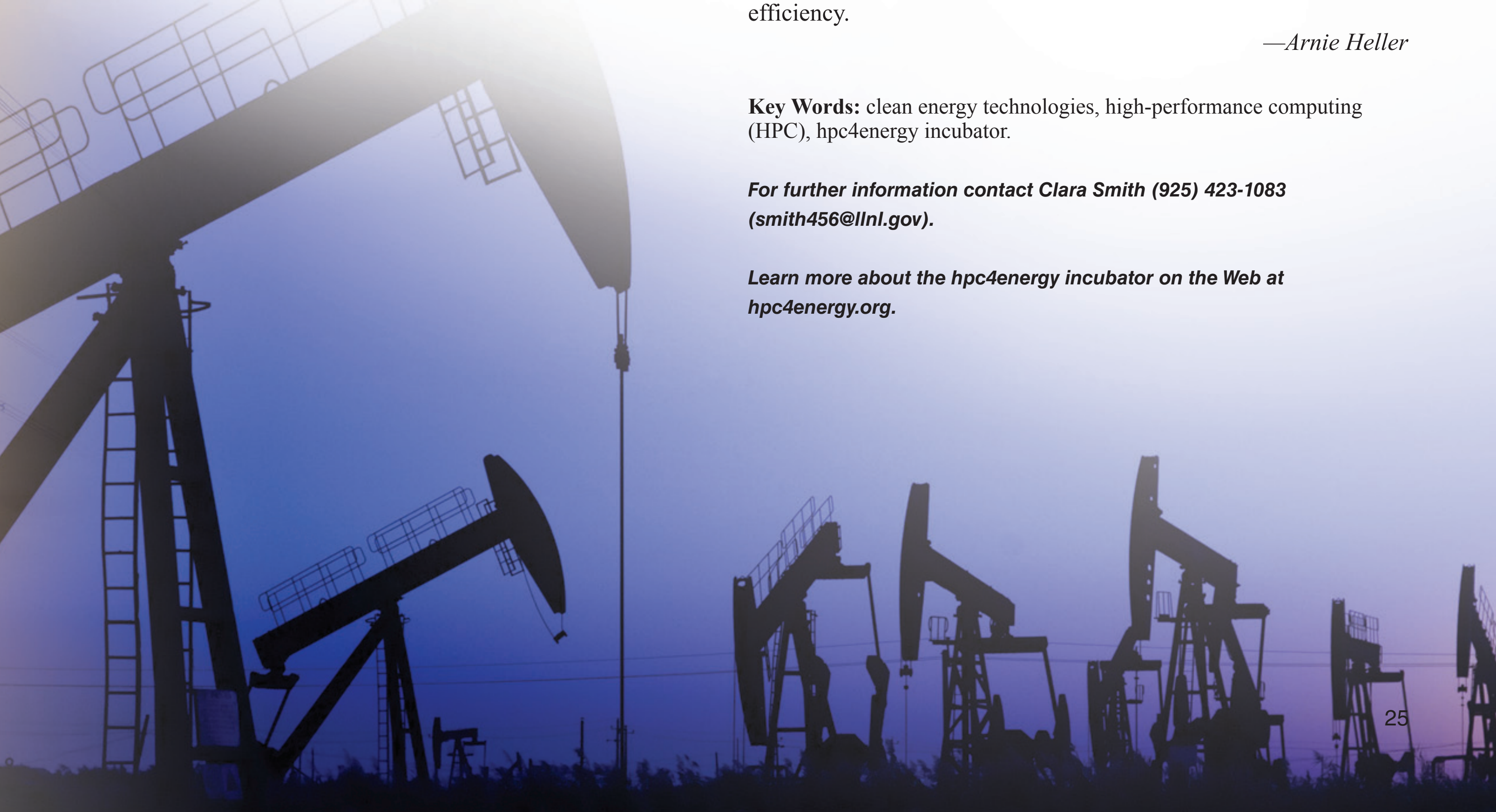
Commercial and residential buildings consume more than 40 percent of U.S. energy. In fact, a building's energy usage may be up to 30 percent greater than predicted in the original design because of uncertainties in the parameters used to estimate energy consumption. A significant barrier to adopting energy-efficient technologies in new building construction is the lack of tools to quantify uncertainty in the design and delivery process. United Technologies Research Center is using Livermore's computational resources to improve methods for analyzing a building's energy efficiency.

—Arnie Heller

Key Words: clean energy technologies, high-performance computing (HPC), hpc4energy incubator.

For further information contact Clara Smith (925) 423-1083 (smith456@llnl.gov).

Learn more about the hpc4energy incubator on the Web at hpc4energy.org.



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

Staged Combustion with Piston Engine and Turbine Engine Supercharger

Larry E. Fischer, Brian L. Anderson, Kevin C. O'Brien
U.S. Patent RE42,875 E
November 1, 2011
This combustion engine increases fuel efficiency and reduces polluting exhaust emissions by burning fuel in a two-stage combustion system. In the first stage, fuel is combusted in a piston engine, producing piston engine exhaust gases. Fuel contained in these exhaust gases is combusted in a turbine engine in the second stage. Turbine engine exhaust gases are used to supercharge the piston engine.

Process for Preparing Energetic Materials

Randall L. Simpson, Ronald S. Lee, Thomas M. Tillotson, Lawrence W. Hrubesh, Rosalind W. Swansiger, Glenn A. Fox
U.S. Patent 8,075,716 B1
December 13, 2011
Solgel chemistry is used to prepare energetic materials (explosives, propellants, and pyrotechnics) so that the materials have improved homogeneity, can be cast to near-net shape, or can be made into precision molding powders. The solgel method is a synthetic chemical process whereby reactive monomers are mixed into a solution. The resulting polymerization leads to a highly cross-linked, three-dimensional solid network that forms a gel. Energetic materials can be incorporated during solution formation or the gel stage of the process. The composition, pore size, primary particle size, gel time, surface area, and density may be tailored and controlled by the solution chemistry. The gel is then dried using supercritical extraction to produce a highly porous, low-density aerogel or by controlled slow evaporation to produce a xerogel. Applying stress during the extraction phase can result in high-density materials. Thus, the solgel method can be used in precision detonator explosive manufacturing and in the production of precision explosives, propellants, pyrotechnics, and high-power composite energetic materials.

Confinement of Hydrogen at High Pressure in Carbon Nanotubes

David H. Lassila, Brian P. Bonner
U.S. Patent 8,076,034 B1
December 13, 2011
In this apparatus, carbon nanotubes capped with a hydrogen-permeable membrane at one or both ends enable the high-pressure confinement and release of hydrogen. One setup uses an array of multiwalled carbon nanotubes, each with first and second ends. The second ends are capped with palladium to enable the high-pressure confinement and release of hydrogen as a function of palladium temperature. The nanotube array can store hydrogen gas at a pressure of at least 1 gigapascal for more than 24 hours. Additional apparatuses and methods are presented.

Method and System for Detecting Polygon Boundaries of Structures in Images as Particle Tracks through Fields of Corners and Pixel Gradients

David W. Paglieroni, Siddharth Manay
U.S. Patent 8,081,798 B2
December 20, 2011
This stochastic system can locate polygon structures in images by detecting a set of best-matching corners with predetermined acuteness for a polygon model. The system uses a set of similarity scores based on the gradient direction-matching features of corners, and it tracks polygon boundaries as particle tracks using a sequential Monte Carlo approach. Polygon boundary tracking is initialized by selecting pairs of corners from the set of best-matching corners to define a first side of a corresponding polygon boundary. The system then uses a particle filter to track all intermediate sides of the polygon boundaries. Boundary tracking terminates when the system determines the last side of tracked boundaries to close the polygon. The particle tracks are then blended to determine polygon matches, which may be used for ranking and inspection.

Multi-Well Sample Plate Cover Penetration System

Neil Reginald Beer
U.S. Patent 8,084,005 B2
December 27, 2011
This apparatus is designed to penetrate the cover over a multiwell sample plate containing at least one individual well. The device includes a cutting head, a cutter, and a robot. The robot moves the cutting head and cutter in a way that allows the cutter to penetrate the cover over the multiwell sample plate, providing access to the individual sample well. When the cutting head is moved downward, the cutter pierces the foil, splitting and folding it inward toward the well. The well is then open for sample aspiration but is protected from cross contamination.

Swelling-Resistant Nuclear Fuel

Athanasios Arsenlis, Joe Satcher, Jr., Sergei O. Kucheyev
U.S. Patent 8,085,894 B2
December 27, 2011
In one setup, a nuclear fuel includes an assembly of nuclear fuel particles. Continuous open channels defined between at least some of the particles allow fission gases produced inside the assembly to escape without causing the assembly to swell significantly. Additional designs and methods are presented.

Metallic Nanospheres Embedded in Nanowires Initiated on Nanostructures and Methods for Synthesis Thereof

Saleem Zaidi, Joseph W. Tringe, Ganesh Vanamu, Rajiv Prinja
U.S. Patent 8,093,474 B2
January 10, 2012
In this nanostructure, a nanowire is formed of metallic spheres that have at least one of a uniform diameter or a uniform spacing between them. In another embodiment, a substrate includes an area with a nanofeature. A nanowire extending from this feature has metallic spheres with at least one of a uniform diameter or a uniform spacing between them. Methods are also presented for forming a nanostructure, reading and writing data, and preparing nanoparticles.

Detection of Contamination of Municipal Water Distribution Systems

John F. Cooper
U.S. Patent 8,097,212 B2
January 17, 2012
This system detects contaminants in fluid flowing through a conduit in a fluid-distribution system. A chemical or biological sensor array connected to the conduit produces an acoustic signal burst when it detects contaminants. A supervisory control system then signals the fluid-distribution system that contaminants are present.

Preparation of Membranes Using Solvent-Less Vapor Deposition Followed by In-Situ Polymerization

Kevin C. O'Brien, Stephan A. Letts, Christopher M. Spadaccini, Jeffrey C. Morse, Steven R. Buckley, Larry E. Fischer, Keith B. Wilson
U.S. Patent 8,101,023 B2
January 24, 2012
A system for fabricating a composite membrane from a membrane substrate uses solventless vapor deposition followed by in situ polymerization. Two monomers are directed into a mixing chamber and are mixed to provide a first and second monomer. A solventless vapor-deposition process then deposits the two mixed monomers onto the membrane substrate in the deposition chamber. The membrane substrate and the mixed monomers are heated to produce in situ polymerization and provide the composite membrane.

Carbon Fuel Particles Used in Direct Carbon Conversion Fuel Cells

John F. Cooper, Nerine Cherepy
U.S. Patent 8,101,305 B2
January 24, 2012
In this system, carbon particles are finely divided and introduced into a fuel cell along with a gas that contains oxygen. The finely divided particles are exposed to either carbonate salts; molten sodium hydroxide, potassium hydroxide, lithium hydroxide, or mixtures of the three; mixed hydroxides; or alkali and alkaline earth nitrates.

Isotopic Response with Small Scintillator Based Gamma-Ray Spectrometers

Norman W. Madden, Frederick S. Goulding, Stephen J. Asztalos
U.S. Patent 8,101,919 B2
January 24, 2012
The intrinsic background of a gamma-ray spectrometer is significantly reduced by surrounding the scintillator with a second (external) scintillator. The opening of the second scintillator is approximately the same diameter as the smaller central scintillator in the forward direction. The second scintillator has a higher atomic number and thus a larger probability for a Compton-scattering interaction than within the inner region. Scattering events that are essentially simultaneous in coincidence to the first and second scintillators, from an electronics perspective, are precluded electronically from the data stream. Thus, only gamma rays that are wholly contained in the smaller central scintillator are used for analytic purposes.

Multi-Pulse Frequency Shifted (MPFS) Multiple Access Modulation for Ultra Wideband

Faranak Nekoogar, Farid U. Dowla
U.S. Patent 8,102,955 B2
January 24, 2012
The multipulse, frequency-shifted technique uses mutually orthogonal short pulses to transmit and receive information in an ultrawideband communication system with multiple users. The system uses the same pulse shape with different frequencies for the reference and data for each user. Different users have a different pulse shape (mutually orthogonal to each other) and different transmit and reference frequencies. At the receiver, the frequency of the reference pulse is shifted to match the data pulse. A correlation scheme followed by a hard decision block detects the data.

Contact Stress Sensor

Jack Kotovsky
U.S. Patent 8,109,149 B2
February 7, 2012
This contact stress sensor has one or more microelectromechanical-system-fabricated sensor elements, each of which includes a thin, nonrecessed portion and a recessed portion with a pressure-sensitive element adjacent to it. An electric circuit connected to the pressure-sensitive element has a thermal compensator and a pressure signal circuit configured to provide a signal when the pressure-sensitive element moves.

Methods for Increasing the Sensitivity of Gamma-Ray Imagers

Lucian Mihailescu, Kai M. Vetter, Daniel H. Chivers
U.S. Patent 8,110,810 B2
February 7, 2012
These methods increase the position resolution and granularity of double-sided segmented semiconductor detectors. They thus increase the imaging resolution of detectors used as Compton cameras or as position-sensitive radiation detectors in spatial- or temporal-modulated imagers, including devices that use single-photon emission computed tomography, positron emission tomography, coded aperture, and multiple pinholes.

Large Dynamic Range Radiation Detector and Methods Thereof

Roscoe E. Marrs, Norman W. Madden
U.S. Patent 8,115,178 B2
February 14, 2012
This radiation detector has a photodiode optically coupled to a scintillator and a bias voltage source electrically coupled to the photodiode. A first detector electrically coupled to the photodiode generates a signal that indicates the level of the charge output by the photodiode. A second detector electrically coupled to the bias voltage source generates a signal that indicates the amount of current flowing through the photodiode.

System of Fabricating a Flexible Electrode Array

Peter Krulevitch, Dennis L. Polla, Mariam N. Maghribi, Julie Hamilton, Mark S. Humayun, James D. Weiland
U.S. Patent 8,122,596 B2
February 28, 2012
In this artificial vision system, an image is captured or otherwise converted into a signal that is transmitted to the retina using an implant. The implant has a polymer substrate made of a compliant material such as poly(dimethylsiloxane), or PDMS, allowing the substrate to conform to the retina's shape. Electrodes and conductive leads embedded in the substrate transmit signals representing the image to the retina, and these signals then stimulate the retinal cells.

Optically-Initiated Silicon Carbide High Voltage Switch

George J. Caporaso, Stephen E. Sampayan, James S. Sullivan, David M. Sanders
U.S. Patent 8,125,089 B2
February 28, 2012
An improved photoconductive switch is made of a silicon carbide or other wide-bandgap substrate material, such as gallium arsenide. Field-grading liners composed of preferably silicon nitride are formed on the substrate adjacent to the electrode or substrate perimeters for grading the electric fields.

Awards

Troy Barbee, a materials scientist in the Laboratory's Physical and Life Sciences Directorate, received the **Alan Berman Research Publication Award** from the **Naval Research Laboratory** (NRL) for his work in collaboration with the NRL X-Ray Astronomy Program and the University of Leicester to examine the makeup of a white dwarf. The paper resulting from this study reports on the first high-resolution spectroscopic observation of the binary DA white dwarf Feige 24 in the extreme-ultraviolet band.

Barbee used the multilayer coated gratings developed at the Laboratory for the team's experiments. The study's results indicate that helium is almost completely lacking in Feige 24, contrary to the makeup predicted by standard models of stellar atmosphere evolution. These findings allowed scientists to gain insight into stellar evolution by looking at the structure of Feige 24.

Livermore chemist **Dawn Shaughnessy** is one of 11 women inducted into the **Alameda County Women's Hall of Fame for 2012**. A group leader for experimental nuclear and radiochemistry in the Physical and Life Sciences Directorate, Shaughnessy leads a research collaboration involving scientists from Lawrence Livermore and the Russian Joint Institute for Nuclear Research. To date, this team has discovered six new elements (113–118) on the periodic table. The Women's Hall of Fame recognized Shaughnessy for her work in science.

The **National Nuclear Security Administration** (NNSA) honored **Sidney Drell** with its highest award, the **NNSA Administrator's Gold Medal of Excellence for Distinguished Service**. NNSA Administrator Thomas D'Agostino presented the award to Drell in recognition of his many years of exceptional contributions to Los Alamos and Lawrence Livermore national laboratories, NNSA, the Department of Energy, and the nation.

Drell is a member of the Board of Governors for Los Alamos National Security, LLC, and Lawrence Livermore National Security, LLC—the managing contractors for both laboratories. He also is a senior fellow at the Hoover Institution and a professor of theoretical physics (emeritus) at SLAC National Accelerator Laboratory, where he served as deputy director until retiring in 1998. In addition, Drell is a founding member of JASON, a group of academic scientists who consult for the government on issues of national importance, and has served as an adviser to the executive and legislative branches of government on issues involving national security and defense.

Abstract

Seeking Clues to Climate Change

The climate change conundrum facing the nation and the world is of vital importance to present and future generations. Climate scientists in Lawrence Livermore's Program for Climate Model Diagnosis and Intercomparison (PCMDI) are working with colleagues worldwide, wrestling with the challenges and ramifications of global warming. In comparing historical and present-day climate data with results from computer simulations, PCMDI scientists are providing insights into why the climate has changed and how it might change in the future. One project is developing a cloud simulation code that mimics the observational process of satellites, helping researchers better evaluate whether climate models correctly simulate clouds. Other efforts are extending climate modeling from global to regional scales so researchers can examine the forces behind shrinking snowpacks in western U.S. mountain ranges and the effects of warmer climate and increased shrub growth in the sub-Arctic boreal regions. Yet another Livermore-led effort investigates whether the results from climate simulations of atmospheric moisture content depend on what model is used.

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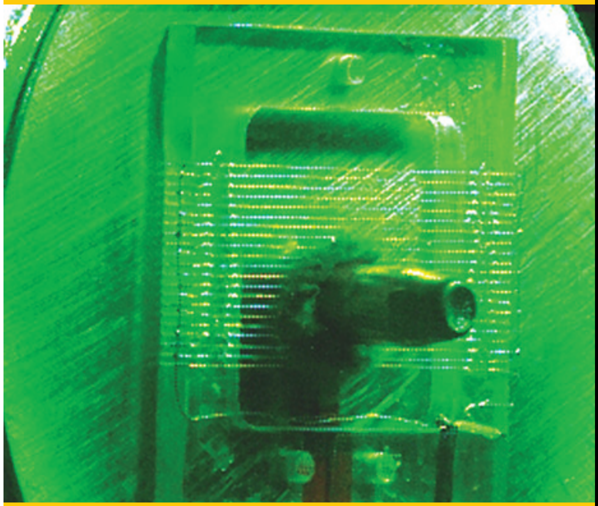
Coming Next Issue

A Home for Energetic Materials and Their Experts



Livermore's Energetic Materials Center is advancing scientific understanding of high explosives.

Also in July/August

• Direct spectroscopy of exoplanets reveals their molecular features and enables researchers to determine the planets' atmospheric makeup.

• Advanced microseismic analysis techniques developed at Livermore will shed light on what happens beneath Earth's surface, where hot rock can serve as an energy source.

• The Education Assistance Program gets "full marks" for helping Laboratory employees stay current in a variety of rapidly changing fields, from computer science to organizational management.

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