Science & Technology Review

September 2005

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Spheromak Plasma Heats Up

Also in this issue:

- **The World's Most Famous Equation**
- **Analytic Solutions Help Verify Codes**
- **Explaining a Mysterious Astronomical Feature**

World Year of PHYSICS 2005

About the Cover

For several decades, Laboratory researchers have been examining both magnetic and inertial confinement methods for generating fusion energy. As the article beginning on p. 4 describes, the magnetized plasmas of Livermore's Sustained Spheromak Physics Experiment (SSPX) represent one possible route to a source of abundant, inexpensive, and environmentally benign energy. Shown on the cover is a high-speed photograph of a spheromak plasma forming inside SSPX.

Cover design: Amy Henke

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on ensuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Prepared by LLNL under Contract No. W-7405-Eng-48

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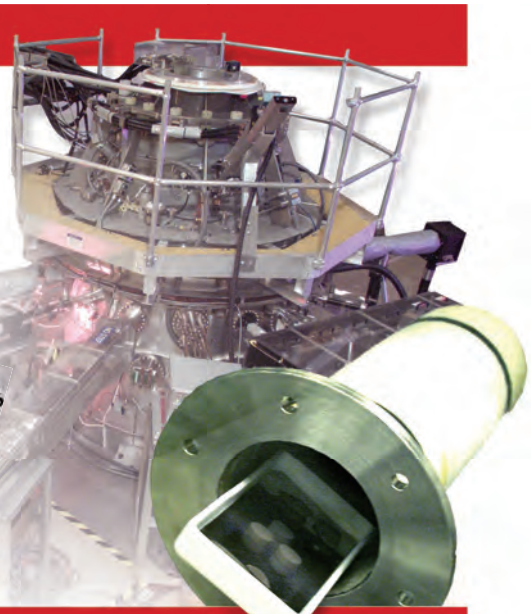

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S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Policy, Planning, and Special Studies.

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

Printed in the United States of America

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

UCRL-TR-52000-05-9
Distribution Category UC-99
September 2005

Lab garners four R&D 100 Awards

Livermore researchers turned in a strong showing in the annual R&D 100 awards competition for top industrial inventions, winning four awards. Each year, *R&D Magazine* presents these awards to the top 100 industrial, high-technology inventions submitted to its competition for outstanding achievements in research and development.

The four Livermore inventions honored are as follows:

• Biological Aerosol Mass Spectrometry system, which is an instrument that can analyze individual aerosol particles in real time and at high rates to almost instantly identify the presence and concentration of harmful biological particles in air samples.

• Adaptable Radiation Area Monitor, which could play an important role in protecting the nation from radiological or nuclear attack. The highly sensitive system uses a thalium-doped sodium iodide crystal to detect small amounts of nuclear material in a number of different applications. Livermore researchers and Innovative Survivability Technologies of Goleta, California, share this R&D 100 Award.

• NanoFoil®, which is a nanoengineered heat source that heats only the interface being joined and permits large and small components to be metallically bonded with no thermal damage. NanoFoil is sold by Reactive NanoTechnologies of Hunt Valley, Maryland, for a variety of commercial applications. Reactive NanoTechnologies shares this award with Livermore researchers and Johns Hopkins University.

• VisIt, which is a visualization tool for the parallel processing of large amounts of data, including simulations comprising trillions of bytes of data. To date, 4,000 users from throughout the world have downloaded this free, interactive tool.

S&TR's October issue will feature detailed reports on these award-wining inventions and the teams that created them.

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New bioinformatics method for analyzing DNA

Scientists at Lawrence Livermore and the Linnaeus Centre for Bioinformatics at Uppsala University in Sweden have developed a new bioinformatics technique for systematically analyzing key regions in DNA that help control gene activity.

Understanding the complex regulatory mechanisms that tell genes when to switch on and off is one of the toughest challenges facing researchers attempting to discover how life works. Binding sites, or areas of DNA that interact with proteins to help control gene expression, can be a long distance on the DNA strand from the genes they influence. In addition, gene expression can be controlled by several regulatory proteins working together at a combination of different binding sites. These regulatory proteins are known as transcription factors. Transcription is the first step in the process by which the genetic information in DNA is decoded by the cell to manufacture proteins, the building blocks of life.

The project's goal was to deduce how many transcription factors at a time, or combinations of factors, are coming together physically and how these combinations regulate genes. The researchers mathematically modeled general rules that could associate known binding sites and gene expression in yeast, which is one of the most widely studied organisms. "The next step," says Krzysztof Fidelis, a computational biologist in Livermore's Biosciences Directorate, "is to test this approach on different organisms, including microbes and vertebrates."

Other institutions collaborating on the project were Warsaw University in Poland and the Polish Academy of Sciences. A report on the joint work appears in the June 2005 issue of *Genome Research*. Primary funding for the research was provided by Livermore's Laboratory Directed Research and Development Program, the Knut and Alice Wallenberg Foundation, and the Swedish Foundation for Strategic Research.

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Trigger for rare bone disease found

A research team from Lawrence Livermore and Lawrence Berkeley national laboratories, the Novartis Institutes for BioMedical Research in Switzerland, and the Department of Energy's (DOE's) Joint Genome Institute in Walnut Creek have tracked down the biological trigger that gives rise to Van Buchem disease. This hereditary, disfiguring bone disorder can cause blindness and deafness. In June 2005, the research team, led by Gabriela Loots of Livermore's Genome Biology Division, reported its findings in the online version of *Genome Research*.

The team found the culprit is a regulatory element in a missing 52,000-base-pair stretch of DNA. This segment of DNA normally directs the sclerostin, or SOST, gene to produce a protein that maintains control of bone formation rates. Without this regulator, bone production goes up, progressively increasing bone density, or osteosclerosis.

Noncoding DNA segments—long stretches of DNA that do not code for proteins and were once thought to have no biological function—are now being found to contain regions that play a key role in switching distant genes on and off. Loot's study is one of the first to pinpoint a disease-associated mutation that alters one of these long-range regulatory elements.

Continued on p. 27

Commentary by William H. Goldstein

The Pursuit of Fusion Energy

FUSION research has been an integral component of Lawrence Livermore's science and technology portfolio from the very beginning. In 2001, the Magnetic Fusion Energy and Inertial Fusion Energy programs were combined to form the Fusion Energy Program (FEP) in the Physics and Advanced Technologies Directorate. Researchers from this program have a long history of involvement in the exploration of magnetic fusion plasma confinement concepts. As described in the article beginning on p. 4, Livermore's Sustained Spheromak Physics Experiment (SSPX) is the latest of these concepts to be explored.

SSPX research is funded through the Department of Energy's (DOE's) Office of Fusion Energy Sciences to study the physics of plasma configurations with the potential to greatly affect future magnetic fusion energy development. SSPX research has led to more than 35 journal papers, including six in *Physical Review Letters*. SSPX researchers have been invited to present their work at national and international fusion conferences. Recently, Livermore joined with the University of Wisconsin, the University of Chicago, and others to form the National Science Foundation's Frontier Science Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas. Through interactions with this center, SSPX experiments and theory contribute to our growing understanding of how some of the largest astrophysical objects form.

Scientists from Livermore's FEP are also conducting research on two other magnetic fusion experiments, the DIII-D tokamak at General Atomics in San Diego, California, and the National Spherical Torus Experiment at Princeton University's Plasma Physics Laboratory. Recently, an international agreement was signed to begin construction of the International Thermonuclear Experimental Reactor (ITER), a large tokamak designed to produce 500 megawatts of fusion power. Magnetic fusion researchers at the Laboratory have been participating in the ITER project since its inception. Livermore scientists working at DIII-D have led the effort to develop new methods for reducing the heat load on the walls of ITER and are developing plasma diagnostics that the U.S. will install on ITER once it is operational.

In parallel with joining the ITER construction project, the U.S. fusion energy community has initiated a new effort, the Fusion Simulation Project, to significantly improve capabilities for simulating tokamak fusion plasmas. Numerical simulation of a magnetically confined fusion plasma is a grand scientific challenge at the forefront of computational physics. The FEP's theory group, building on the success of a Laboratory Directed Research and Development project, recently won a DOE competition to begin work on the Fusion Simulation Project. Livermore scientists will focus on understanding how tokamak plasmas spontaneously form insulating surface layers where plasma temperatures drop from more than 40 million degrees to a few thousand over a distance of just a few centimeters.

Research on inertial fusion, in which the plasma is confined by laser-driven energy fields rather than by magnetic fields, is also moving forward in exciting new directions. Historically, Livermore has been involved in all aspects of inertial fusion energy research and development, including target physics, laser and heavy-ion drivers, and fusion chambers. To address key issues and developmental needs for inertial fusion energy, FEP personnel work closely with colleagues in the National Ignition Facility (NIF) Programs, Defense and Nuclear Technologies, and Engineering directorates as well as with researchers from other national laboratories, universities, and industry. Currently, the focus of this research is on laser-driven inertial fusion—part of a coordinated national effort known as the High Average Power Laser Program—and fast ignition, an alternative to conventional hot-spot ignition that has the potential for high target gain with less driver energy. In addition, Livermore participates in the national Heavy-Ion Fusion Program, which aims to achieve very intense beams for basic physics research, such as high-energy-density physics. These results will also benefit the heavy-ion approach to inertial fusion energy. All of these programs offer opportunities to explore physics and advanced technologies that are at the forefront of international efforts.

The pursuit of fusion energy is an endeavor rich in scientific and technological challenges, with the potential to yield tremendous benefits to energy security, economic competitiveness, and international stability. As such, fusion research has always been an attractive field for young, talented scientists and engineers. Many key science and engineering leaders at Livermore have been associated with magnetic fusion research and projects at some point in their careers. The prospect of lighting the fusion fire at NIF and ITER portends an exciting future for fusion research at Livermore.

■ William H. Goldstein is associate director of Physics and Advanced Technologies.

A Dynan

With a view to eventually generating fusion electricity, a Livermore team is exploring a type of matter with an internal magnetic dynamo.

CRANK up the electrical current, mix in a magnetic field, add a puff of hydrogen, and—if conditions are just right—you will have the kind of magnetized plasmas that the Sun and other celestial bodies are generating perpetually. Huge solar flares are magnetized plasmas that separate from the Sun and bombard the Earth and other planets with a magnetic field large enough to interfere with communication systems. The magnetized plasmas in Lawrence Livermore's Sustained Spheromak Physics Experiment (SSPX) are much smaller and far shorter lived than their celestial cousins, but the two varieties, nevertheless, share many of the same properties.

In both instances, fluctuating magnetic fields and plasma flows create a dynamo that keeps the ionized hydrogen plasma alive and confined in space. Magnetic fields pass through the flowing plasma and eventually touch one another and reconnect. When a reconnection occurs, it generates more plasma current and changes the direction of the magnetic fields to confine the plasma. This "self-organizing" dynamo is a physical state that the plasma forms naturally.

Magnetic reconnection is key for confining the plasma in space and sustaining it over time. In an experimental ion such as SSPX, an initial electrical is applied across two electrodes, ng a plasma linked by a seed etic field. Reconnection events ated by the plasma itself convert ed field into a much stronger etic field that shapes the plasma and prevents it from touching the walls of the spheromak's vessel.

The Laboratory's interest in creating such plasmas and learning how they function derives from Livermore's long history of exploring fusion energy as a source of electrical power. If a self-organizing plasma can be made hot enough and sustained for long enough to put out more energy than was required to create it, the plasma could prove to be a source of fusion energy. For several decades, researchers have been examining both magnetic and inertial confinement methods for generating fusion energy. The magnetized plasmas of Livermore's spheromak represent one possible route to a source of abundant, inexpensive, and environmentally benign energy. (See the box on p. 7.)

Now semiretired, physicist Bick Hooper was assistant associate director for Magnetic Fusion Energy in the mid-1990s when he participated in a review of data from Los Alamos National Laboratory's spheromak experiments conducted in the early 1980s. The reanalysis suggested the plasma's energy was confined up to 10 times better than originally calculated and that plasma confinement improved as the temperature increased. The reviewers theorized that as temperatures increase in the plasma, electrical resistance decreases and energy confinement improves, promoting the conditions for fusion. In light of this reanalysis, the scientific community and the Department of Energy (DOE) decided to pick up where the Los Alamos experiments had left off

The magnetized plasmas of Livermore's Sustained Spheromak Physics Experiment (SSPX) represent one possible route to a source of fusion energy.

SSPX was designed to determine the spheromak's potential to efficiently create hot fusion plasmas and hold the heat.

Early investment in research on spheromak plasmas by Livermore's Laboratory Directed Research and Development Program was instrumental in the decision to build SSPX at Livermore. (See *S&TR*, December 1999, pp. 18–20.) Since 1999, when SSPX was dedicated, a team led by physicist Dave Hill has boosted the plasma's electron temperature from 20 electronvolts to about 350 electronvolts, a record for a spheromak. "We're still a long way from having a viable fusion energy plant," acknowledges Hill. "For that, we would need to reach at least 10,000 electronvolts." However, conditions obtained to date are a significant step toward achieving fusion with a spheromak.

"The science of these plasmas is fascinating," says Hill. "Not only might they prove useful for producing fusion energy, but also their physics is essentially the same as the solar corona, interplanetary solar wind, and galactic magnetic fields. However, we still have much to learn about magnetized plasmas. For instance, we do not completely understand how magnetic dynamos work. We know that Earth's magnetic core operates as a dynamo, but scientists have barely begun to model it. Magnetic reconnection, essential for containing and sustaining the plasma, is another phenomena that is not well understood."

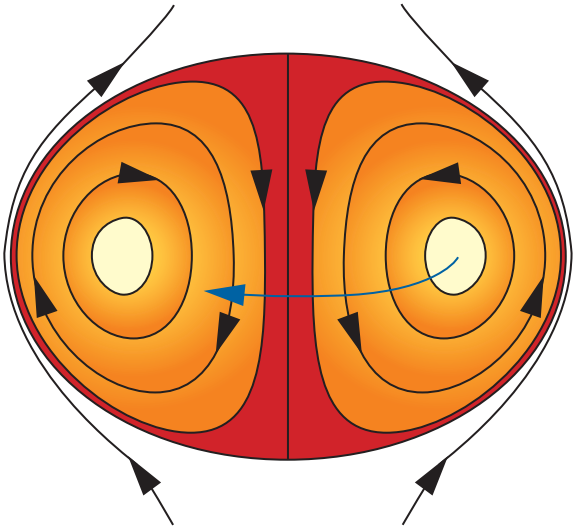
Livermore's spheromak research is aimed primarily at increasing the plasma's temperature and gaining a better understanding of the turbulent magnetic fields and their role in sustaining the plasma. "We need some turbulence to maintain the magnetic field, but too much turbulence kills the plasma," says Livermore physicist Harry McLean, who is responsible for diagnostics on SSPX. "It's a complicated balancing act."

Because scientists want to learn more about what is going on inside the fusion plasma and find ways to improve its behavior, experiments on SSPX are augmented by computational modeling using a code called NIMROD. The code was developed by scientists at Los Alamos, the University of Wisconsin at Madison (UWM), and Science Applications International Corporation. Results from SSPX experiments and NIMROD simulations show good agreement. However, NIMROD simulations are computationally intensive. Modeling just a few milliseconds of activity inside the spheromak can take a few months on a parallel supercomputing cluster.

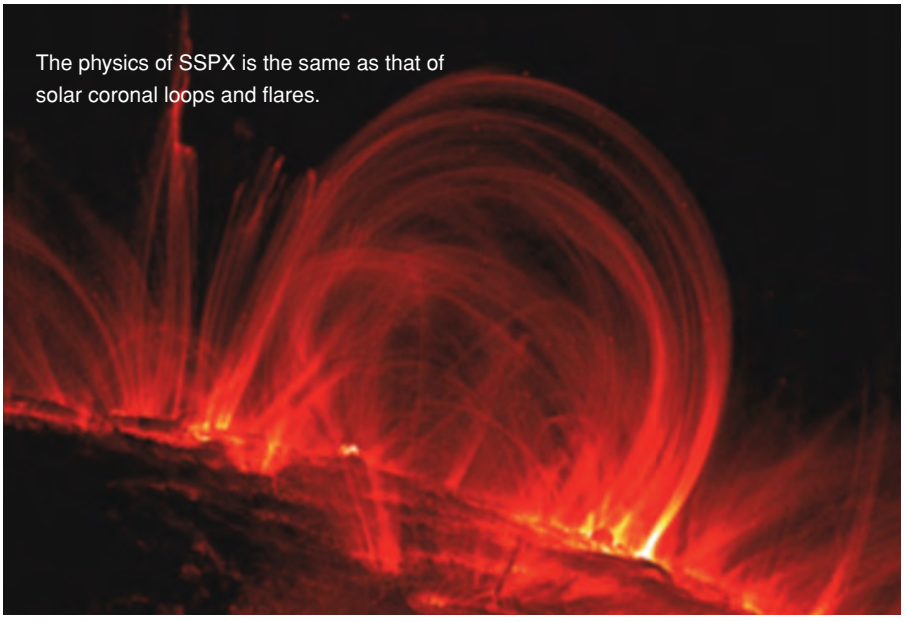
Collaborators in the SSPX venture include the California Institute of Technology (Caltech), UWM, Florida A&M University, University of Chicago, Swarthmore College, University of Washington, University of California at Berkeley, and General Atomics in San Diego, California. Through the university collaborations, an increasing number of students are working on SSPX and making important contributions. Livermore is also a participant in the National Science Foundation's (NSF's) Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas.

A Spheromak Up Close

When spheromak devices were first conceived in the early 1980s, their shape was in fact spherical. But now the vessel in which the plasma is generated, called a flux conserver, is cylindrical in shape.



Inside the SSPX's flux conserver, the hot plasma forms a doughnut shape called a torus.



The physics of SSPX is the same as that of solar coronal loops and flares.

Inside the flux conserver, the swirling magnetized, ionized hydrogen looks like a doughnut, a shape known as a torus.

Livermore physicist Reg Wood is operations manager for SSPX and managed the team that built the device in the late 1990s. Hooper and others were responsible for its design. According to Wood, "The design incorporates everything anyone knew about spheromaks when we started designing in 1997. The injector has a large diameter to maximize the electrode surface area. The shape of the flux conserver and the copper material used to form it were selected to maximize the conductivity of the walls surrounding the plasma. The vessel would be somewhat more effective if we had been able to build it with no holes. But we needed to be able to insert diagnostic devices for studying the plasma."

The earliest SSPX experiments in 1999 were not a success. "The first few yielded no plasma at all," says Wood. The electron temperature in the first plasma was just 20 electronvolts, but it has climbed steadily ever since.

Getting a spheromak plasma started requires a bank of capacitors to produce a high-voltage pulse inside a coaxial gun filled with a small seed magnetic field. Two megajoules of energy zap a puff of hydrogen, and a plasma then forms inside the gun with a now much larger magnetic field, called a helicity. A lower current pulse from a second capacitor bank helps to sustain the magnetic field.

As shown in the figure below, magnetic pressure drives the plasma and the magnetic field within it downward into the flux

The Promise of Fusion Energy

For 50 years, scientists worldwide have been striving to harness the energy source of the Sun and stars and use it to generate energy on Earth. On our Sun, hydrogen nuclei are continually fusing and, in the process, releasing enormous amounts of energy.

The nuclear power plants in use around the world today fission, or split, heavy atoms to release energy for electricity. A fusion power plant, on the other hand, will generate energy by fusing atoms of deuterium and tritium—two isotopes of hydrogen, the lightest element. Deuterium will be extracted from seawater, and tritium will be produced by the transmutation of lithium, a common element in soil.

A fusion power plant would produce no greenhouse gas emissions, operate in a continuous mode to meet demand, and produce lower levels of radioactive by-products than current fission power plants. A fusion power plant would also present no meltdown danger. Because nuclear fusion offers the potential for plentiful, safe, and environmentally benign energy, the Department of Energy (DOE) has made fusion a key element in the nation's long-term energy plans.

The Sustained Spheromak Physics Experiment (SSPX) at Livermore is part of a DOE program to study options for eventually producing power from magnetic fusion. Most research in magnetic fusion energy has centered on the doughnut-shaped tokamak. Livermore collaborates in experiments using the DIII-D tokamak at General Atomics in San Diego. Computational and experimental work there will have important implications for the performance of the International Thermonuclear Experimental Reactor, a major international tokamak project with significant U.S. participation.

SSPX is one of about 20 alternative concepts to the tokamak funded by DOE's Office of Fusion Energy Science through a program called Innovative Confinement Concepts. Experiments are being fielded at universities and national laboratories to study the spherical torus, the stellarator, and other self-organized mechanisms besides the spheromak. Livermore's SSPX is the largest experiment among these alternative concepts.

The plasma inside a spheromak is more complex and difficult to control than the plasma in a tokamak. If challenges can be overcome, a spheromak reactor offers several advantages over the tokamak for eventually generating electricity. The magnetic fields that confine the spheromak plasma are generated by currents flowing in the plasma itself rather than by the external magnet systems used for the tokamak. The tokamak's large, external magnetic coils are expensive and complex. If one coil needs repair, the entire unit must be taken offline. A spheromak reactor could be smaller than a comparable tokamak and would require far fewer magnets than a tokamak. A spheromak would be less costly to construct, less difficult and expensive to maintain, and could generate fusion energy at a lower cost.

Livermore collaborates on experiments being performed at the DIII-D tokamak at General Atomics in San Diego. The photograph shows an upper inside view of the tokamak.

conserver. As the plasma continues to expand further down into the vessel, magnetic fluctuations increase until magnetic field lines abruptly pinch off and reconnect.

When a magnetic reconnection event occurs, the magnetic field in the core disconnects from the incoming electrodes. Soon, the plasma's magnetic field is arranged in nested flux layers, some of which reconnect and close, while others closer to the wall of the vessel remain open. The overall magnetic field is nonuniform, more poloidal (parallel to the poles) at the outer edge and primarily toroidal (parallel to the equator) at the torus's closed core. The temperature is also nonuniform, hotter at the center and cooler at the walls. In this initial chaos, many small and large reconnection events occur until an equilibrium is reached. If the plasma and its confining magnetic field form a smooth, axisymmetric torus, a high-temperature, confined plasma can be sustained.

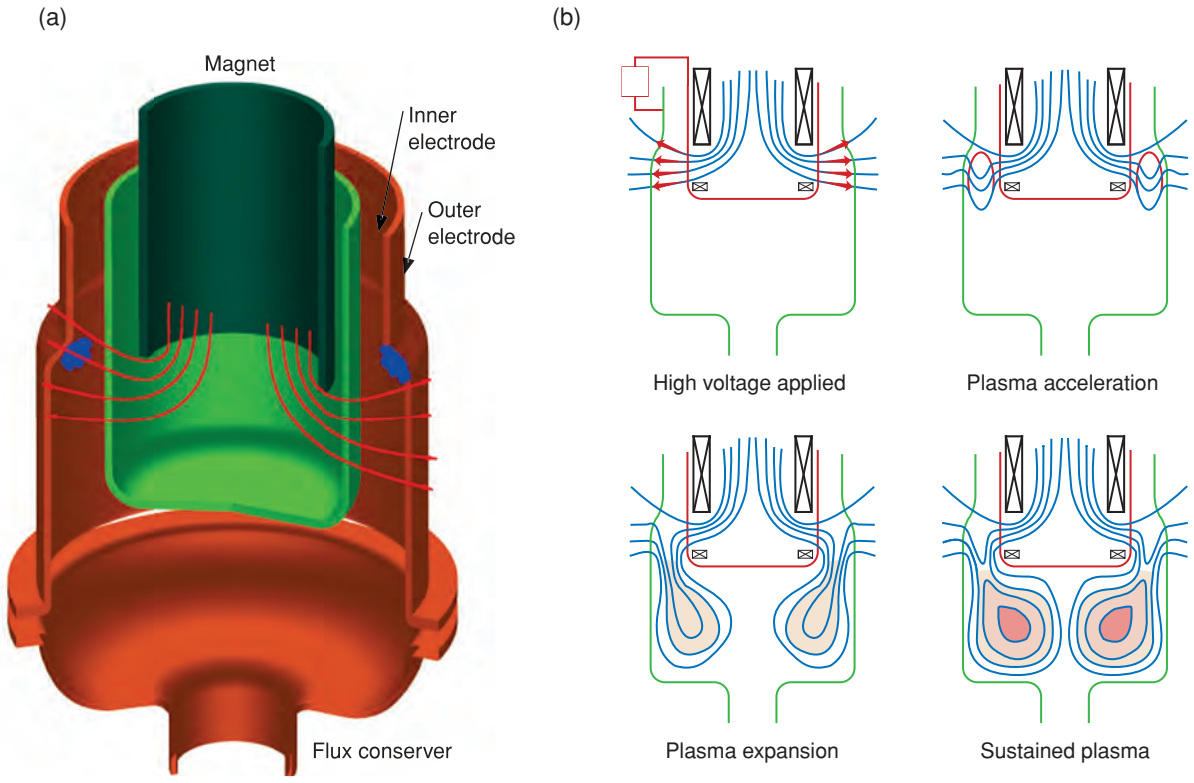
A certain amount of turbulence in the plasma's interacting magnetic fields is essential for the dynamo to sustain and confine the plasma. But magnetohydrodynamic instability can cause small fluctuations and islands in the magnetic fields, undercutting axisymmetry and lowering confinement and temperature. Controlling fluctuations is key. "We want a nice tight torus," says Hooper, "but if it is too tight, that is, it has too little fluctuation, electrical current can't get in. We want to hold in the existing energy and also allow in more current to sustain the magnetic fields." Even under the best conditions, plasmas in SSPX have lasted a maximum of 5 milliseconds.

The team pulses SSPX 30 to 50 times per day, usually three days a week, and each experiment produces an abundance of data. "Our ability to run experiments rapidly outstrips our ability to analyze the data," notes McLean.

Taking the Plasma's Measure

The plasma formed in a spheromak is highly sensitive to many kinds of perturbations. For example, if a diagnostic probe is inserted into the hot plasma, the probe's surface can be vaporized, which will introduce impurities and cause the plasma's temperature to drop. Another challenge is that the plasma's fast motion, high heat, and low emissivity can damage cameras and similar optical devices if they are mounted too closely. Therefore, few direct measurements are possible.

Most diagnostic devices are mounted at the median plane of the vacuum vessel housing the flux conserver, with ports allowing access into the flux conserver. Probes and magnetic loops at the outer wall of the flux conserver affect the plasma only minimally. Spectrometers look for light emission characteristic of impurities. Data from a series of devices that measure the magnetic fields around the plasma as well as the plasma's temperature and



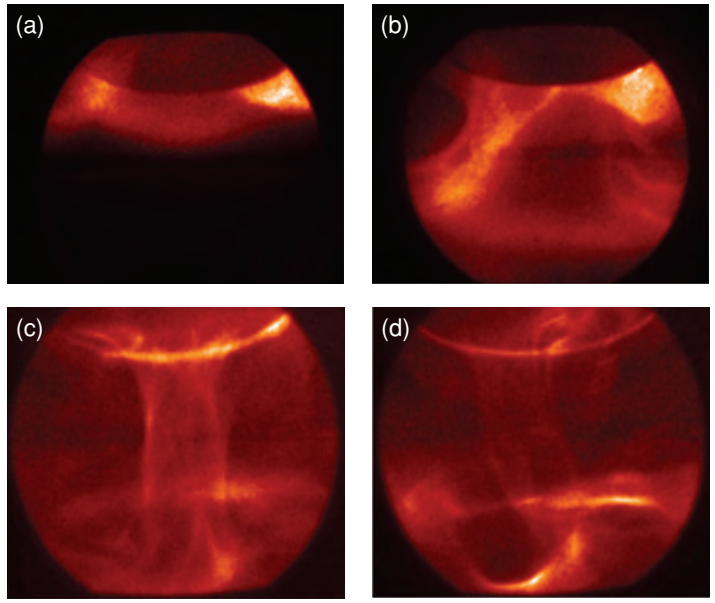
(a) An initial electrical pulse is applied across two electrodes (the inner and outer walls of the flux conserver), forming a plasma linked by a seed magnetic field. (b) In these cutaway views, the growing plasma expands downward into the flux conserver, which is a meter wide and a half meter tall. Magnetic reconnection events convert the seed magnetic field into a much stronger magnetic field that sustains and confines the plasma.

density are fed into CORSICA, a computer code that infers the plasma's internal electron temperature, electrical current, and magnetic fields. (See *S&TR*, May 1998, pp. 20–22.)

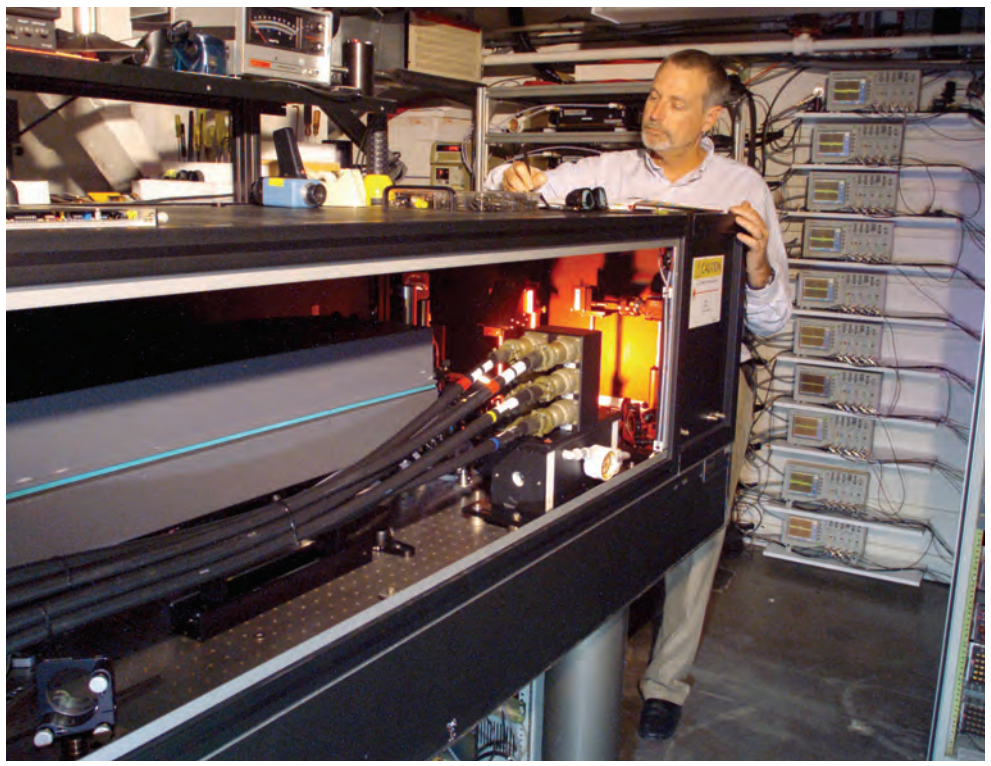
The primary diagnostic tool shines a laser beam through the plasma to scatter photons off electrons in the plasma—a process known as Thomson scattering. The scattered light is imaged at 10 spots across the plasma onto 10 optical fibers, which transport the light into polychrometer boxes commercially produced by General Atomics. Detecting the light's spread in wavelength provides temperature measurements from 2 to 2,000 electronvolts and is the best way yet to infer temperature with minimal disturbance to the plasma.

The SSPX team has hosted several graduate students whose doctoral research involved developing and applying diagnostics for the experiment. A University of Washington graduate student, Chris Holcomb, installed a novel diagnostic tool that shot a glass bullet through the plasma at 2 kilometers per second in an attempt to measure magnetic field profiles inside the plasma. "Although the instrument never produced the kind of data I wanted," says Holcomb, "the experience of developing an instrument for a fusion experiment was invaluable." Holcomb is now a Livermore postdoctoral fellow assigned to General Atomics, where he is designing diagnostics that ultimately will be used on the International Thermonuclear Experimental Reactor, an international project aiming to produce 500 megawatts of fusion power in a tokamak.

Carlos Romero-Talamás, a Livermore postdoctoral fellow since February, developed a way to insert the lens for a high-speed camera up close to the SSPX plasma as part of his Ph.D. thesis for Caltech. This camera, installed 3 years ago, offers the most direct images of the plasma. Three ports mounted at the vessel's median plane allow the camera to be moved to take wide-angle, 2-nanosecond images from different



A camera captures (false-color) images of the plasma forming inside the flux conserver. (a) The plasma begins to balloon out of the injector gun at about 35 microseconds and (b) reaches the bottom of the flux conserver at 40 microseconds. (c) A column forms at about 50 microseconds. (d) At 80 microseconds, the column bends, which researchers think may precede an amplification of the magnetic field.



Measurements of electron temperature and density are obtained using Thomson scattering. This 1-micrometer-wavelength pulsed laser sends photons into the plasma where they scatter off free electrons. Data from 10 spots across the plasma are collected in 10 polychrometer boxes behind physicist Harry McLean.

viewpoints. An intensifier increases the brightness of the images from the short exposures.

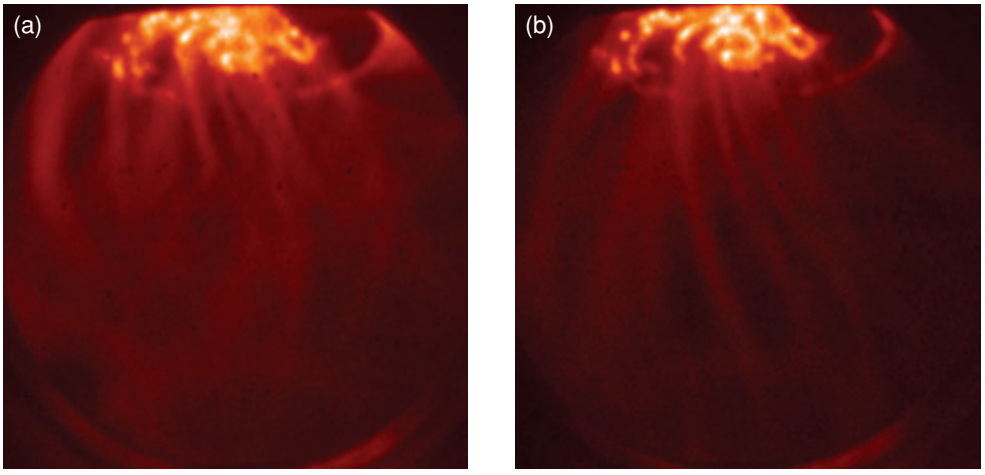
Images of the plasma during the first 100 microseconds of its lifetime show the central column in the torus forming and bending (see the sequence in the figure on p. 9). At 100 microseconds, the electrical current continues to increase, making the plasma highly ionized and too dim to see. "Unfortunately," says Romero-Talamás, "we can't see into the plasma as the column is 'going toroidal.' It's the most interesting part of the process."

As the current falls and is set to a constant value, the flux becomes more organized. The contrast improves, and images reveal a stable plasma column. Measurements of the column's diameter based on these images compare well with the magnetic structure computed by the CORSICA code. At about 3,800 microseconds, the column expands into a messy collection of filaments and then reorganizes itself by 3,900 microseconds. The team is unsure why this process occurs.

Measurements of local magnetic fields within the plasma are not available with existing diagnostics. But they are necessary to make better sense of some of the camera's images and to help determine when and where reconnection occurs. More magnetic field data may also show whether the bending of the plasma column precedes reconnection. A long, linear probe to measure local magnetic fields in the plasma was installed this summer. If the probe survives and does not perturb the plasma beyond acceptable levels, two more probes will be installed. The three probes together will provide a three-dimensional (3D) picture of changes in the torus's central column.

Help from Supercomputers

The design of a spheromak device is relatively simple, but the behavior of the plasma inside is exceedingly complex. Diagnostic data about the plasma are limited, and CORSICA calculations, although valuable, reveal a picture of the plasma that is restricted to be cylindrically symmetric. Obtaining dynamic 3D predictions is possible only with simulations using the most powerful supercomputers. In addition to an in-house cluster, the team also uses the supercomputing power of the National Energy Research Scientific Computing (NERSC) Center at Lawrence Berkeley National Laboratory.



Toward the end of the plasma's lifetime, its central column may become (a) a messy collection of filaments and then (b) reorganize itself. (Images are false color.)

Livermore physicists Bruce Cohen and Hooper, working closely with Carl Sovinec of UWM, one of the developers of NIMROD, are using NIMROD to simulate SSPX plasma behavior. They and their collaborators use simulations to better understand and improve energy and plasma confinement.

To date, the team has successfully simulated the magnetics of SSPX versus time. The differences between the experimental data and simulations are at most 25 percent and typically are much less. The team found no major qualitative differences in the compared results, suggesting that the resistive magnetohydrodynamic physics in the code is a good approximation of the actual physics in the experiment. More recently, with improvements in the code, they have been able to compute temperature histories that agree relatively well with specific SSPX data. Even so, because of the complexity of spheromak physics, NIMROD still cannot reproduce all the details of spheromak operation.

Cohen notes that, "Simulation results are tracking SSPX with increasing fidelity." The simulations are using more realistic parameters and improved representations of the experimental geometry, magnetic bias coils, and detailed time dependence of the current source driving the plasma gun. The latest simulations confirm that controlling magnetic fluctuations is key to obtaining high temperatures in the plasma.

Higher Temperatures on the Way

Now that the team has learned how to produce temperatures above 300 electronvolts, they can begin using SSPX experiments to examine magnetic reconnection in astrophysical objects. Livermore physicist Dmitri Ryutov, a theorist, notes that the relatively high temperatures and conductivities achieved recently in SSPX make its plasmas look enough like the magnetic plasmas of solar flares and sunspots for

this research to be possible. "Typically, laboratory experimental facilities do not achieve a high enough conductivity level," says Ryutov. "SSPX is one of the better experimental facilities for duplicating the conditions of astrophysical objects. However, SSPX must be able to produce even higher temperatures and conductivities than it does now."

SSPX is one of four experiments participating in the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas. The other three experiments are at UWM, Princeton Plasma Physics Laboratory, and Swarthmore College. Because scientists want to learn more about how magnetic structures on the Sun and elsewhere in the universe rearrange themselves and generate superhot plasmas, the experiments focus on various processes of magnetic self-organization: dynamo, magnetic reconnection, angular momentum transport, ion heating, magnetic chaos and transport, and magnetic helicity conservation and transport.

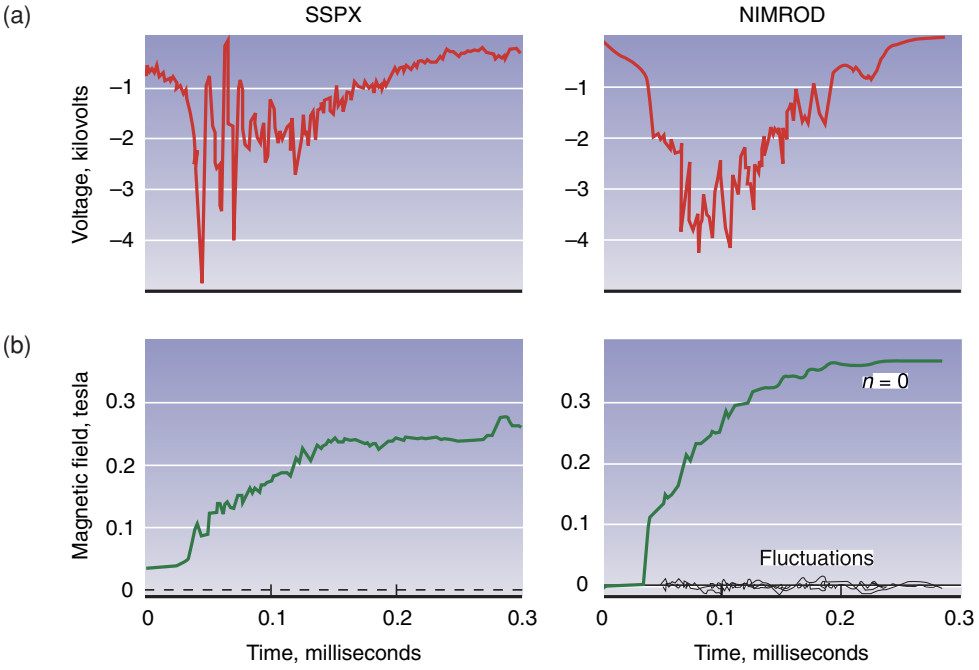
Ryutov is not alone in wanting SSPX to produce a higher temperature plasma. Anything closer to fusion temperatures is a move in the right direction. The Livermore team was able to make the leap from 200 to 350 electronvolts by learning how to optimize the electrical current that generates the magnetic fields. However, achieving still higher temperatures will require new hardware. Today, a larger power system that includes additional capacitor banks and solid-state switches is being installed. More current across the electrodes will increase the magnetic field, which will translate into a considerable increase in the plasma's temperature, perhaps as high as 500 electronvolts. The solid-state switches offer the additional benefit of doing away with the mercury in the switches now being used.

With the larger power source, the team can better examine several processes. They hope to understand the mechanisms that generate magnetic fields by helicity injection. They will explore starting up the spheromak using a smaller but steadier current pulse to gradually build the magnetic field. A higher seed magnetic field may improve spheromak operation. Data from both simulations and experiments also indicate that repeatedly pulsing the electrical current may help control fluctuations and sustain the plasma at higher magnetic fields.

The team hopes to add a beam of energetic neutral hydrogen particles to independently change the temperature of the plasma core. Besides adding to the total plasma heating power and increasing the peak plasma temperature, the beam would also allow the team to change the core's temperature without changing the magnetic field. The group will then have a way to discover the independent variables that control energy confinement and pressure limits.

Only by understanding the complex physics of spheromak plasmas can scientists know whether the spheromak is a viable path to fusion energy. The potential payoff—cheap, clean, abundant energy—makes the sometimes slow progress worthwhile. At the moment, the science occurring within a spheromak is well ahead of researchers' understanding. But this team is working hard to close that gap.

—Katie Walter



Time histories of data from an SSPX experiment (left column) and a NIMROD simulation (right column) show considerable similarity. Shown here are the (a) injector voltage and (b) poloidal magnetic field measured by a probe near the midplane of the flux conserver ($n = 0$ denotes the toroidally averaged edge magnetic field). These data are for the first 30 microseconds of a plasma's lifetime, the time during which a plasma is being formed.

Key Words: fusion energy, magnetic reconnection, NIMROD code, Sustained Spheromak Physics Experiment (SSPX).

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How One Equation

The world's most famous equation, $E = mc^2$, revolutionized physics, redefined strategic arms, and promises to transform our economy and environment with plentiful, clean energy.

IN many respects, Lawrence Livermore's national security and energy missions are part of—and a tribute to—Albert Einstein's legacy. A number of Livermore research projects are linked to a three-page paper written by Einstein in September 1905. This short paper, which contained no footnotes or references, turned physics upside down by linking mass and energy in a way never before postulated.

Published in the German journal *Annalen der Physik*, the paper was entitled "Does the Inertia of a Body Depend on Its Energy Content?" It was a supplement to Einstein's work on special relativity that appeared in the same physics journal earlier that year. The text begins: "The results of an electrodynamic investigation recently published by me in this journal lead to a very interesting conclusion, which will be derived here."

The paper applied the special theory of relativity to light being emitted from a stationary object. Einstein concluded that if a body emits an amount of energy, E, in the form of radiation, then its mass, m, must be reduced by the amount E/c^2, where c is the speed of light. This reasoning led to the equation $E \quad mc^2$, probably the most famous equation in the world. $E \quad mc^2$

Changed the World

does not appear explicitly in the 1905 paper; however, it does appear in Einstein's later work in 1906 and 1907.

Because the speed of light is a very large number—299,792,458 meters per second—and is multiplied by itself, a small amount of matter is equivalent to an enormous amount of energy. For example, a kilogram of mass converts to 21 million tons of TNT energy.

Einstein did not expect his result to be easily confirmed because it would have been too difficult to measure the small amounts of mass converted in the radiation emissions that were experimentally accessible at the time. He concluded his paper by conjecturing that radioactive materials, such as radium salts, might provide a means to test the theory.

Full confirmation of the equation did not occur until the 1930s, following elucidation of the structure of the nucleus as an assemblage of neutrons and protons. In 1932, James Chadwick discovered the neutron. That same year, John Cockcroft and E. T. S. Walton bombarded a lithium nucleus with a proton and produced a nuclear reaction. The experiment demonstrated the accuracy of Einstein's equation by showing that a small amount of mass could be converted into energy. One year later, Irène and Frédéric Joliot-Curie demonstrated the reverse process, when they took a photograph showing the conversion of energy into subatomic particles.

Over time, scientists grew to realize that huge amounts of energy could be liberated in nuclear reactions, such as those that occur in the Sun and stars. (See the box on p. 17.) For example, the Sun fuses hydrogen nuclei (protons) into helium nuclei (containing two protons and two neutrons each), a process called fusion that goes on for billions of years. The masses

of the protons at the start of a fusion event are slightly heavier than the mass of the helium nucleus at the end of the process: the missing mass is converted to energy. For stars more massive than the Sun, the carbon–nitrogen–oxygen cycle is the primary vehicle for fusing hydrogen nuclei into helium nuclei.

Today, in a nuclear reactor, a heavy element, such as uranium, is split into two lighter elements during a process called fission. Once again, the combined mass of the products is lighter than the original nucleus. The difference in mass is converted to energy, which is used for boiling water to drive turbines.

Probing Subatomic Particles

$E = mc^2$—together with the development of quantum mechanics and advances in nuclear physics—spawned new kinds of experiments in which physicists bombard targets with high-energy subatomic particles. Sometimes the particle collisions lead to new particles. In this respect, turning energy into matter is a well-tested method of uncovering the substructure of the universe.

In one such project, Livermore physicists Peter Barnes, Doug Wright, and Ed Hartouni are participants in an international experiment centered at the Fermi National Accelerator Laboratory (Fermilab) in Illinois. The experiment focuses on measuring how one type of neutrino transforms into another type, a process called oscillation. (See *S&TR,* April 2003, pp. 13–19.) The results promise to help scientists better understand particle physics as well as the role of neutrinos in the universe. "Without $E = mc^2$," says Barnes, "scientists might not have postulated the neutrino. Particle physics would be completely different; the field would be mainly a mystery."

The Main Injector Particle Production (MIPP) experiment at Fermi National Accelerator Laboratory (Fermilab) will measure subatomic particle production from beams of protons, pions, and kaons. Livermore physicist Peter Barnes (right) works on one of the experiment's detectors, called the Time Projection Chamber. Also shown is Fermilab technician Walt Jaskierny.

Neutrinos, the most mysterious of subatomic particles, are difficult to detect because they rarely interact with other forms of matter. Although they can easily pass through a planet or solid walls, they seldom leave a trace of their existence. Three types of neutrinos exist—the electron neutrino, muon neutrino, and tau neutrino, which are related, respectively, to the common electron and the less common muon and tau particles. Evidence of neutrino oscillations proves that neutrinos are not massless but instead have a mass less than one-hundred-thousandth that of an electron.

The Fermilab experiment, called the Main Injector Neutrino Oscillation Search (MINOS), uses a neutrino beamline, completed in early 2005, that has an energy spectrum of 0.5 to 8 gigaelectronvolts. One goal of the MINOS experiment is to discover the rate at which neutrinos "change flavors," or oscillate from one type to another.

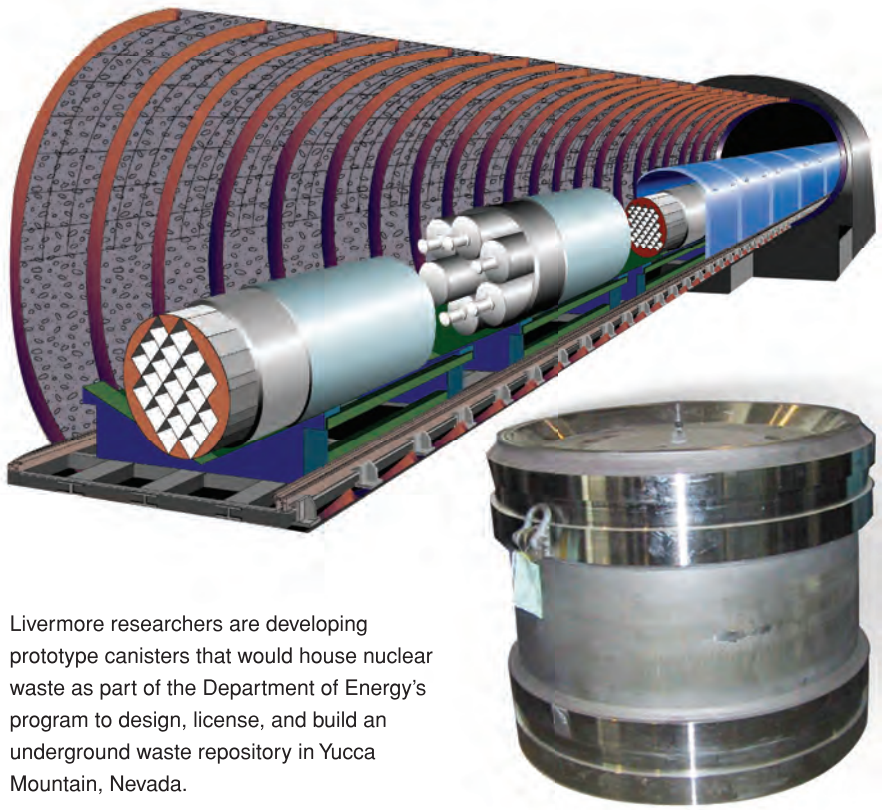
The MINOS researchers use two giant detectors—one at Fermilab and a 6,000-ton detector lying in a historic iron mine at Soudan, Minnesota. A narrow beam of neutrinos is generated and characterized by the near detector at Fermilab. The beam is aimed at the far detector in Minnesota. The neutrino beam energy is chosen so that the distance between the two detectors corresponds to an expected maximum in the probability that a neutrino produced at Fermilab will oscillate to another flavor. Physicists compare the muon neutrino beam flux and spectrum measured by the near detector with that from the far detector in Minnesota to understand the properties of neutrino oscillations. In this way, they can determine the relative mass differences between the neutrino types.

Livermore physicists are also part of a project funded by the Laboratory Directed Research and Development (LDRD) Program to analyze data needed

to accurately model the MINOS neutrino beam. The Fermilab Main Injector Particle Production (MIPP) experiment measures particle production from proton, pion, and kaon beams, ranging from 5 to 120 gigaelectronvolts, directed on targets, including liquid hydrogen, beryllium, copper, carbon, bismuth, and depleted uranium. Pions and kaons are mesons, which help to bind the nucleus.

Barnes explains that the kinetic energy of the incoming beam is converted into new particles, including pions, the precursors to the muon neutrinos in the MINOS beam. Scientists are measuring the species that are produced, their energies, and the angle at which they leave the target.

MIPP results will aid Livermore's stockpile stewardship efforts. Livermore has been exploring the use of high-energy protons to create radiographs similar to x-ray images. (See *S&TR*, November 2000, pp. 12–18.) Proton radiographs could be used in stockpile stewardship to image deep inside explosive experiments and obtain information about materials too dense for x rays to penetrate. However, proton radiographs tend to be blurry, in part because the proton beam that reaches the detector also contains subatomic particles produced as the beam passes through the object being imaged. Stockpile stewards need to know the exact identity of these secondary particles and how they affect the final image in order to make quantitative measurements.



Livermore researchers are developing prototype canisters that would house nuclear waste as part of the Department of Energy's program to design, license, and build an underground waste repository in Yucca Mountain, Nevada.

New Uses for Warhead Material

$E = mc^2$ and subsequent advances in quantum and nuclear physics ushered in a new age of energy production without carbon emissions or depletion of nonrenewable hydrocarbon fuels. Nuclear energy supplies 20 percent of the electricity in the U.S. and 16 percent of that used throughout the world. Livermore researchers have long worked on different aspects of nuclear energy. For example, as part of the Department of Energy's (DOE's) program to design, license, and build an underground nuclear waste repository in Yucca Mountain, Nevada, the Laboratory is designing a waste package and barrier system. Researchers have also developed computer codes that predict the performance of the system for thousands of years.

Livermore nuclear experts are also helping to oversee an unusual source of uranium fuel for U.S. power plants. The collapse of the Soviet Union created a grave threat of proliferation, with hundreds of weapons and thousands of kilograms of weapons-usable materials potentially at risk to theft and misuse.

Signed in 1993, the Highly Enriched Uranium (HEU) Purchase Agreement between the U.S. and the Russian Federation commits the U.S. to purchasing 500 metric tons of HEU (90 percent ^{235}U) extracted from dismantled Russian nuclear weapons over a period of about 20 years. The U.S. receives low-enriched uranium (LEU), which has been blended down from HEU so that it contains less than 5 percent ^{235}U. The LEU is used as fuel in U.S. commercial nuclear power reactors.

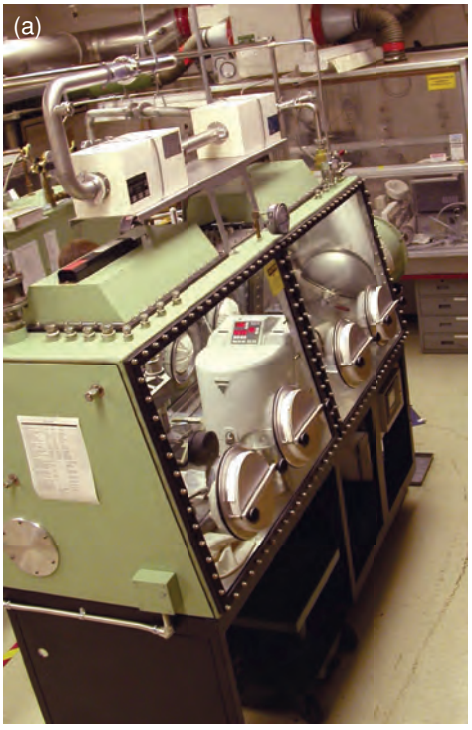
Currently, Russian plants are processing about 30 metric tons of HEU per year into about 875 metric tons of LEU. This amount meets half the annual fuel requirement for U.S. nuclear power plants and provides the fuel to generate 10 percent of the electricity used in the U.S.

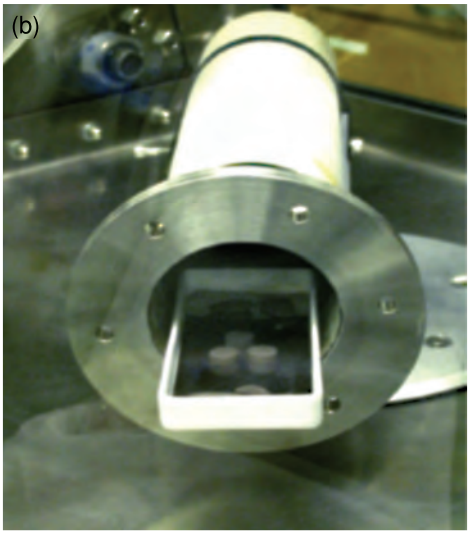
The Highly Enriched Uranium Transparency Program provides confidence that Russian LEU sold to the U.S. under the 1993 agreement is derived from dismantled Russian nuclear weapons. The program monitors the Russian process of converting weapons-usable HEU into LEU. A Transparency Monitoring Office was established in 1996 by DOE and is staffed in part by Livermore workers.

Livermore physics and nuclear chemistry experts, headed by engineer

Al DiSabatino, use portable, nondestructive assay equipment to ensure that the HEU, checked in closed containers, is 90 percent ^{235}U. In addition, the U.S.-supplied Blend Down Monitoring System provides a continuous, unattended, and independent monitoring of the blending process at Russian facilities. Experts from Livermore and other DOE laboratories and contractors make transparency-monitoring visits to each of the four Russian uranium-processing facilities. The Russian Federation also monitors U.S. facility operations to ensure the peaceful use of LEU delivered to the U.S.

DiSabatino notes that the HEU Purchase Agreement will reach a historic milestone this year—the conversion and permanent elimination of 250 metric tons of HEU from Russian stockpiles, the equivalent of 10,000 nuclear devices and the halfway point toward the goal of eliminating 500 metric tons of HEU.





Livermore researchers are developing fuels for the small, sealed, transportable, autonomous reactor (SSTAR). (a) A glove box was used to manufacture mono-uranium-nitride powder, which was then (b) hydraulically pressed and heated into small pellets.

Advancing Nuclear Power

Livermore researchers are also working on advanced nuclear fuels and fuel-cycle technologies that are cleaner, more efficient, and more resistant to proliferation. For example, nuclear engineer Jor-Shan Choi, chemist Bart Ebbinghaus, and mechanical engineer Tom Meier, funded by LDRD, are developing fuel for the small, sealed, transportable, autonomous reactor (SSTAR).

SSTAR, a DOE collaborative project, is a liquid-metal cooled, fast reactor that can supply 10 to 100 megawatts of electrical power. The reactor will measure about 15 meters tall by 3 meters wide. Its weight will not exceed 500 tons, so it can be transported by ship or heavy transport truck. (See *S&TR*, July/August 2004, pp. 20–22.)

By using lead or lead–bismuth as a cooling material instead of water, high-pressure vessels and piping normally needed to contain reactor coolant will not be necessary. Nuclear fuel will be contained within the sealed, tamper-resistant reactor vessel, which will be shipped to the user country and returned to the supplier country without the need for it to be opened during its anticipated operating lifetime of about 30 years. Because the reactor uses no refueling or onsite storage of spent fuel, the reactor will not raise concerns about diversion of nuclear materials and nuclear proliferation.

"With a typical nuclear power plant, some of the spent fuel must be removed every 12 to 18 months," says Choi. "With SSTAR, onsite refueling and long-term storage of radioactive wastes is not necessary."

The requirements for a sealed, long-life reactor impose significant challenges to developing the nuclear fuel and its cladding. Factors that affect the selection of the reactor fuel for SSTAR include coolant compatibility, economics, long life, proliferation resistance, and safety. The Livermore team chose an advanced mononitride-based fuel because of its suitability for a liquid-cooled fast reactor and its potential to meet other selection factors. Choi notes that the National Aeronautics and Space Administration and DOE have identified mononitride-based uranium fuel as one of the preferred fuels for nuclear reactors used in space exploration.

The selected fuel's thermal conductivity is 10 times higher than traditional uranium oxide, and its melting temperature is much higher than that of metal fuel. To ensure that the uranium in the fuel is not attractive for use in clandestine nuclear weapons, the ^{235}U enrichment is limited to 20 percent and contains inert materials not readily separated from the fuel.

The research team is using recently constructed laboratories at Livermore to develop advanced nitride-based reactor fuel pellets. Researchers are evaluating the pellet's characteristics and verifying their quality. In optimizing the formulation, the team is using additives such as zirconium and hafnium nitrides for improved stability and burn-up characteristics. Samples of the manufactured fuel pellets will undergo irradiation tests.

An important element of the project is applying Livermore's modeling capability

Tapping the Potential of the Nucleus

The neutrons and protons are kept stable in every atom's nucleus by attractive nuclear forces. The relative stabilities of the nuclei of different elements are determined by their binding energies, that is, how much energy is required to remove a proton or neutron from the nucleus. If the binding energy of each nucleus is plotted as a function of the number of protons and neutrons it contains, a curve of binding energy is obtained.

As seen in the figure below, nuclei with a small number of neutrons and protons have a low binding energy. Such nuclei are easier to break apart and are not as stable as nuclei with larger numbers of protons and neutrons. As the number of neutrons and protons increases, the binding energy reaches a peak and then drops off again. Nuclei at the peak are the most tightly bound and correspond to elements near iron in the periodic table. As neutrons and protons continue to be added, the nucleus becomes less tightly bound.

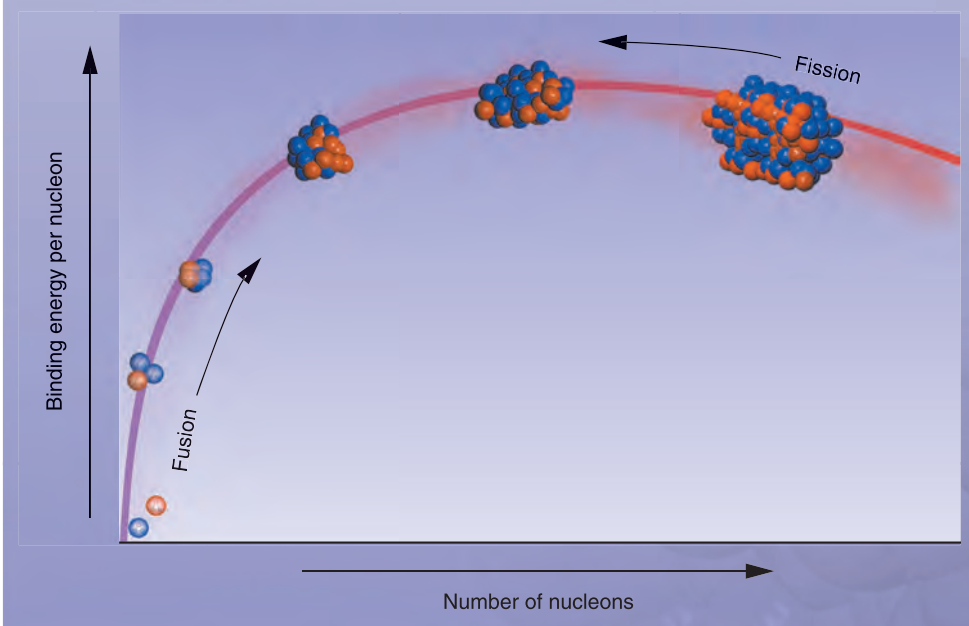
If uranium and plutonium nuclei, at the far right end of the plot, break into smaller nuclei, the pieces are harder to break apart. Thus, if a way can be found to break a uranium or plutonium nucleus, energy will be released. This process, known as fission, is typically started by trickling neutrons into such nuclei. The neutrons give these nuclei just enough energy to undergo fission. When such nuclei split, extra neutrons are given off. Under the right conditions, a self-sustaining set of reactions can occur in which more and more fissions occur. This process can either lead to a runaway reaction, as in a fission bomb, or can be kept at a steady state, as in a nuclear reactor.

If very light nuclei such as hydrogen or deuterium are forced together, in a process called fusion, the resulting nucleus is in a lower energy state, and the extra energy is given off as radiation or energetic neutrons. This fusion process is more difficult to achieve than fission because the electrical repulsion of the nuclei must be overcome to get the nuclei to fuse. In the center of the Sun and other stars, nuclei have the very high temperatures and densities required for thermonuclear fusion.

The high temperatures and densities required for fusion have been achieved on Earth for only very short periods of time in thermonuclear bombs and a few research machines such as fusion tokomaks and the Laboratory's Nova laser, which operated from 1985 to 1995.

Controlled fusion for energy production is being attempted in two different ways: magnetic fusion and inertial confinement fusion. In magnetic fusion, intense magnetic fields confine low-density plasma at temperatures and densities needed for fusion. In inertial confinement fusion, lasers or accelerators compress extremely small pellets to the very high densities and temperatures needed for fusion.

It is interesting to compare the temperatures, densities, and confinement times of these approaches. Confinement time is the amount of time it takes for the energy in the plasma to be released. Magnetic confinement requires densities of only 10^{-9} grams per cubic centimeter, temperatures of roughly 100 million kelvins, and a confinement time of several seconds. Inertial confinement requires densities of 1,000 grams per cubic centimeter, temperatures of about 100 million kelvins, and confinement times of 10^{-11} seconds. The center of the Sun is calculated to reach densities of greater than 100 grams per cubic centimeter and temperatures of 16 million kelvins. Because of gravitational forces, the Sun's confinement time is as long as the age of the Sun.



Nuclei with a small number of neutrons and protons have a low binding energy. As the number of neutrons and protons increases, the binding energy reaches a peak and then drops off. Uranium and plutonium nuclei are at the far right end of the plot. If they break into smaller nuclei (fission), the pieces become more bound. For very light nuclei such as hydrogen or helium, more nuclear binding energy can be obtained if the nuclei are forced together (fusion).

to study nuclear fuel performance. Computer codes will determine how many years the advanced fuels will likely last.

Choi says successful development of the fuel should make nuclear power more acceptable for worldwide use, including in developing nations.

Two Roads to Nuclear Fusion

Like nuclear fission, controlled nuclear fusion could generate electricity without producing atmospheric pollution. Thermonuclear fusion of hydrogen is the energy source for the Sun and the stars. For equal amounts of fuel, the energy from fusion is about 1 million times greater than that released from burning fossil fuels. For such fusion reactions to proceed at high enough rates to be practical, the fusion fuels (heavy hydrogen) must be heated to temperatures of about 100 million degrees Celsius. Two ways are being pursued to contain fusion fuel at the required temperature and density: magnetic confinement and inertial confinement.

The earliest controlled fusion effort at Livermore focused on magnetic confinement, in which deuterium fuel is trapped in a magnetic field for extended periods of time. In this concept, the fuel is at typically 100,000 to 1 million times lower density than air. These low densities are needed for sustained confinement at pressures corresponding to the high temperatures needed for fusion.

Research during the early years of this effort, called Project Sherwood, was classified because, if successful, it could have provided a prodigious source of 14-megaelectronvolt neutrons for breeding plutonium from uranium.

Magnetic confinement fusion was of interest to scientists on both sides of the Cold War. In the late 1950s, the Livermore program was declassified and has now evolved to be a part of the Laboratory's Fusion Energy Program. Today, Livermore researchers collaborate with General Atomics in San Diego, California, on tokamak fusion reactors. An alternative to the tokamak concept is Livermore's Sustained Spheromak Physics Experiment, built in 1997. (See the article on p. 4.)

Livermore researchers have developed advanced computational models to study magnetic fusion reactions. Results of these simulations will aid the International Thermonuclear Experimental Reactor (ITER), for which Livermore led the conceptual design activity. The 10-meter-diameter ITER will be built in Cadarache, France, by a six-party consortium (European Union, Japan, Russia, U.S, China, and Korea). It is expected to produce 500 megawatts of fusion energy for 400 seconds of operation after it becomes operational in 2020. Contributions from the U.S. include diagnostics, superconducting central solenoid magnets, physics analysis, and tritium handling. Livermore is contributing to the central solenoid and diagnostics. ITER construction will begin in 2006.

"Although tremendous strides have been made over the past decade, scientific questions still remain. For example, we want to understand how the fusion plasma spontaneously forms an insulating surface layer a few centimeters thick where the temperature drops from 40 million degrees to a few thousand," says Livermore fusion scientist Dave Hill.

Hill maintains that the biggest technological challenge for magnetic fusion energy is developing advanced materials that can survive a harsh environment; the economics of fusion energy is also challenging. In the future, fusion engineers must replace steel with materials such as vanadium and ceramics, or find ways to protect the vessel wall material, for example, with a thick liquid layer. He also notes that modeling magnetic fusion processes is particularly difficult because space scales must range from a few millimeters to meters, and time scales from millionths of a second to hours. A new code, TEMPEST, is under development by Livermore scientists to simulate the insulating plasma surface layer.

Using Lasers to Achieve Fusion

Another way to achieve controlled nuclear fusion is to implode BB-size capsules of frozen fusion fuel to the needed temperatures and densities using laser energy. This technique, called inertial confinement fusion, was pioneered at Livermore. Under the high densities involved in this concept, the fusion burn occurs in less than 100 trillionths of a second, and the inertia of the fuel itself provides the necessary confinement.

According to physicist John Lindl, former Livermore Director Johnny Foster appointed Ray Kidder to lead the Laboratory's first small laser fusion program in 1962. Beginning in 1960, John Nuckolls, Stirling Colgate, Ron Zabawski, and other physicists used weapons design codes to calculate the indirect drive approach to igniting fusion microexplosions. It seems possible that giant lasers might someday be focused to compress and ignite a small quantity of deuterium–tritium fuel for weapons applications. The challenge of inertial fusion is that laser heating alone is not enough to generate net energy, even with lasers as large as 1 megajoule. To achieve energy gain, the laser also must compress the fuel to 1,000 or more times its liquid density.

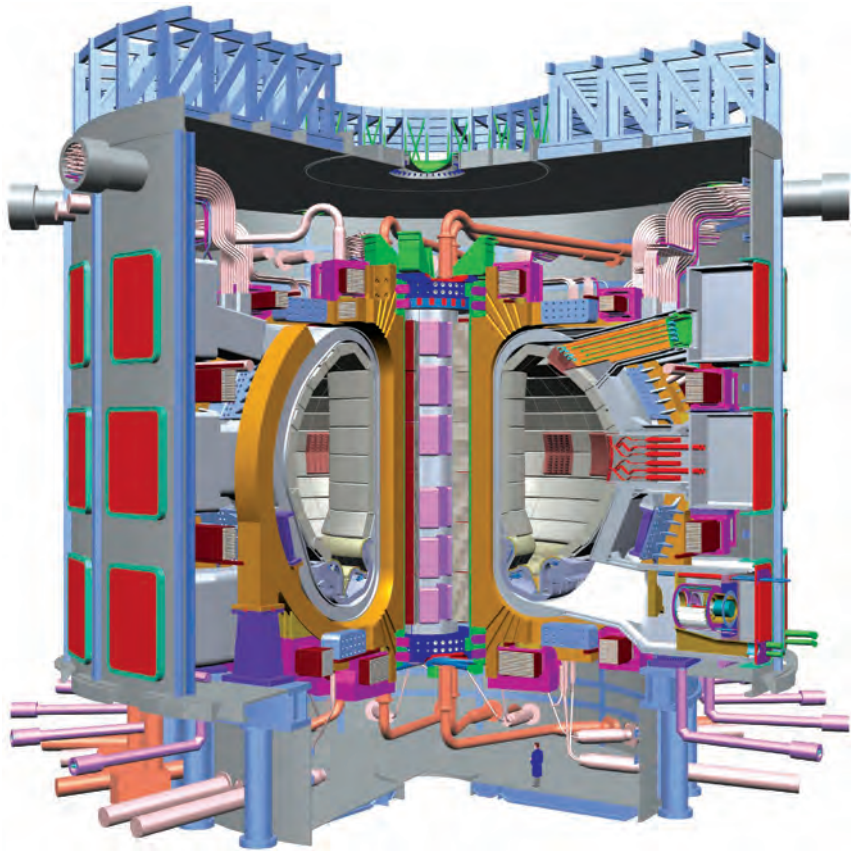
"Compression is the key issue," says Lindl. "If we could compress the fuel to a high enough density while heating a small fraction of it to the temperatures required for fusion, we could achieve ignition and significant gain with a reasonable-size laser." The ignition pellets being designed for the National Ignition Facility (NIF), which is undergoing final assembly in Livermore, will be compressed to a density and temperature about 10 times those that exist in the center of the Sun.

In 1972, Livermore's laser fusion efforts expanded with the formation of the Inertial Confinement Fusion (ICF) Program. Its goal was to demonstrate fusion in the laboratory and to develop laser science and technology for both defense and civilian applications. Experiments were carried out on a succession of increasingly sophisticated lasers—Janus, Cyclops, Argus, Shiva, and Nova. "We continually bootstrapped our capabilities and knowledge," says Lindl.

With Nova, researchers made good progress on laser fusion codes, diagnostics, and target design and fabrication. Livermore's laser fusion research also took advantage of underground experiments conducted at the Nevada Test Site (NTS). The data from Nova and NTS experiments guided scientists in planning NIF.

As part of Livermore's NIF Programs Directorate, the current ICF Program advances design, fabrication, target experiments, and fusion target theory. The Laser Science and Technology Program advances the required laser and optical science and technology both for NIF and for future lasers that might be suitable for fusion energy applications. Much of this research supports DOE's Stockpile Stewardship Program to maintain the U.S. nuclear deterrent. Another goal is exploring ICF as a clean and inexhaustible source for commercial electric-power production.

In 2004, NIF's Early Light experiments met the first milestone of Livermore's ICF Program. Ultraviolet light from NIF's first quad of lasers was aimed at gas-filled targets. The tests showed good agreement between calculations and the observed beam propagated through the target. "These experiments were very successful," says Lindl.



Livermore researchers are helping to design and build the International Thermonuclear Experimental Reactor (ITER). The 10-meter-diameter ITER will produce 500 megawatts of fusion energy for 400 seconds at a time. (Published with permission of ITER.)

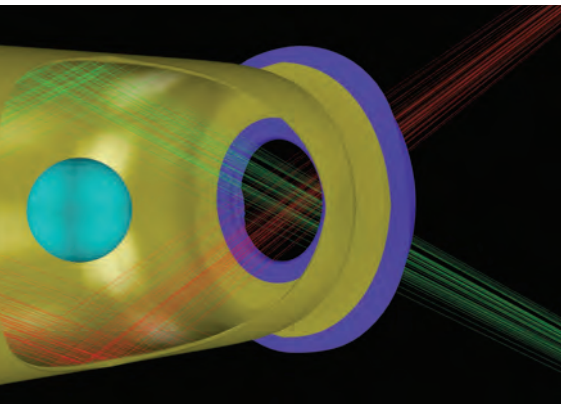
Nuclear Weapons a Popular Icon

Einstein was sometimes—and unfairly—called the "father of the atomic bomb." He did not foresee the release of enormous amounts of destructive energy by bombarding the nuclei of atoms. However, building on the many advances in nuclear physics that occurred after the $E = mc^2$ paper, Otto Hahn and Fritz Strassman discovered nuclear fission in uranium in 1939. Later that year, Leo Szilard conceived a way to use fission in a self-sustaining chain reactor.

Aware of the progress that had been made splitting uranium atoms, Szilard and other scientists feared that Germany might be working on an atomic bomb. In late July 1939, Szilard visited Einstein to finalize the draft of a letter to warn President Franklin D. Roosevelt of the danger. The Laboratory's cofounder, Edward Teller, drove Szilard to Einstein's summer cabin on Long Island and joined them in the meeting.

The Einstein letter to Roosevelt dated August 2, 1939, helped set in motion the Manhattan Project, the mammoth effort to build an atomic bomb. Einstein did not participate in the Manhattan Project, and, in 1946, he became chairman of the Emergency Committee of Atomic Scientists, whose goal was to place nuclear energy under international control.

The bomb that was dropped on Hiroshima had an explosive force equivalent to 15,000 tons of TNT. The Hiroshima bomb was a purely fission device, using the same nuclear process as occurs in nuclear reactors. In contrast, all current U.S. nuclear weapons rely on



The ignition pellets being designed for the National Ignition Facility (NIF) will be compressed to densities and temperatures about 10 times those that exist in the center of the Sun. In this HYDRA simulation of an ignition target for NIF, laser beams are seen entering one end of a capsule called a hohlraum, which contains the fusion fuel (blue). The beams strike the inside of the hohlraum wall and create x rays that cause the capsule to implode and release energy.

a mixture of fission and fusion for their explosive power.

Bruce Goodwin, associate director for Defense and Nuclear Technologies, says most people's immediate reaction to $E = mc^2$ is the recollection of a photo or movie of an atmospheric nuclear detonation. "A nuclear weapon is the icon for $E = mc^2$ because it presents the possibility of Armageddon," he says. "However, the deployment of nuclear weapons among the world superpowers has led to a state of deterrence, which kept the Cold War cold." Indeed, the number of deaths caused by war has dropped precipitously since 1945, when atomic bombs were dropped on Hiroshima and Nagasaki.

Goodwin points out that during the Cold War, the Soviets were rational adversaries. Although they enjoyed significant advantages in conventional armaments, particularly in the early stages of the Cold War, they knew that any attack would be met with NATO nuclear weapons, if necessary. "Nuclear weapons successfully prevented world-scale war while East and West were foes," Goodwin says.

Although the possibility of a crisis that could lead to an Armageddon has been dramatically reduced, the danger of a single nuclear detonation by a terrorist group or rogue nation has increased. In addition to supporting stockpile stewardship, one of Livermore's primary national security missions is to prevent nuclear weapons, materials, and know-how from reaching the wrong hands.

Many scientists, like Goodwin, argue that the world needs to move to a fusion economy. "Nuclear weapon designers have understood fusion for 50 years. The challenge is to harness that understanding for producing civilian energy." He notes that NIF will be the first laboratory to have controlled nuclear fusion, a critical step toward clean and abundant energy. In that light, $E = mc^2$, Goodwin says, offers to transform life on Earth because of the prospect of abundant clean energy.

"Lawrence Livermore, with its expertise of nuclear weapons, the environment, and fusion, is uniquely poised to be a world leader in energy and in keeping the peace."

—Arnie Heller

In the current era of no underground nuclear testing, Livermore researchers participate in the nation's Stockpile Stewardship Program, which uses, in part, advanced simulation technology. Visualization engines turn the data produced by supercomputers into images displayed on individual computer monitors, large-scale screens, or massive powerwalls, such as the one shown above. Simulations help scientists better understand how weapons materials age and how they perform under extreme conditions.

Key Words: Albert Einstein, $E = mc^2$, fission, fusion, Highly Enriched Uranium (HEU) Purchase Agreement, inertial confinement fusion, International Thermonuclear Experimental Reactor (ITER), magnetic fusion energy, Main Injector Neutrino Oscillation Search (MINOS), Main Injector Particle Production (MIPP), National Ignition Facility (NIF), neutrinos, SSTAR (small, sealed, transportable, autonomous reactor), Stockpile Stewardship Program.

For information on Lawrence Livermore's activities for the World Year of Physics, see www.llnl.gov/pao/WYOP.

Recycled Equations Help Verify Livermore Codes

CODES that model complicated hydrodynamics are an important component of Livermore's stockpile stewardship efforts. A persistent concern for code developers and users is how well these codes model reality. Before scientists trust the results from a model, they must quantify the difference, or error, between the simulations it produces and physical reality.

Two kinds of errors may exist in the simulation: those due to code design and those due to code implementation. Design errors occur because the input parameters or the equations being solved do not accurately reflect the physical processes to be modeled. These errors result primarily because scientists do not have the detailed information needed to completely understand the physics. To address design errors, scientists must collect higher fidelity data, for example, by conducting experiments in laboratories. The resulting data help them determine which parameters to include and which equations the code must solve to accurately model the problem. This process of confirming that the code is solving the correct equations is called code validation.

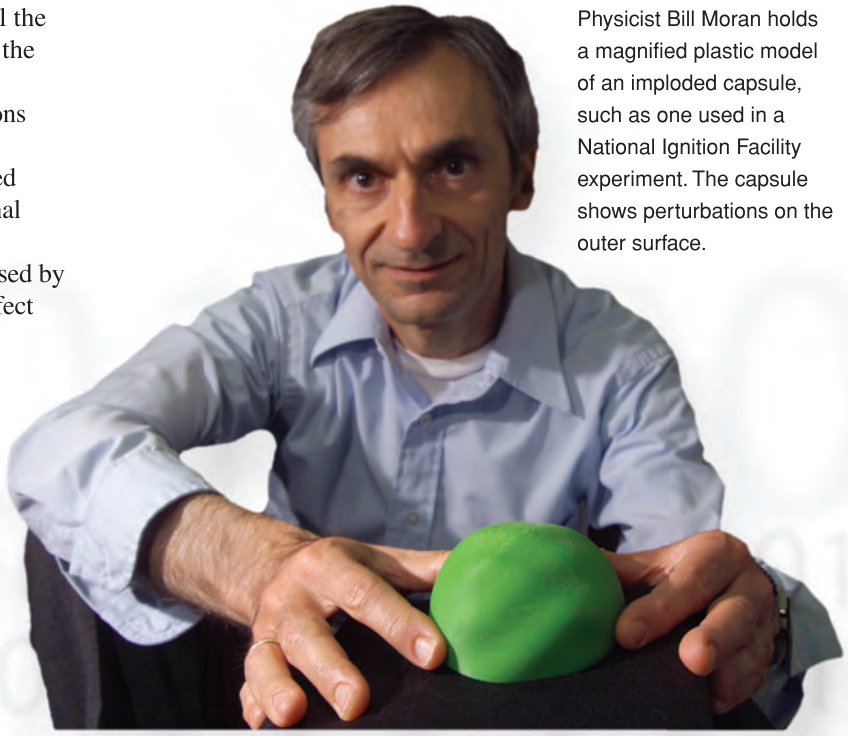
Scientists must also confirm that the code solves the equations correctly, a process called code verification. Implementation errors can sometimes occur because the equations are not solved correctly. A modern hydrodynamics code with three-dimensional (3D) capabilities has more than 500,000 lines of coding and 5,000 modules. Any mistake or bug in the coding, whether caused by a typographic error or insufficient computing resources, can affect the model's accuracy.

Use of Test Problems

One reliable approach to verification is to have a code run test problems with known answers. These problems are simple enough to be solved analytically—that is, by working through differential equations and other mathematical expressions to determine the exact answer to each problem. The computer code also processes these test problems. Then by comparing the known solution with the code-generated one, scientists can determine code error for these problems.

Over the years, Livermore researchers have developed sets of test problems for verifying the implementation in hydrodynamics codes, such as those used to study the implosion and explosion of a capsule in a National Ignition Facility (NIF) experiment. However, test problems have limitations as a verification method because they do not adequately represent all of the physical processes that occur in a NIF capsule. They also do not, in general, account for the 3D nature of the implosion. For example, in a direct drive experiment, the finite number of laser beams impinging on a capsule introduces perturbations. These perturbations can alter the implosion and affect the capsule's performance. Those effects, however, will not appear in simulations of typical one-dimensional test problems because of the simplified physics. Thus, when scientists compare results of the test problems with more complex simulations of imploding capsules, they cannot accurately quantify the uncertainties in the code's calculations.

To address this problem of code verification, Livermore physicist Bill Moran has developed new test problems that have analytic solutions for an imploding shell under exponentially decaying pressure. "The test problems are analogous to the hydrodynamics of an imploding capsule, such as inertial confinement fusion (ICF) targets," says Moran. "Although the solutions are still simplified, they can include 3D effects in a way that can be checked exactly."



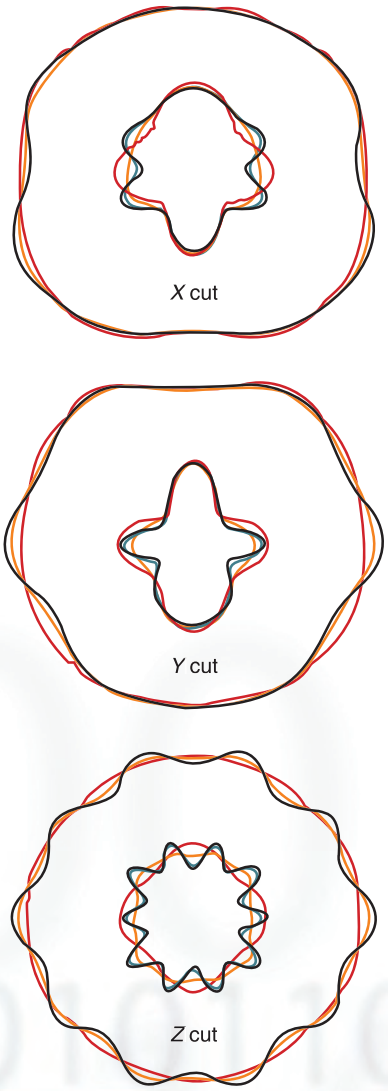
Physicist Bill Moran holds a magnified plastic model of an imploded capsule, such as one used in a National Ignition Facility experiment. The capsule shows perturbations on the outer surface.

The test problems provide an independent check of the 3D codes developed for the National Nuclear Security Administration's (NNSA's) Advanced Simulation and Computing (ASC) Program. They also help scientists compare the efficiency of the algorithms and codes used in NIF capsule implosion simulations.

Analyze This

Moran's solutions build on a previous assignment, in which he studied the containment of underground nuclear experiments for the Laboratory's former Nuclear Test Program. This containment research focused on geophysical applications and seismic decoupling. Moran realized he could "recycle" those past analyses by turning the problems inside out to model an imploding shell. In the containment problem, a nuclear device explodes in an underground cavity, and the resulting pressure is a force on the inside pressing out on a surface. In a NIF capsule, the impinging laser beams ablate the outer surface and create a force on the outside pressing in on a shell—the NIF capsule.

To investigate how well new codes model the hydrodynamics of imploding capsules, Moran developed test problems for three kinds of shells. The first kind is an incompressible fluid shell. This shell deforms easily but maintains its volume, much like a balloon filled with water. The balloon can be squeezed and deformed, but the volume of water inside it does not change. The second is a compressible shell filled with gas. This shell is similar to a pillow that, if compressed uniformly, can be deformed and reduced in volume. The third is also an incompressible fluid shell, but it has minor perturbations (small bumps) on both the inner and outer surfaces.



One test problem compared the cavity shape of an imploded inertial confinement fusion shell. The comparisons view the shape across three planes: (a) a horizontal, or *X*, cut; (b) a vertical, or *Y*, cut; and (c) an axial, or *Z*, cut. The black curve shows the known solution for the test problem, red is from a simulation with two-degree zoning, blue is with one-degree zoning, and green is with one-half-degree zoning. Note that, in places, the two-degree calculation is out of phase with the known solution, showing the importance of zoning appropriately.

Getting Closer to Reality

Moran added several realistic features in the test problems, so the solutions more closely reflect what happens in a NIF capsule. For example, he includes the initial shell thickness of a typical capsule, the initial inner radius, and the initial density of the capsule. He also incorporates a mathematical form of the applied pressure, chosen to be close to the pressure experienced by an imploding capsule.

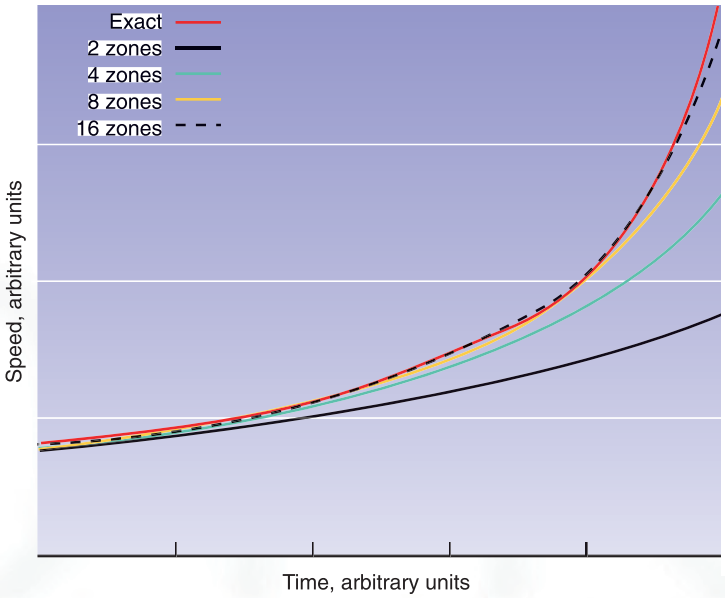
Solving for a shell that has minor perturbations on its inner and outer surface was another way to bring the analytic approach closer to the geometry of a real capsule. For example, during capsule manufacturing, small surface perturbations are always present. Assessing how accurately a code simulates these small deviations is important to ensure that numerical artifacts in the code do not drown the small signal being measured. "The size of mesh we choose—whether we use more zones or fewer zones to model a shell—can determine whether we see the signal," says Moran. "Comparing the known analytic solutions with the code's results can help us determine what the trade-off is between the cost of running a simulation and its accuracy." Code users often consider this trade-off because increasing the accuracy requires a mesh with more zones and smaller mesh sizes, making the code run longer.

Putting Codes through Their Paces

In one test problem, Moran considered an incompressible shell with a representative pressure on the outer surface of the shell and analytically solved for the jump-off velocity—the velocity of the inner surface at the time pressure first affects it. Determining

the jump-off velocity provides a test of a code's ability to model shock propagation. The known solution to this problem was then compared to code calculations, and the error quantified for various mesh resolutions. Next, the analytic time evolution of the speed at the inner surface of the shell was compared to code calculations. Moran also worked out analytic solutions for pressure, strain rate, and strain across the shell thickness for various initial configurations.

To verify the 3D capabilities of the ASC codes, Moran adapted into a test problem the work on perturbation growth of Livermore physicist Karnig Mikaelian. "A practical concern we have in achieving a symmetric implosion is whether tolerances are more critical on one surface for reducing perturbations," says Moran. "So we run calculations that simulate the perturbation on one surface at a time. The results for thin shells indicate that both surfaces are critical. Having only one surface perfectly smooth won't stop the perturbations from feeding through to the other surface." Moran notes that these calculations model the cavity as a void without gas. "A more realistic representation would have the gas pushing back on the inner surface as the shell implodes. When a light material—the gas, in this case—pushes on a denser material—the shell—the surface becomes more susceptible to instability growth."



Code simulations of an incompressible fluid shell show the convergence toward the exact solution with finer meshes. When the number of mesh zones is reduced, the error in the calculation increases rapidly.

Moran compared the exact solution of the cavity hot spot with 3D simulations using different resolutions, including two-degree, one-degree, and one-half-degree zoning. The result: the smaller the zones, the better. "In fact," he says, "in the simulation with the coarse two-degree zoning, the amplitude of the instabilities is out of phase—has the opposite sign—at some locations compared with the exact result." Moran also made solid models of the cavity from the two-degree calculation using a rapid-prototype machine, which takes 3D code results and turns them into plastic models. The plastic models showed that, for two-degree calculations, the mesh is imprinted on the cavity surface, effectively drowning out small details.

Analytic solutions also can be used to evaluate the efficiency of various algorithms and codes by comparing the computer run time required to achieve a given accuracy in solving a specific problem. For instance, with a code running on 64 processors of the ASC Frost supercomputer, Moran modeled half of a spherical shell using one-half-degree zoning and various radial resolutions. In Lagrangian mode, the code required 80 radial zones and a processing time of 20,000 seconds (about 5.5 hours) to calculate the peak pressure with an accuracy of 0.5 percent. In arbitrary Lagrange–Eulerian mode, where the nodes were evenly distributed in the radial direction every cycle, the code achieved the same accuracy with only 24 radial zones in 10,000 seconds (about 2.75 hours).

Solutions Are Just the Start

Lawrence Livermore scientists and their colleagues at other locations are creating new test problems building on Moran's research. These problems will be added to existing ones, forming an enlarged suite for scientists to use.

Cynthia Nitta, who formerly led Livermore's verification and validation effort, notes that Moran's work is a breakthrough in code verification, particularly for 3D codes. "Bill's work represents important 3D verification analysis in imploding geometries for code simulation capabilities. The results on the effects of mesh size also provide critical information for evaluating future computer platform capability and capacity requirements."

—Ann Parker

Key Words: Advanced Simulation and Computing (ASC) Program, analytic solutions, code verification and validation, hydrodynamics, stockpile stewardship, three-dimensional (3D) modeling.

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Dust That's Worth Keeping

This image of the Horsehead nebula shows a large cloud of gas and dust in interstellar space. In the dark areas, absorption and scattering by dust particles block the light from stars. (Image courtesy of the National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation.)

IMAGES taken of interstellar space often display a colorful canvas of portions of the electromagnetic spectrum. Dispersed throughout the images are interstellar clouds of dust and gas—remnants ejected from stars and supernovae over billions and billions of years. For more than 40 years, astronomers have observed that interstellar dust exhibits a consistent effect at a spectral wavelength of 2,175 angstroms, the equivalent of 5.7 electronvolts in energy on the electromagnetic spectrum. At this wavelength, light from stars is absorbed by dust in the interstellar medium, blocking the stars' light from reaching Earth. The 2,175-angstrom feature, which looks like a bump on spectra, is the strongest ultraviolet–visible light spectral signature of interstellar dust and is visible along nearly every observational line of sight.

Scientists have sought to solve the mystery of what causes the 2,175-angstrom feature by reproducing the effect in the laboratory. They speculated a number of possibilities, including fullerenes (buckyballs), nanodiamonds, and even interstellar organisms. However, none of these materials fits the data for the unique spectral feature. Limitations in the energy and spatial resolution achievable with electron microscopes and ion microprobes—the two main instruments used to study samples of dust—have also prevented scientists from finding the answer.

A collaborative effort led by Livermore physicist John Bradley and funded by the National Aeronautics and Space Administration (NASA) has used a new-generation transmission electron microscope (TEM) and nanoscale ion microprobe to unlock the mystery. The Livermore group includes physicists Zu Rong Dai, Ian Hutcheon, Peter Weber, and Sasa Bajt and postdoctoral researchers Hope Ishii, Giles Graham, and Julie Smith. They collaborated with the University of California at Davis (UCD), Lawrence Berkeley National Laboratory, Washington University's Laboratory for Space Sciences in St. Louis, and NASA's Ames Research Center for their discovery.

The team analyzed micrometer-size interplanetary dust particles (IDPs), each about one-tenth the diameter of a human hair. Within the particles, they found carriers of the 2,175-angstrom feature: organic carbon mixed with amorphous silicates (glass with embedded metals and sulfides, GEMS), two of the most common materials in interstellar space. Ishii says, "Organic carbon and amorphous silicates are abundant in interstellar dust clouds, and abundant carriers are needed to account for the frequent astronomical observation of the 2,175-angstrom feature. It makes sense that this ubiquitous feature would come from common materials in interstellar space."

The group's results increase scientific understanding of the starting materials for the formation of the Sun, solar system, and life on Earth.

Where Does the Dust Come From?

Production of the 2,175-angstrom spectral feature is generally believed to originate from electronic transitions occurring at the surface of very small grains (about 15 nanometers) in interstellar space. The grains eventually aggregate to become part of what

composes IDPs, some of which make their way to Earth and are collected from the stratosphere by NASA using ER2 aircraft. These aircraft fly at an altitude of 20 kilometers and carry a suite of instruments for atmospheric research and prototype satellite sensors.

Most interstellar dust is thought to form in the ejecta of evolving stars and exploding stars, or supernovae. Some of the dust has unusual isotope ratios. In the formation of the solar system, the isotopes from various stellar sources became homogenized, resulting in identical isotopic ratios of the elements that formed the Sun, Moon, Earth, and other celestial bodies. Presolar system grains, on the other hand, retain the original isotopic ratios of their parent stars, and these isotopic ratios can be significantly different from solar system materials.

Presolar grains can be carried by comets or primitive asteroids and delivered to Earth in meteorites and IDPs. According to the U.S. Geological Survey, each year tens of thousands of tons of interstellar dust falls to Earth, carried mostly in IDPs.

Analyzing Specks of Interstellar Dust

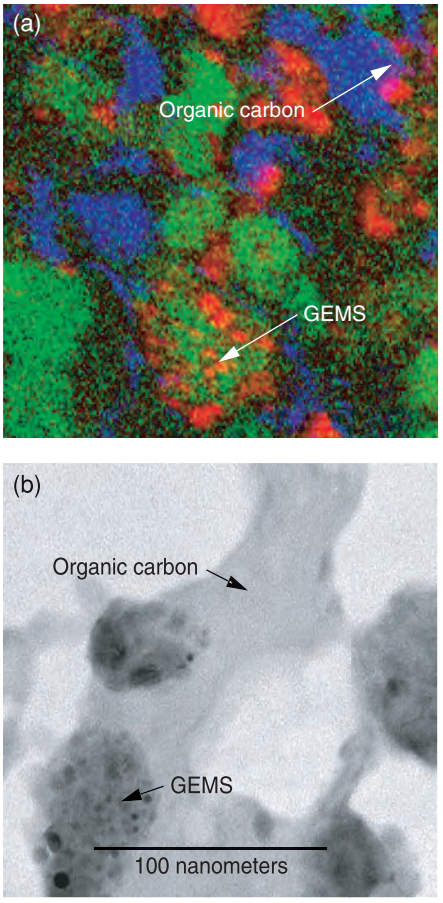
Because presolar grains are typically a micrometer or smaller in diameter, sensitive equipment is needed to analyze them. The nanoscale secondary ion mass spectrometer (NanoSIMS), a new-generation ion microprobe, is capable of studying the isotopic ratios of grains at these small scales. Prior to the development of NanoSIMS, ion microprobes measured dozens of presolar grains at a time, providing only an average of the isotopic properties for the samples. In addition, the limited resolution was insufficient to detect an isotopic anomaly located in a single grain.

The first step in the analysis process is to determine the isotopic composition of an IDP, which confirms whether any of the grains within the IDP are presolar. NanoSIMS was used at Lawrence Livermore and the Laboratory for Space Sciences to measure the isotopic composition of IDPs. A 16-kiloelectronvolt cesium-133 primary ion beam was focused on a 100- to 150-nanometer-diameter area of the sample. Researchers compared the composition of isotopically anomalous hot spots (areas where the highest concentration of a given isotope is found) with the rest of the particle to identify anomalies. Results showed several submicrometer-size areas whose compositions of carbon, nitrogen, or oxygen clearly indicated presolar origin.

Next, the team used a focused ion beam to extract samples smaller than 100 nanometers from targeted isotopically anomalous regions of the grains. These sections were then analyzed with the new-generation TEM to determine their chemical composition. Collaborators from UCD added a specialized monochromator to a 200-kiloelectronvolt TEM at Lawrence Berkeley's National Center for Electron Microscopy. The monochromator allowed researchers to observe the region known as the valence electron energy-loss region, which ranges from 0 to about 100 electronvolts and includes the 2,175-angstrom feature (at 5.7 electronvolts).

In the experiment, electrons in a tightly focused beam strike a sample and interact with its atoms, losing energy in the process. The lost energy is unique to each type of atom the electrons encounter. By measuring the energy of the scattered electrons and subtracting that amount from the known energy of the incident beam, researchers can determine what type of atoms the electrons interacted with and can identify the chemical composition and other details about a sample. The results showed that GEMS mixed with organic carbon give rise to a 2,175-angstrom feature similar to that seen in astronomical observations.

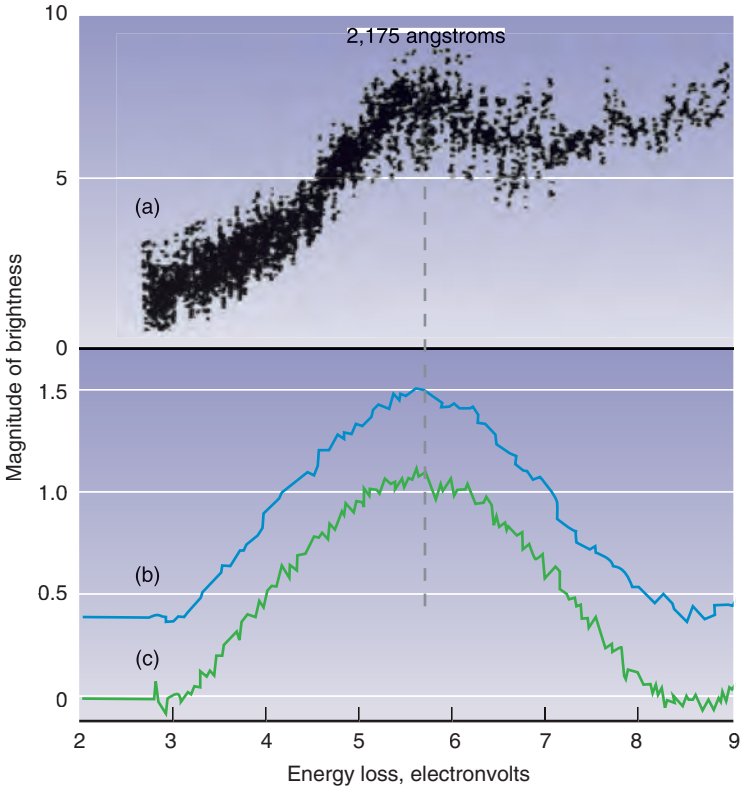
The team also measured infrared spectral properties in a sample grain. Using the Advanced Light Source (ALS) synchrotron facility at Lawrence Berkeley, they focused an infrared beam onto a 3- to 10-micrometer area of the grain. Synchrotrons can produce highly intense infrared beams that allow scientists to study very small objects and choose resolution in photon energy as small as tenths of electronvolts to observe a specific spectral feature. The



(a) A 200-kiloelectronvolt transmission electron microscope (TEM) image shows organic carbon and glass with embedded metals and sulfides (GEMS) within an interplanetary dust particle. (b) Using electron energy-loss spectroscopy in a monochromated TEM, researchers created energy-filtered maps of iron (red), magnesium (green), and carbon (blue) to determine the composition of any grains with anomalous isotopic ratios. These images show that GEMS and organic carbon give rise to a 2,175-angstrom feature similar to that seen in astronomical observations.

infrared measurements confirmed the data acquired from the TEM and provided information on the chemical structure of the amorphous carbon grains. The infrared properties of the sample examined at ALS agreed with the chemical results obtained using electron energy-loss spectroscopy and verified that organic carbon is one carrier of the 2,175-angstrom feature.

Laboratory spectral signatures for the 2,175-angstrom feature show a peak at a wavelength consistent with astronomical observations of spectral signatures that cause the extinction of light. However, the bandwidths on laboratory signatures are broader than those on astronomical spectral signatures. The team theorizes this bandwidth difference is due to several factors. One factor, for example, is physical change over time. Ishii explains, "The grains are no longer free-floating in the interstellar medium where they originally averaged about 15 nanometers in diameter. After 5 billion years, they have changed physically by clumping together to form aggregate particles, which affects their spectral characteristics."



(a) The astronomical 2,175-angstrom spectral feature is compared with (b) an electron energy-loss spectrum from organic carbon in an interplanetary dust particle and (c) an electron energy-loss spectrum from amorphous silicates in another dust particle. The laboratory spectral signatures show a peak in the central portion of the wavelength that is consistent with astronomical observations of spectral signatures.

What Can Interstellar Dust Tell Us?

Particles entering the atmosphere are exposed to temperatures exceeding 350°C, which could potentially cause modifications to organic components and GEMS. Because the particles' physical properties can change as they interact with other elements in the atmosphere, scientists are particularly interested in cometary dust particles, which are more pristine and less processed than those from asteroids or in meteorites. Comets orbit beyond the giant planets and have experienced less heating and aqueous alteration. Bradley, who is director of the Laboratory's Institute of Geophysics and Planetary Physics, has formed a team that will analyze dust from the Comet Wild 2 when NASA's Stardust space mission returns to Earth in 2006. (See *S&TR*, June 2004, pp. 24–26.) The mission will be the first to deliver material from a comet to Earth.

Tiny specks of dust, such as those that will be returned from the Stardust mission, promise to provide answers to a number of long-pondered questions about how interstellar organic matter was incorporated into the solar system. Scientists will also learn about the nature of the particulate material found throughout the galaxy that is responsible for the collapse of interstellar clouds and the formation of stars, planetary systems, and ultimately, life.

—Gabriele Rennie

Key Words: 2,175-angstrom feature, focused ion beam, glass with embedded metals and sulfides (GEMS), interplanetary dust particle (IDP), nanoscale secondary ion mass spectrometer (NanoSIMS), presolar grains, transmission electron microscope (TEM).

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Continued from p. 2

To locate the specific enhancer sequence responsible for SOST regulation, the team compared human and mouse DNA and found seven common segments within the 140,000-base-pair SOST region. Scientists assume DNA segments that have been "conserved" from one organism to another during evolution play a biological role, or they would have been discarded as organisms evolved. By introducing the conserved segments into cells similar to osteoblasts (bone-forming cells), the team found that a 250-base-pair conserved region named ECR5 was able to drive SOST expression.

The findings provide insight into long-range gene regulation and could lead to new treatments for osteoporosis and other crippling bone disorders. Funding for the research was provided by DOE's Office of Science and by the National Institutes of Health.

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BlueGene/L retains Top500 ranking

Livermore's BlueGene/L reaffirmed its ranking as the world's most powerful computer on the Top500 list, the leading industry authority for high-performance computing. The Top500's new list was announced June 22 at the 2005 International Supercomputing Conference in Heidelberg, Germany. IBM's BlueGene/L system, developed in partnership with the National Nuclear Security Administration (NNSA) and with the collaboration of Livermore scientists, demonstrated a sustained performance of 136.8 trillion operations per second (teraops) on the industry standard LINPACK benchmark. The Laboratory's Thunder machine is seventh on the list, with a sustained performance of 19.94 teraops.

Researchers are running science applications with BlueGene/L's 32 racks—half the final 64-rack configuration. "Even as we are bringing the machine to its full configuration, we are doing science critical to NNSA's mission to ensure the safety, security, and reliability of the nation's nuclear stockpile," says Dona Crawford, associate director for Computation. "This represents a great team effort led by NNSA's Advanced Simulation and Computing (ASC) Program. Working with our partners at IBM and Los Alamos and Sandia national laboratories, we are simultaneously advancing scientific discovery and the high-performance computing that makes it possible. The capabilities we are now beginning to apply to our national security missions will also be applicable to other domains."

According to Dimitri Kusnezov, director of the NNSA ASC Program, "Once complete, NNSA will have available the kind of national security tool needed to rapidly analyze urgent nuclear weapon stockpile aging issues. It will be used to run a broad range of simulation codes that support certification of our stockpile.

Contact: Dona Crawford (925) 422-1985 (crawford13@llnl.gov).

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

Patents

Integrated Electrical Connector
William J. Benett, Harold D. Ackler
U.S. Patent 6,897,557 B2
May 24, 2005
A sheet of electrically conductive material lies between two layers of nonconducting material that comprise the casing of an electrical chip. This electrical connector is attached to an electrical element embedded within the chip. An opening in the sheet is concentrically aligned with a pair of larger holes bored through the nonconducting layers. The opening is smaller than the diameter of an electrically conductive contact pin. The sheet is composed of flexible material so that the opening adapts to the diameter of the pin when the pin is inserted. The periphery of the opening applies force to the sides of the pin when the pin is inserted, thus holding the pin within the opening and in contact with the sheet using friction. The pin can be withdrawn from the connector by applying sufficient axial force.

Parasitic Oscillation Suppression in Solid State Lasers Using Optical Coatings
Eric C. Honea, Raymond J. Beach
U.S. Patent 6,904,069 B2
June 7, 2005
A laser gain medium has a layered coating on certain surfaces. This layered coating has a reflective inner material and an absorptive scattering outer material.

Solid Phase Microextraction Device Using Aerogel
Fred S. Miller, Brian D. Andresen
U.S. Patent 6,905,031 B1
June 14, 2005
A sample collection substrate of aerogel or xerogel materials bound to a support structure is used as a solid-phase microextraction (SPME) device. The xerogels and aerogels may be organic or inorganic and doped with metals or other compounds to target specific chemical analytes. The support structure is typically formed from a glass fiber or a metal wire (stainless steel or Kovar). The devices are made by applying gel solution to the support structures and drying the solution to form aerogel or xerogel. Aerogel particles may be attached to the wet layer before drying to increase the surface area of the sample collection. These devices are robust, stable in fields of high radiation, and highly effective at collecting gas and liquid samples, while maintaining superior mechanical and thermal stability during routine use. Aerogel SPME devices are advantageous for use in gas-chromatography and mass-spectrometry analyses because of their lack of interfering background and their tolerance for gas-chromatography thermal cycling.

Portable Pathogen Detection System
Billy W. Colston, Jr., Matthew Everett, Fred P. Milanovich, Steve B. Brown, Kodumudi Venkateswaran, Jonathan N. Simon
U.S. Patent 6,905,885 B2
June 14, 2005
This portable pathogen detection system detects multiple targets in biological samples onsite. The system includes microbead specific reagents, an incubation–mixing chamber, a disposable microbead-capture substrate, and an optical measuring and decoding unit. This system is based on a highly flexible liquid array that uses optically encoded microbeads as the templates for biological assays. Target biological samples are optically labeled and captured on the microbeads, which are in turn captured on a disposable substrate that has either an ordered or disordered array. The samples are then optically read.

Laser Driven Ion Accelerator
Toshiki Tajima
U.S. Patent 6,906,338 B2
June 14, 2005
This system and method for accelerating ions in an accelerator optimizes the energy produced by a light source. Several parameters can be controlled in constructing a target to adjust performance of the accelerator system. These parameters include the target's material, thickness, geometry, and surface.

Halbach Array Generator–Motor Having Mechanically Regulated Output Voltage and Mechanical Power Output
Richard F. Post
U.S. Patent 6,906,446 B2
June 14, 2005
A generator–motor has its stationary portion (that is, the stator) positioned concentrically within its rotatable element (that is, the motor) along the axis of the rotor's rotation. The rotor includes a Halbach array of magnets. The voltage and power outputs are regulated by varying the radial gap between the stator windings and the rotating Halbach array. The gap is varied by extensible and retractable supports that are attached to the stator windings and can move the windings in a radial direction.

Electronic Noncontacting Linear-Position Measuring System
Richard F. Post
U.S. Patent 6,906,528 B2
June 14, 2005
A noncontacting linear-position location system uses a special transmission line to encode and transmit magnetic signals to a receiver on the object whose position is to be measured. This invention is useful as a noncontact linear locator of moving objects. It can be used, for example, in determining the location of a magnetic levitation train for the operation of the train's linear-synchronous motor drive system.

Application of the Phase Shifting Diffraction Interferometer for Measuring Convex Mirrors and Negative Lenses
Gary E. Sommargren, Eugene W. Campbell
U.S. Patent 6,909,510 B2
June 21, 2005
A reference beam and a measurement beam are both provided through a single optical fiber to measure a convex mirror. A positive auxiliary lens is placed in the system to provide a converging wave front on the convex mirror being measured. A measurement is taken that includes the aberrations of the convex mirror as well as the errors due to two transmissions through the positive auxiliary lens. A second measurement provides the information to eliminate this error. A negative lens can also be measured in a similar way. Again, there are two measurement setups. A reference beam is provided from an optical fiber, and a measurement beam is provided from a second optical fiber. A positive auxiliary lens is placed in the system to provide a converging wave front from the reference beam onto the negative lens being measured. The measurement beam is combined with the reference wave front and is analyzed using standard methods. This measurement includes the aberrations of the negative lens as well as the errors due to a single transmission through the positive auxiliary lens. A second measurement provides the information to eliminate the error.

Abstracts

A Dynamo of a Plasma

The Sustained Spheromak Physics Experiment (SSPX) at Lawrence Livermore is creating magnetized plasmas that have two distinct applications: for fusion energy as a source of electrical power and for studying astrophysical magnetic plasmas such as solar flares. In magnetic plasmas, magnetic reconnection events create a dynamo, which confines the plasma in space and sustains it over time. But magnetic reconnection is poorly understood; examining its physics is the primary focus of SSPX experiments. Since 1999 when SSPX was dedicated, the Livermore team has boosted the electron temperature of plasmas in SSPX from 20 electronvolts to about 350 electronvolts, a record for a sustained spheromak. Although this temperature is a long way from the minimum 10,000 electronvolts needed for a viable fusion energy power plant, it is a significant step toward achieving fusion with a spheromak.

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How One Equation Changed the World

Many Livermore research efforts are linked to a three-page paper written by Albert Einstein in September 1905. This short paper turned physics upside down by linking mass and energy in a way never before postulated. The paper led to the equation $E = mc^2$, probably the most famous equation in the world. $E = mc^2$ underlies nuclear fission and fusion, energy sources that do not produce carbon emissions or deplete nonrenewable hydrocarbon fuels. For fusion energy, two ways are being pursued to contain fusion fuel at the required temperatures and densities to produce energy: magnetic confinement and inertial confinement. $E = mc^2$ offers to transform life on Earth because of this prospect for abundant, clean energy.

World Year of Physics events at Livermore: www.llnl.gov/pao/WYOP.

U.S. Government Printing Office: 2005/783-059-10011

Livermore's Award-Winning Technologies

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Livermore won four awards in *R&D Magazine's* annual competition for the 100 most significant technological products and processes.

Also in October

- *Using molecular dynamics calculations run on the Thunder supercomputer, Laboratory researchers are examining how water behaves under extreme conditions.*

- *Livermore scientists are producing lightweight sources of x rays to backlight inertial confinement fusion experiments and radiation-effects tests.*

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

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