December 2007

Science & Technology Review

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Safeguarding Nuclear Materials

Also in this issue:

- Unlocking the Secrets at Earth's Core
- Improved Security for Wireless Communication
- Teller's Legacy in Nuclear Power Research

About the Cover

The International Material Protection and Cooperation Program, operated by the Department of Energy's National Nuclear Security Administration, is working with the Russian Federation to keep nuclear material out of the hands of terrorists. As described in the article beginning on p. 4, researchers at Livermore and other national laboratories have trained Russian personnel to perform vulnerability analyses and install protection devices such as barriers, monitoring systems, alarms, access controls, and vehicle inspection facilities. As a result of the program, security has been enhanced at Russia's weapon design institutes, naval bases, uranium and plutonium storage sites, fuel processing centers, and nuclear power reactors. The cover shows ships moored at a Russian port.

Cover design: Alexandria Ballard. Photographer: Pavel Parmenov.

About the Review

At Lawrence Livermore National Laboratory, 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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Science & Technology REVIEW

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National
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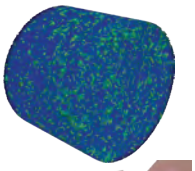

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NanoSIMS digs deep to study microorganisms in soil

Scientists may soon be able to examine microhabitats within soils using Livermore's nanometer-scale secondary-ion mass spectrometer (NanoSIMS). This precise tool can determine the elemental and isotopic content of soil with a resolution of 50 nanometers. Results from a collaborative study, published in the August 2007 issue of *Soil Biology & Biochemistry*, showed that NanoSIMS can qualitatively determine how nitrogen and carbon isotopes assimilate into soil microorganisms. Researchers at the University of Western Australia also found that the high-resolution tool can detect isotopically enriched bacterial cells in soil.

Soils are highly complex porous mixtures that are structurally heterogeneous. Microorganisms act as go-betweens for a range of reactions occurring between the physical, chemical, and other biotic components of the soil environment. Because soils and the microorganisms in them are so small, a precise instrument such as NanoSIMS is required to evaluate these interactions.

"NanoSIMS shows promise for studying the heterogeneity and microbial activity in soil's microhabitats," says Jennifer Pett-Ridge, a postdoctoral researcher on the Livermore team. "However, this application is still at a very early stage." The Livermore research also indicates that NanoSIMS could trace the uptake of fertilizer and other organics, track the stabilization of organic matter in soil, determine the spatial distribution of active microorganisms, distinguish the microorganisms associated with specific minerals, and establish the role of fungi in soil.

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Simulations indicate laser is on track

Computer simulations based on data from the National Ignition Facility (NIF) 2003–2004 Early Light Campaign produced results that mirror experimental measurements to an unprecedented degree. The simulations, which are discussed in the October 2007 edition of *Nature Physics*, indicate that NIF's laser beams will propagate effectively in plasma-filled targets designed to produce the world's first laboratory demonstration of inertial confinement fusion. "Getting agreement on that scale is something new," says Livermore scientist Siegfried Glenzer, who led the simulation team.

The *Nature Physics* paper examined two experimental situations. In one simulation, an unsmoothed laser beam entering the target stalled in the hot plasma. As a result, about 30 percent of the laser's light backscattered and failed to reach the target's center. The second simulation tracked a smoothed laser beam as the beam moved through a 7-millimeter-long tube of carbon dioxide. In the inertial confinement fusion experiments planned for NIF, laser beams must pass through a large volume of plasma to reach the target center and ignite a sustained fusion reaction.

The computer simulation tracked 3.5 nanoseconds of laser beam pulse, more than 1,000 times longer than the pulse usually modeled by a laser–plasma code. The results showed how the target and beam geometry changed over time, revealing details down to the wavelength scale—a few hundred nanometers, or billionths of a meter. Livermore researchers are using simulations such as these to design upcoming NIF experiments.

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Global warming increases atmospheric moisture

A collaboration involving researchers from Lawrence Livermore and eight other institutions has confirmed that human-induced global warming is affecting the total moisture content of the atmosphere. The study, which appeared in the September 25, 2007, *Proceedings of the National Academy of Sciences*, combined observational data from the satellite-based Special Sensor Microwave Imager with results from 22 climate models.

During the past 20 years, the total atmospheric moisture content over oceans has increased each decade by 0.41 kilogram per square meter, an amount that cannot be explained by natural variation alone. The research team, led by Livermore scientist Benjamin Santer, found that this increase in water vapor is not caused by solar forcing or the gradual recovery from particulates ejected by the 1991 Mount Pinatubo volcanic eruption. Instead, the research results showed that the primary driver for this atmospheric moistening is the increased levels of carbon dioxide caused by burning fossil fuels.

"When you heat the planet, you increase the ability of the atmosphere to hold moisture," says Santer, who works in the Laboratory's Program for Climate Model Diagnosis and Intercomparison. Water vapor is itself a greenhouse gas, so increasing amounts of water vapor will amplify the warming effect from carbon dioxide buildup. The team's results indicate that the increase in water vapor is about 6 to 7.5 percent per °C of warming in the lower atmosphere.

When combined with similar studies of continental-scale river runoff, zonal mean rainfall, and surface-specific humidity, these findings point toward a human-caused signal in the cycling of moisture between the atmosphere, land, and ocean. "This work shows that the climate system is telling us a consistent story," says Santer. "The observed changes in temperature, moisture, and atmospheric circulation fit together in an internally and physically consistent way."

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Homeland Security Begins Abroad

LONG before the terrorist group Al Qaeda burst onto the world stage, Lawrence Livermore and other national laboratories were quietly working far from home to secure a first line of defense against nuclear terrorism.

Following the collapse of the Soviet Union in 1991, the security apparatus for protecting the vast stocks of Soviet nuclear materials was in jeopardy as guards, scientists, and other nuclear workers went unpaid for months. Former Laboratory director John Nuckolls was one of the first to call attention to the possibility that poorly secured weapons or materials could fall into the hands of proliferators or terrorists or that economic necessity might tempt weapons scientists to accept employment with rogue states or terrorist groups.

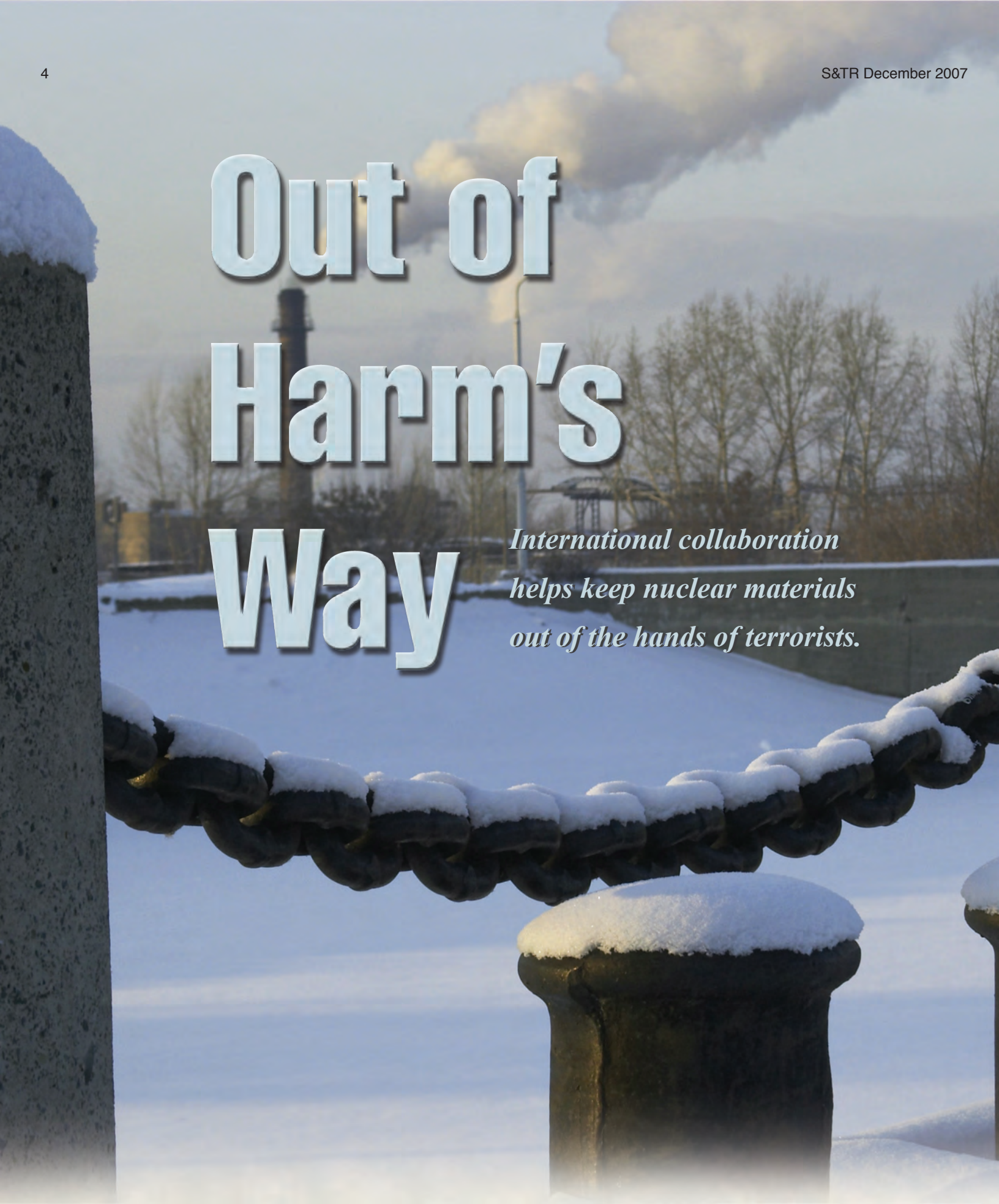
Congress responded with legislation launching a suite of nonproliferation programs, including the Department of Defense's Cooperative Threat Reduction Program and the Department of Energy's laboratory-to-laboratory program. Over the past 16 years, these efforts have significantly advanced global security. They have led to the deactivation and destruction of thousands of nuclear warheads, hundreds of intercontinental ballistic missiles, nuclear surface-to-air missiles, and submarine-launched missiles as well as nuclear submarines, nuclear bombers, submarine and mobile missile launchers, missile silos, and nuclear test tunnels. In addition, hundreds of tons of weapons-usable nuclear material at facilities across the former Soviet Union have been secured.

During this period, Laboratory personnel have made countless trips to Russia and other former Soviet states to work with their counterparts at sites from Moscow to Murmansk to Kamchatka. In addition to the work to secure at-risk nuclear material under the International Material Protection and Cooperation Program, Livermore personnel have helped to improve Russian border security and the interdiction of smuggled nuclear materials and to recover at-risk and orphan radioactive sources. They have held numerous training workshops aimed at implementing more rigorous procedures to prevent the export of Russian dual-use technologies. They have also worked with many hundreds of former Soviet weapons scientists to help develop nonmilitary applications of their technologies and establish self-sustaining civilian enterprises that will employ former weapons workers.

The attacks on September 11, 2001, turned the country's focus to the threat of terrorism and the possibility that terrorists might acquire and use weapons of mass destruction (WMD). The U.S. established the Department of Homeland Security and launched the global war on terrorism, appropriating billions of dollars to support these efforts. The Laboratory has contributed much to improve security at home and abroad, from developing advanced detectors for biological, explosive, and radiological materials to tracking terrorist efforts to acquire WMD capabilities.

And all the while, as described in the article beginning on p. 4, Laboratory personnel have continued to work quietly but steadily to address the most important step in nuclear terrorism prevention—securing nuclear materials at the source. These unsung heroes will never capture the spotlight with a spectacular smuggling bust or the invention of an amazing new detector, but surely and steadily, they are helping to improve the protection and control systems for securing materials that could fuel the flames of WMD proliferation and terrorism.

■ John C. Doesburg is principal associate director for Global Security.



Out of Harm's Way

International collaboration helps keep nuclear materials out of the hands of terrorists.

THE September 11, 2001, attacks on the U.S. and subsequent bombings in Madrid, Bali, London, and Moscow vividly demonstrate the determination of terrorist groups to strike fear and inflict mass destruction. Keeping nuclear materials and weapons safe and secure is imperative.

Nowhere has the challenge of protecting these materials been greater than in the former Soviet Union. The security system for protecting vast stockpiles of nuclear warheads and materials fell into disarray when the Soviet Union split into individual states in 1991. With the Russian government in transition, financial support for nuclear sites was chaotic at best. A social and economic malaise set in. Scientists and other nuclear workers were not paid for months, and the infrastructure at nuclear facilities began to crumble.

This situation was ripe for clandestine operations by rogue nations or terrorists who wanted to acquire these extremely dangerous materials. Reports of stolen nuclear material began to surface. Poverty-stricken nuclear scientists with their weapons know-how became targets for bribery.

Sixteen years later, the Russians have markedly improved their security, thanks in part to several programs implemented by the Department of Energy (DOE) in the early 1990s. One such program is called International Material Protection and Cooperation (IMPC). Now managed by DOE's National Nuclear Security Administration (NNSA), the IMPC Program focuses on upgrading protection, control, and accountability systems to safeguard nuclear materials.

Through IMPC, Russian facilities are now equipped with alarmed fences, electronic access control and delay systems, vehicle inspection facilities, and alarm control and display consoles. Accounting and control systems also measure, track, and monitor nuclear material inventories, and new regulations and procedures help protect Russia's civilian and military nuclear sites.

Perhaps most importantly, scientists and nuclear workers in Russia recognize that protecting these materials is fundamental to global security. To further promote a culture of nuclear safety and security, NNSA sponsored a graduate program on the protection, control, and accounting

of nuclear materials at the Moscow State Engineering Physics Institute. Program graduates are ardent proponents of the multilayered approach to security that is common at U.S. facilities.

Cooperation Is Key

NNSA's IMPC Program, formerly called the Material Protection, Control, and Accountability Program, is a cooperative effort with the Russian Federation. The program focuses on protecting facilities that process or store weapons-usable nuclear materials. Security has been enhanced at various locations, including weapon design institutes, naval bases, uranium and plutonium storage sites, fuel processing centers, and nuclear power reactors. Livermore has been a leader in the program from the beginning. (See *S&TR*, September 1997, pp. 14–23; September 2000, pp. 4–12.) Since the early 1990s, dozens of security projects have been implemented across Russia.

The NNSA program receives high-level governmental support in both countries. Russian Prime Minister Viktor Chernomyrdin worked with U.S. Vice President Al Gore to place presidential emphasis on the initial program. Later, DOE Secretary Bill Richardson signed some of the first protocols with the Russian military. At a 2005 summit in Bratislava, Slovakia, U.S. President George W. Bush and Russian President Vladimir Putin agreed to enhance and accelerate their countries' cooperation in defending against nuclear terrorism.

The 9/11 attacks gave the program a sobering boost. "We had been humming along, improving protections at an array of sites, when 9/11 happened," says Mike O'Brien, the deputy program leader for Livermore's IMPC effort. "Almost overnight, we had a much larger project. We had to evaluate more sites and develop more improvements—all within a much shorter turnaround time."

The initial work focused on securing points of origin, such as storage sites and nuclear research facilities, and on creating a first line of defense around them. IMPC is also addressing the second line of defense, developing methods to better monitor Russia's border crossings and shipping ports.

Protecting the Goods

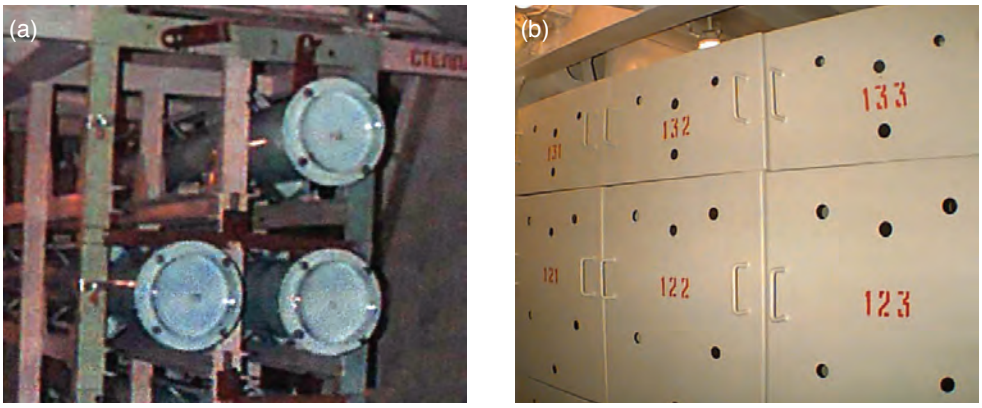
Personnel at a U.S. nuclear weapons laboratory such as Livermore deal with this issue daily and understand the multiple layers of security. "Guns, guards, and gates are obvious tools for protecting nuclear materials," says Mo Bissani, who leads Livermore's IMPC Program. Even more important, however, are the less noticeable regulations and procedures, such as material accounting and monitoring procedures, vulnerability analyses, protection plans, training programs, and an ever-present awareness by employees of safety and security. For example, a basic rule throughout DOE's NNSA complex is that two people must be present when working with nuclear materials. This two-person rule not only improves safety but also helps prevent insider threats, where site personnel attempt to steal materials.

According to Bissani, the first step in protecting materials against both external and insider threats is to characterize a site's inventory. Laboratory staff work with Russian personnel to evaluate how much nuclear material a facility has, how "attractive" the material is for terrorist activities, where the material is stored, and what those storage conditions are. The collaborative teams then examine improvement options, often using computer models to compare choices, and validate the results before implementing protective upgrades.

The Livermore IMPC team also helps train Russian technical personnel to perform vulnerability analyses using the Analytic System and Software for Evaluating Safeguards and Security (ASSESS) methodology, which was developed at the Laboratory. IMPC team member Bill Abramson has been teaching the vulnerability analysis concept since 1996. Since then, hundreds of technical staff members at Russian facilities have been trained.

The first site to implement ASSESS was the Kurchatov Institute, Russia's premier nuclear physics research laboratory. A DOE team worked with the Moscow institute to install an array of physical protection and monitoring systems. Today, Livermore personnel provide support to maintain these upgrades.

ASSESS is also being deployed at Chelyabinsk-70—a site of special interest



(a) Before the Department of Energy initiated the International Material Protection and Cooperation Program, the Russian Federation stored highly enriched uranium in canisters with tamper-indicating devices but no alarms. (b) Today, canisters are behind alarmed doors that must be opened remotely.

for the Laboratory. Chelyabinsk-70 is the second nuclear weapons design facility established in the Soviet Union and home of the All-Russian Scientific Research Institute of Technical Physics. Now called Snezhinsk, the town is the sister city for Livermore, California.

Seals and tamper-indicating devices are essential parts of material protection and control. At U.S. nuclear sites, these are electronic devices that trigger alarms and other alerts when material security has been compromised. Before IMPC, such devices at Russian facilities often consisted of string and sealing wax. A broken seal indicated that someone had tampered with the goods. But these inexpensive seals cannot identify who accessed material or when, and they do not prevent theft. Resealing a container is also relatively easy. To improve security at the Russian facilities, personnel from Livermore and other national laboratories led workshops demonstrating the importance and use of more secure tamper-indicating technologies.

The Laboratory's IMPC team has been involved in vulnerability analyses and protective upgrades at nuclear bases operated by the Russian Navy. The Navy's northern fleet is headquartered near Murmansk and has bases along the northern coastline of the Barents Sea above the Arctic Circle. The Pacific fleet, headquartered in Vladivostok, has bases along the Pacific coastline and around the Kamchatka Peninsula. IMPC teams have worked with the 12th Main Directorate and the Strategic Rocket Forces of the Russian Ministry of Defense to address security concerns at these remote bases.

O'Brien, who has worked with IMPC since the program began, recalls that success with the icebreaker fleet at Murmansk was key to winning over officials of the Ministry of Defense and the Russian Navy. The Murmansk effort demonstrated NNSA's dedication to the IMPC Program. The administration assigned a team of researchers from Lawrence Livermore, Los Alamos, Oak Ridge, and Sandia national laboratories to work solely with the Russian Navy. At the time, these four institutions were the only U.S. laboratories authorized to work with the Russian Ministry of Defense.

Abramson continues to travel to four naval bases on the far eastern coast of Russia where he leads a project to improve nuclear security. He worked with the Russian teams to conduct vulnerability analyses at each site. Since then, the bases have installed barriers, closed-circuit television monitoring systems, alarms, access controls, and portal monitors.

"In an area that averages 10 meters of snow annually, an important upgrade was better facilities for guards," says Abramson. Not only are the facilities improved from a security standpoint, but they now also have more protected muster areas, break rooms, and places for workers to escape the cold

Security has been upgraded at civilian and military nuclear sites throughout the Russian Federation.

while on duty. Vehicle inspection portals can now be enclosed in winter so inspectors are protected from the cold and flying snow. Because the weather is harsh and the bases are remote, upgrades included emergency generators to ensure that lighting, alarms, and computer-controlled systems operate continuously.

Another way to keep weapons-grade nuclear materials out of harm's way is to mix them with other substances, a process called down-blending. The result is a material that is less attractive to terrorists because it is more difficult to use in an improvised nuclear explosive device. Down-blended materials are analytically verified and stored in a secure location. Material that cannot be down-blended is consolidated, when possible, for storage. The Laboratory's IMPC team helped standardize packaging containers and develop machine-readable identification codes for container labels.

Maintaining Control

In the past, the Soviets accounted for special nuclear materials in financial terms rather than by quantity and did not maintain a national-level automated accounting system. In 1996, Livermore's IMPC team began leading a project to help Russia implement a more effective approach. The Federal Information System (FIS) is designed to track and monitor nuclear materials in Russia's civil sector. The system is based on the Nuclear Materials Management and Safeguards System used by DOE, NNSA, and the U.S. Nuclear Regulatory Commission and meets the reporting requirements of the International Atomic Energy Agency and other international standards and treaties.

In 1998, following a series of training workshops, Russian scientists produced a report that summarized how the DOE/NNSA system could be applied in Russia. Livermore and Russian scientists then jointly developed software specifications, levels of reporting, types of reports, and documentation for the Russian system. "FIS standardizes the codes that the civil sector uses in Russia," says Rusty Babcock, who joined the FIS project in 1997 and has led it since 2000. "FIS also standardizes the rules and frequency of reporting for a national material control and accounting program."

Russia began deploying this comprehensive system at its civilian nuclear sites in 2001. The 60-plus sites under the authority of the Federal Agency for Atomic Energy reported data to the system for the first time in January 2002. Each facility has several areas where nuclear materials are located. Data are summarized at the site level and eventually reported to the central Russian government.

Currently, FIS reports are compiled annually, but more frequent and detailed reporting cycles are planned. The U.S.

At one Russian site, a new facility was built so that guards are stationed closer to the materials they protect, which shortens response time in an emergency.

Weapons-grade nuclear material is "down-blended" by mixing it with other substances before it is placed in permanent storage. This down-blended material is less attractive for terrorist activities.

has supported the hardware and software developments needed to improve Russia's electronic infrastructure so that remote sites can submit reports to FIS.

Keeping It Running

Livermore's IMPC team also helps Russia ensure that upgraded sites are kept in top condition. "After 15 years, we are wrapping up the security upgrade phase of the project," says Bissani. "We are working with our counterparts to develop systems for maintaining the protective infrastructure." Comprehensive regulations, continued training, systematic inspections, and routine maintenance are considered key to sustaining the effectiveness of protections in place.

O'Brien leads an effort with the Kurchatov Institute to develop regulations related to nuclear security for the Russian Federation's Ministry of Defense. The team has identified the regulatory needs for the military services and anticipates completing the work in 2012.

Training for the Russian military is an important element of IMPC's sustainability phase. A recent achievement is the Kola Technical and Training Center established for the Navy's northern fleet. Oak Ridge worked with the Livermore team to design the center at Severomorsk, about 640 kilometers northeast of Moscow. In July 2005, the center was officially dedicated by Russian leaders and NNSA administrator Linton Brooks.

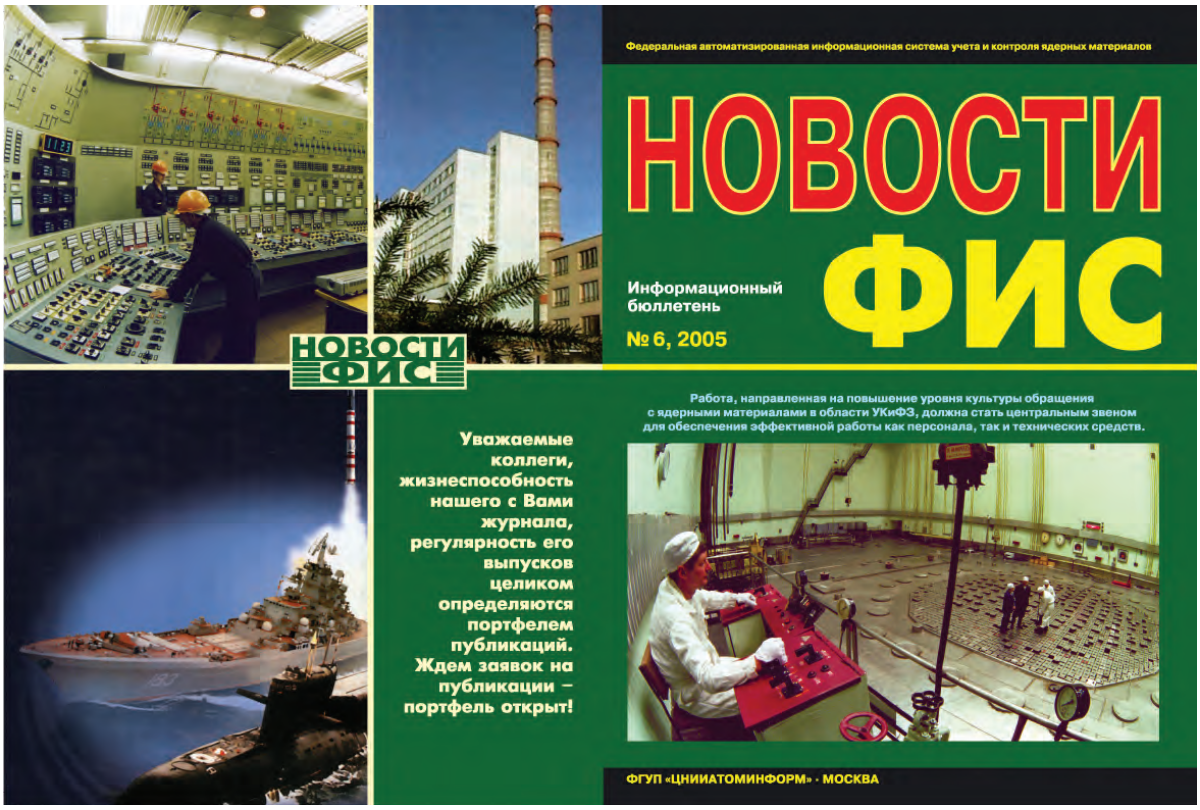
More than 600 naval personnel, including security managers and system operators, receive training each year at the Kola center. Laboratory scientist Mary Huddleston led the team assigned to develop the center's training courses. Approximately 40 courses address such issues as console operation; badging procedures; access control; security system design and maintenance; and management procedures for material protection, control, and accounting.

Abramson is helping the Russian Navy establish a similar facility for its Pacific fleet. Livermore's Melinda Lane will adapt the Kola training program for use at the Pacific facility.

The Bigger Picture

In 2006, NNSA began a collaboration with Ukraine and Kazakhstan to strengthen the nuclear security regulatory systems and standards in those countries. At a joint workshop in June 2006, researchers from Lawrence Livermore and Pacific Northwest national laboratories met with their counterparts in Ukraine and Kazakhstan to review assessments and prioritize the proposed schedule for modifying regulatory documents and developing new ones.

The IMPC Program is also exploring areas of cooperation with China. A joint



Russia's nuclear material accounting system is called the Federal Information System (FIS). The National Nuclear Security Administration initiated an annual magazine, *News FIS*, to keep nuclear staff informed about training, procedures, forms, and other system updates. The magazine's Web site (www.fisnews.ru) also helps employees stay up to date.

program between IMPC and NNSA's Office of Nonproliferation and International Security enlisted personnel from Lawrence Livermore, Sandia, Los Alamos, and Oak Ridge to collaborate with their technical counterparts in China.

In 2005, as part of a coordinated material protection, control, and accounting demonstration, Livermore and Sandia worked together to upgrade systems at the Fast Neutron Critical Facility and a materials storage facility for the China Institute of Atomic Energy. A safeguards laboratory at the institute hosted technical exhibits in conjunction with the demonstration. At the exhibit, O'Brien presented DOE/NNSA-approved procedures for vulnerability assessments, physical protection, regulations, and inspections to Chinese safeguards engineers and analysts and civilian nuclear industry officials. Livermore's Wayne Ruhter discussed nondestructive analysis techniques, and Babcock explained national-level nuclear material accounting procedures. In the current phase of the program, O'Brien is training Chinese nuclear personnel to analyze insider threats.

Largely because of 9/11 and its aftermath, NNSA is overseeing a second program, called the Global Threat Reduction Initiative, to reduce and secure radiological materials at research reactors and other locations throughout the world. This initiative is being carried out in cooperation with the International Atomic Energy Agency and other global partners.

Continued training is an important component of sustaining the security upgrades and new mind-set about security. The Kola Technical and Training Center, which opened in 2005, serves personnel of the Russian navy's northern fleet.

Livermore scientist Mike O'Brien presented a technical briefing on nuclear security to staff at the China Institute of Atomic Energy.

In response to evolving threats, Livermore and other national laboratories have helped lay the groundwork for safer, better protected nuclear sites in Russia and other countries. Laboratory scientists have gotten to know their Russian counterparts very well, a concept unimaginable not so many years ago. Together, they are imbuing a culture of safety and a sense of collective responsibility within the Russian nuclear community because, in the end, personnel reliability and trust are the keys to nuclear material protection. And safeguarding those materials is central to global security.

—Katie Walter

Key Words: China; Federal Information System (FIS); International Material Protection and Cooperation (IMPC) Program; Material Protection, Control, and Accountability Program; nonproliferation; nuclear materials; Russian Federation.

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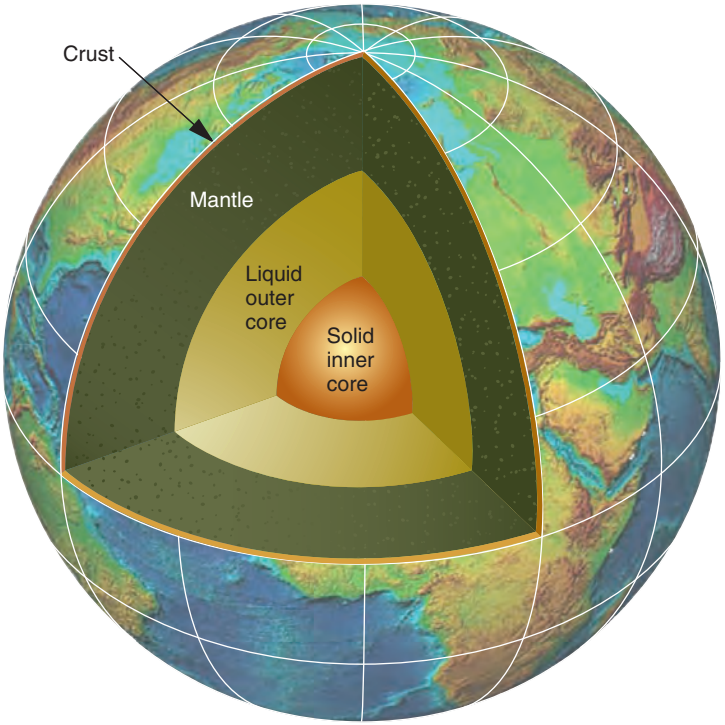
A Calculated Journey to the Center of the Earth



A cutaway view of Earth shows the planet's solid inner core composed mostly of iron, surrounded by a molten outer core, followed by a mantle and a thin crust of rocky, silicate material.

PLANET Earth still holds many scientific mysteries. One that particularly intrigues scientists is how and when the planet's core formed. In Jules Verne's 1864 novel *Journey to the Center of the Earth*, an inquisitive scientist hikes down the inside of an Icelandic volcano to examine the inner Earth. Uncovering the truth of what lies beneath Earth's crust is even more difficult in life than it was in Verne's fiction. Scientists have yet to travel through the planet. Instead, they use indirect methods such as examining meteorites and conducting seismic studies to deduce how and when Earth's core formed.

However, a technique developed by a team of Livermore scientists has, for the first time, allowed researchers to measure the permeability of molten iron compounds in olivine, a mineral in the upper mantle, under conditions that mimic those at the center of planetesimals—the precursor bodies to new planets. Because this physical parameter is experimentally constrained, geophysicists have a key measurement to help them evaluate models of core formation and examine other geologic processes, such as heat flow, tectonics, volcanism, and magnetism. Understanding these mechanisms will help unlock the secrets of Earth and other terrestrial-like planets, meteorites, and planetesimals.

The Core Issue

Using meteorites and seismic records as clues, scientists have determined that all terrestrial planets have cores. Earth has a solid inner core composed mostly of iron, surrounded by a molten outer core, followed by a mantle and a thin (5- to 50-kilometer-deep) crust of rocky, silicate material. Most scientists agree that density is the driving force behind this layered formation, resulting in chemical fractionation—a process in which substances in a mixture separate or segregate depending on their physical and chemical properties. In this critical process, denser materials such as iron migrate toward the center, while lighter materials such as silicates are forced toward the surface. However, scientists have yet to determine how this segregation occurs.

"Several models have been proposed," says experimental geophysicist Jeff Roberts, who leads the Livermore research. For example, the "magma ocean" model starts with a planet that has a large molten region—the magma ocean layer in which molten metals and minerals commingle. In this model, gravity draws the molten metal through the lighter liquids in a lava-lamp-like process until the metals and silicates separate into layers. The percolation model, on the other hand, proposes a slower mechanism in which the denser molten metal trickles down between solid silicate mineral grains, akin to water percolating through sand.

Squeeze, Heat, and Image

To evaluate the percolation model, researchers must determine the percolation threshold—the point at which the molten metal begins to migrate through, or permeate, the matrix of minerals rather than form isolated pockets. The percolation threshold varies a few percent based on the wetting or nonwetting behavior of the materials involved. For example, the estimated threshold for nonwetting metal mixtures ranges from 3 to 7 percent by volume. Estimates for permeability, a parameter that measures a material's ability to transmit fluid, vary even more, by many orders of magnitude.

Directly measuring the percolation threshold under temperatures and pressures relevant to core formation has been impossible up to now. Roberts and his team, which included geochemists Rick Ryerson and Julien Siebert and physicist John Kinney, changed all this. With funding from Livermore's Laboratory Directed Research and Development Program, they combined experiments and simulations to determine the percolation threshold and

permeability of molten iron sulfide migrating through a crystalline olivine matrix at temperatures and pressures representative of Earth's interior.

To create realistic samples of what would have existed early in Earth's geologic history when the core was forming, the team examined the composition of meteorites. Ryerson and Siebert prepared the samples by mixing finely ground olivine crystals, one of the most common minerals in Earth, with iron sulfide or an iron–nickel sulfide powder. The proportion of molten metal to crystal olivine in the mix varied from 2 to 13 percent. "This proportion spans the estimates established for the percolation threshold—the amount of molten metal needed to form a continuously connected melt," says Siebert. The concentration of nickel varied from 0 to 10 percent, a range that researchers believe matches the proportion of nickel in Earth's core.

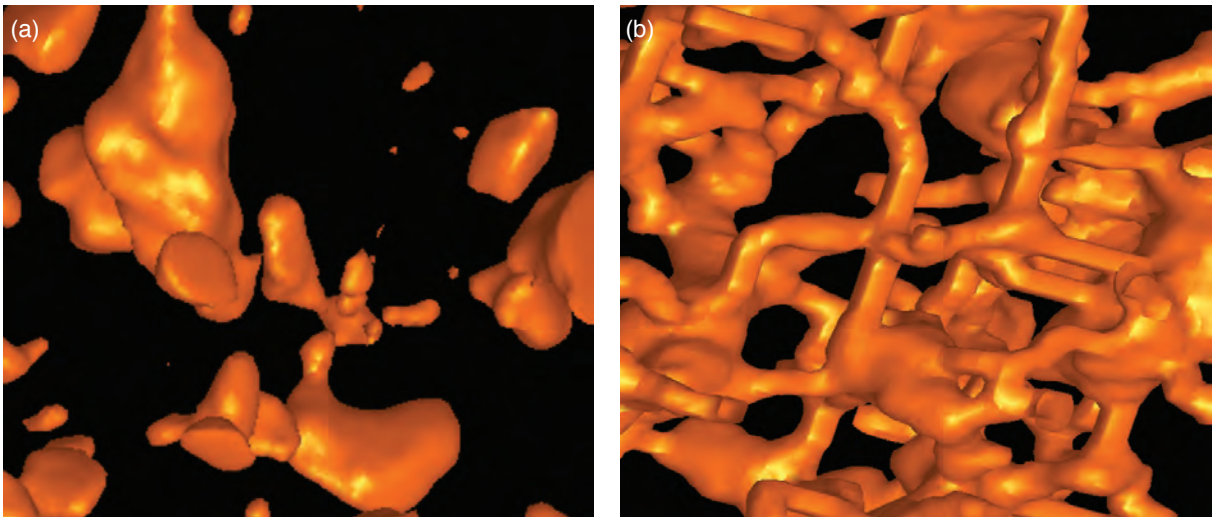
Samples, each about the size of a pencil eraser, were created with a piston cylinder press, using techniques originally developed by Livermore's William Minarik to study Earth's formation. (See *S&TR*, December 1996, pp. 21–23.) For 24 hours, the samples were subjected to temperatures of 1,350°C and pressures of 1 gigapascal, conditions believed to be characteristic of Earth's interior early in the planet's formation. The samples were then quenched, freezing the molten metal within the olivine matrix.

To examine the structure of this metal, Roberts imaged the samples at Lawrence Berkeley National Laboratory's Advanced Light Source using an x-ray tomography beamline and software Kinney developed while researching bone structure. (See *S&TR*, September 2006, pp. 20–22.) Their efforts yielded striking three-dimensional images showing the structure of the metal–olivine samples with a spatial resolution of 1.6 micrometers.

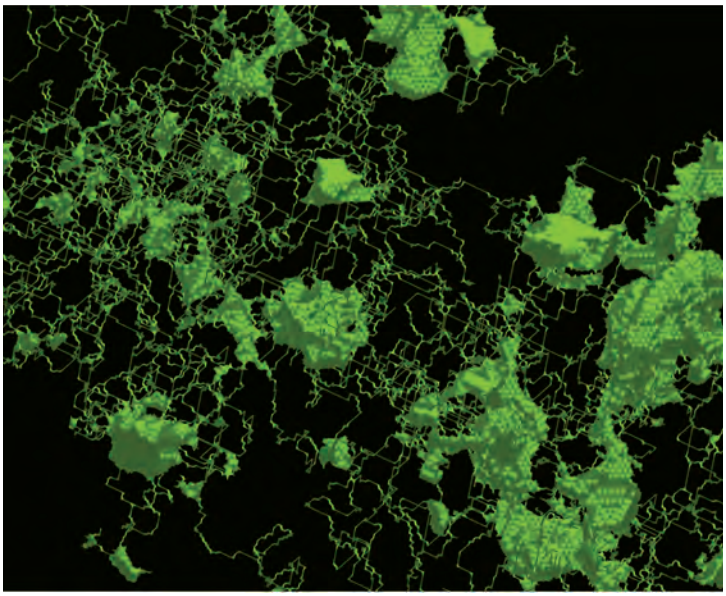
"The metal is more opaque to x rays than the olivine matrix, making it easy to distinguish the structure of the melts," says Kinney. In the images, percolating and nonpercolating melt fractions clearly differed. The distribution of the metal melts, their degree of interconnectivity throughout the matrix, and the pockets of melted metal were also apparent.

Going with the Flow

Next, the team used the x-ray computed tomography data in computer simulations to determine a sample structure's permeability. For these calculations, each image was divided into discrete computational (mathematical) spaces, called lattices. The team then used a lattice Boltzmann solver, an algorithm that speeds the calculation, to solve the Stokes flow equation for the defined lattices. In this type of flow, the inertial forces are smaller than the viscous forces, and flow is laminar.



X-ray computed tomography images distinguish the structure of molten metal within an olivine matrix. (a) In a sample with a 4-percent melt of iron sulfide, the molten metal exists primarily in pockets. (b) With a 6-percent melt of iron–nickel sulfide, these pockets are connected by tiny channels of metal.



Computer calculations indicate that permeability depends on small tubules of molten metal connecting melt pockets.

With the resulting images and calculations, the scientists calculated permeabilities for different melt fractions and put limits on previous estimates. They also established the percolation threshold for various percentages of melt to olivine and determined that percolation may have contributed to planetary core formation. For example, the team calculated that a 100-kilometer-diameter meteorite with a melt fraction of 10 percent has a permeability of approximately 2×10^{-15} square meters. This measurement indicates that the molten metal would migrate about 1.5 centimeters per year.

"Iron-rich cores apparently formed in these types of objects within about 3 million years," says Roberts, "which corresponds to a melt velocity of about 3.3 centimeters per year. Thus, the calculated migration rates are consistent with percolation being the formation mechanism." He added that the team's calculated permeabilities probably form a lower boundary. "We used an average grain size of 45 micrometers for the olivine," he says. "The larger grain sizes observed in meteorites would support an even higher permeability."

A Closer Look at Other Processes

Research using the team's techniques is examining core formation and other processes. Livermore researchers are collaborating with colleagues at the University of Minnesota and the University of California at Davis to explore deformation in more detail. For example, in some samples, the molten metal formed stand-alone "melt pockets." The research team wants to determine whether deforming and twisting the sample—a shearing-type action that often occurs during earthquakes and other geologic events—might cause the pockets to connect and allow the metal to flow.

In a project funded by the Department of Energy's Office of Basic Energy Sciences, the researchers are attempting to estimate permeability using the measured electrical conductivity for a sample of interconnected melt. "An interconnected melt is a continuous web of essentially very tiny wire," says Roberts. "In theory, we could run a current through it to learn more about the melt's structure."

Researchers are adapting the team's measurement technique to examine other geologic materials. For instance, a collaboration involving the U.S. Geological Survey and the University of Oregon is using the Livermore approach to study the explosive nature of volcanic materials. "Basically, they are imaging different volcanic glasses such as tuff and pumice and calculating the permeability of gases in the materials," says Roberts. "With those results, they can determine which conditions will allow gas to flow through and escape and which will trap it in pockets and possibly cause an explosion."

The Livermore technique, which measures a previously unobtainable physical parameter, also has applications beyond the team's initial focus. "Now that this method exists," says Roberts, "we'll be interested to see where the research goes from here."

—Ann Parker

Key Words: Advanced Light Source, core formation, iron sulfide, magma ocean, mantle, olivine, partial melt, percolation, permeability, volcanic glass, x-ray computed tomography.

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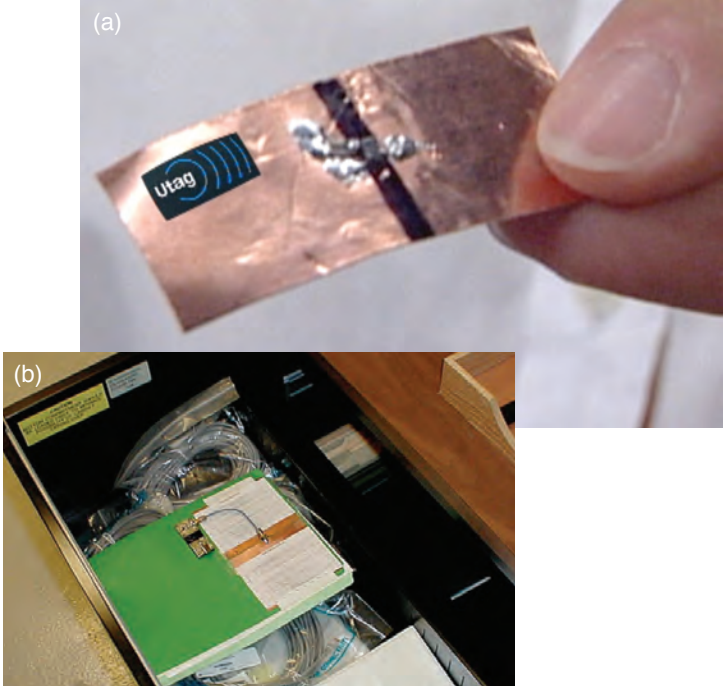
Wireless That Works



(a) Utags are small, lightweight radio-frequency identification devices that use ultrawideband signals to monitor cargo containers. (b) In tests, Utags were attached to documents and placed inside metal cabinets. Results showed the metal did not interfere with the transmitted signals.

EVEN though cell phones and other wireless communication technologies are in widespread use, reception is notoriously poor in certain places such as underground or in tunnels and dense urban landscapes. Livermore engineer Faranak Nekoogar calls these hard-to-reach areas "harsh propagation environments." Nekoogar, who works in the Laboratory's Engineering Directorate, leads an effort to develop wireless communication technologies that will work where conventional devices are limited or fail altogether.

"Radio-frequency communications use narrowband signals, which are inherently limited," says Nekoogar. "In harsh propagation environments, the signals attenuate as they are reflected by metal, concrete, and other objects." When radio signals bounce from structure to structure, the repeated reflections, called multipath phenomena, can cause signals to fade or be canceled. To overcome these limitations and improve transmissions, the Livermore team is using ultrawideband (UWB) electromagnetic pulses, which can penetrate concrete buildings and metallic obstructions.

Low-Power, Long-Range Transmissions

Traditional narrowband wireless technologies transmit strong, continuous-wave signals, which are easily detected, intercepted, and jammed. Narrowband electronics also require extensive circuitry to filter and extract information from the signal. In addition, licensing the required bandwidth can be expensive. Livermore's UWB technology sends extremely short electromagnetic pulses across a wide band of frequencies. High-speed digital receivers record the pulses reflected by nearby objects. (See *S&TR*, September 2004, pp. 12–19.)

UWB pulses last only a few trillionths of a second, so interfering with a transmission is difficult. The pulse power is spread over a broad frequency range, resulting in extremely low power levels at any given frequency. Best of all, devices can be designed so that UWB signals will not affect other wireless technologies such as flight radios, ground-based beacons, the Global Positioning System, and cell phones. Also, the technology uses the entire radio spectrum, so there is no cost for licensing a particular frequency.

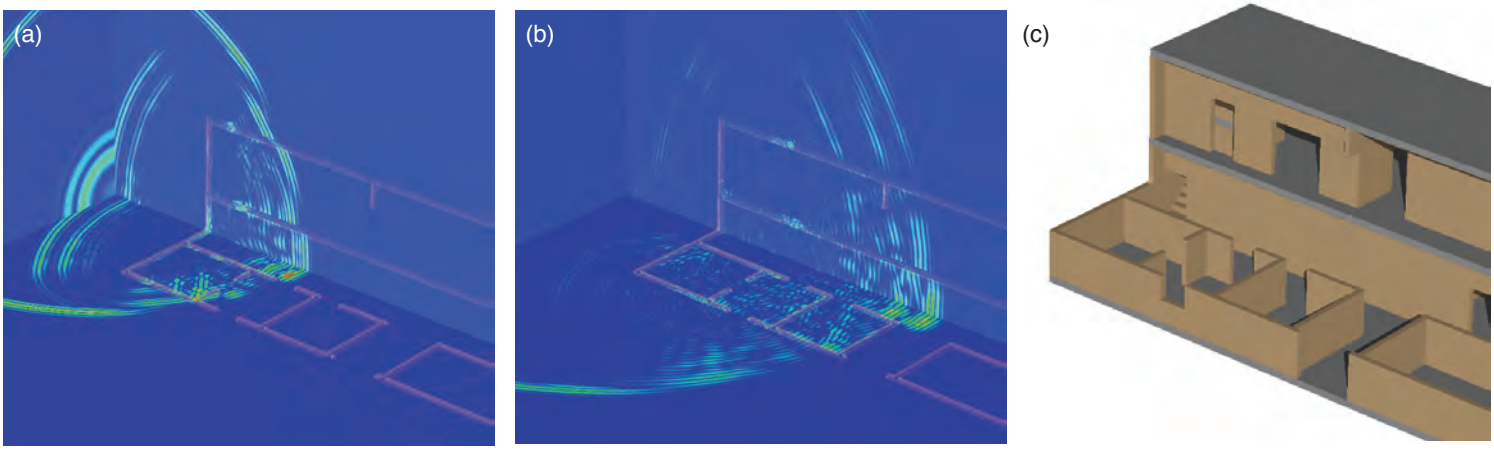
The range of a UWB transmitter and receiver pair is affected by the transmitted power and the frequency bandwidth used. Because the Federal Communications Commission mandates a frequency between 3.1 and 10.6 gigahertz for commercial UWB systems, they are typically used for short-range applications, within about 10 meters. However, the bandwidth at that range is so high that UWB systems can process gigabytes of data per second, allowing them to simultaneously transmit high-resolution voice, video, and data recordings in real time.

Private industry has focused its research on developing short-range, high-data-rate communication systems, but UWB technologies offer more than improved communications. The low power levels and wideband features make the signals ideal for secure, covert transmissions in combat settings or for surveillance systems. Livermore engineer Peter Haugen is leading several research efforts that focus on optimizing UWB communication technology for long-range applications. Laboratory engineers are also designing UWB technologies to address national security needs. For example, they have developed intrusion sensors, rapidly deployable perimeter networks, and noncontact triage and sensing devices.

Improving Port Security

Each year, more than 18 million cargo containers enter U.S. ports from overseas. Security officials are concerned that one of them will contain a threat material or have had its contents tampered with. To address those concerns, Nekoogar's team developed a small, lightweight UWB radio-frequency identification tag, called Utag.

Utags work without batteries and can be placed inside metal containers to identify the container, keep a record of its contents, and detect intrusions. Security personnel can use the tags to monitor a container's contents from up to 20 meters away, a distance 20 times greater than the passive narrowband tags currently available. According to engineers Greg Dallum and Dave Benzel, the team plans to extend the receiving range to 100 meters in the near future. Utags can also be connected to radiation monitoring hardware, which will transmit results to a computer aboard ship or to a handheld reader.



(a, b) Large-scale simulations modeled ultrawideband radar propagating through a building. (c) The resulting data were used to determine the building's internal structure.

Because Utags have geolocation capability, they can be used to track objects or individuals. Once a Utag is attached to a target, receivers can remotely query the tag and process the returned signal into images. By viewing the images in sequence, researchers can estimate where the target is moving. The inexpensive, tamper-resistant Utags could help combat units track soldiers, supplies, and munitions. The devices could also be adapted to monitor hazardous or dangerous materials, search for lost children or pets, and secure assets such as jewelry.

VisiBuilding Sees through Walls

Another application for the Livermore technology supports the VisiBuilding Program directed by Ed Baranoski in the Department of Defense's Defense Advanced Research Projects Agency. VisiBuilding combines radar, signal processing, statistical analysis, and deconvolution algorithms to map a building's floor plans and track insurgents—all from outside the structure.

For this project, Livermore engineers in collaboration with SRI International and Signetron, Inc., developed a model-based methodology that uses noncontact UWB imaging to reconstruct building interiors and determine what lies behind the walls. Led by Laboratory engineer Farid Dowla, the team's first goal was to ensure that the concept would work as expected. Using Livermore's massively parallel supercomputers, the team simulated UWB wave propagation inside various structures. The simulations took into account how the signals would be received and determined the optimal locations for receivers.

With these results, the team developed algorithms to translate the simulated signals into physical models that predict a building's contents. The full system—including modeling algorithms, system planning knowledge, and hardware—will be developed in the project's next phase. (See *S&TR*, November 2007, pp. 4–10.)

Secure Communication at Sea

Livermore's engineers envision many ways to apply UWB communication technology to problems of national importance and are continuing to examine potential innovations. Most recently, a team led by project manager Kique Romero conducted large-scale field exercises to demonstrate a UWB wireless communication system that works aboard ships. The small, highly metallic corridors on ships create virtually unlimited paths for signal reflections. In the demonstration tests, the Livermore prototype transmitted voice and video data from a ship's top deck down to the engine room, even as normal activity continued with hatches opening and closing.

The Laboratory has licensed many UWB applications, and several inventions have received R&D 100 awards, including the noninvasive pneumothorax detector. (See *S&TR*, October 2007, pp. 4–5.) Livermore innovations include locating buried plastic and metallic land mines, inspecting bridges, imaging roadbeds, and detecting motion inside protected areas. (See *S&TR*, January/February 1996, pp. 16–29.)

"As we investigate the broader realm of wideband and UWB systems, we are just beginning to dream of possibilities," says Romero. "Thanks to recent advances both in industry and at Livermore, we are generating innovative solutions that were not even possible a few years ago."

—Karen Rath

Key Words: radio-frequency identification tag, ultrawideband (UWB) radar, Utag, VisiBuilding project, wireless communication technology.

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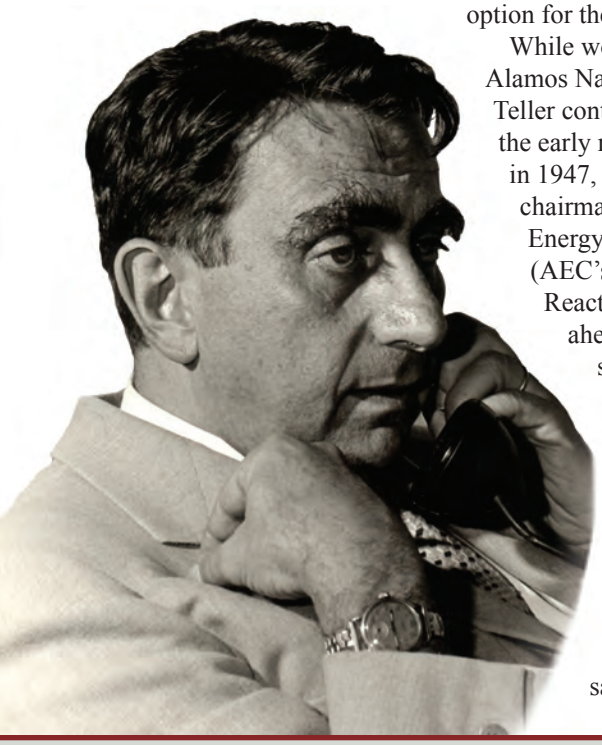
Power to the People

Teller's Contributions to Nuclear Power Research

January 15, 2008, marks the 100th anniversary of Edward Teller's birth. This highlight is the ninth in a series of 10 honoring his life and contributions to science.

WHEN nuclear fission was discovered in 1939, Edward Teller saw its enormous potential for both military and civilian uses. In particular, he and others recognized that nuclear power offered a potentially clean and inexpensive alternative to other sources of energy. Likewise, his lifelong interest in fusion led the Laboratory to establish a fusion energy program, which continues today.

Teller realized that the 21st century would present serious energy-related issues. The developing world would significantly increase its energy consumption as its standard of living rose. Burning fossil fuels to meet that demand would likely exhaust the world's petroleum supplies and could cause dangerous levels of pollution. Later in Teller's life, scientists began to acknowledge that large-scale fossil-fuel consumption increased the atmospheric concentration of carbon dioxide, leading to dramatic climate changes. In *Memoirs*, Teller noted that, "Alternative energy sources, such as wind power and solar energy, are not quantitatively significant." He thus saw nuclear power as a key option for the long term.



While working at Los Alamos National Laboratory, Teller contributed to some of the early reactor projects, and in 1947, he became the first chairman of the Atomic Energy Commission's (AEC's) Committee on Reactor Safeguards. Far ahead of his time in stressing reactor safety, he guided the committee to develop an approach for including accident probabilities when designing a reactor's safety features.

Teller also challenged researchers to design a foolproof reactor small enough for use in university research and in diagnostic and treatment procedures at hospitals. Teller's mandate was to "design a reactor so safe . . . that if it was started from its shut-down condition and all its control rods instantaneously removed, it would settle down to a steady level of operation without melting any of its fuel." That is, the reactor's safety features must be inherent—guaranteed by nature. Such a design would prevent a catastrophic accident even if the engineered safety features were bypassed.

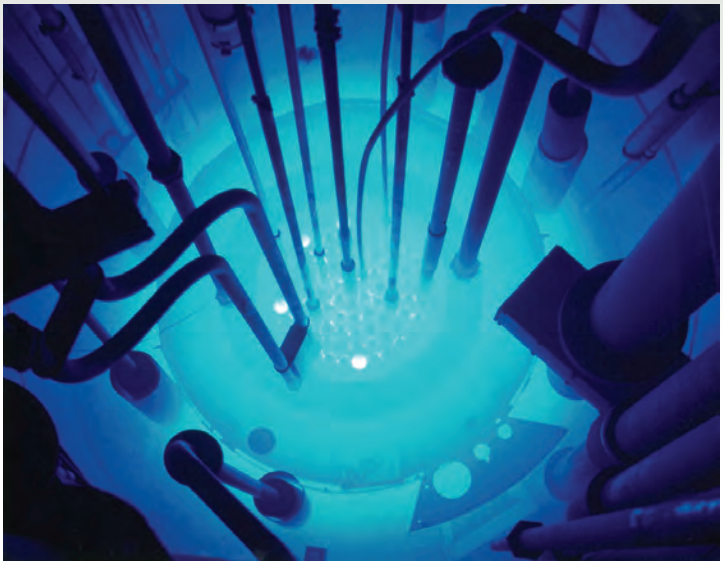
In 1956, a team of distinguished physicists at General Atomics, including Frederic de Hoffmann, Freeman Dyson, and Ted Taylor, achieved this goal, designing a light-water reactor known as TRIGA® (Training, Research, Isotopes, General Atomics). The fuel rods in TRIGA reactors act as power regulators. In an emergency, they will shut down a reactor within a few thousandths of a second—faster than an engineered safety feature can respond. General Atomics installed the first TRIGA reactors in 1958. Today, more than 65 TRIGA facilities have been built in 24 countries. (For further information on TRIGA reactors, see triga.ga.com.) In the biographical memoir Dyson wrote on Teller for the National Academy of Sciences, he says, "I had one of my happiest experiences, working with Teller on the design of a safe nuclear reactor."

In 1957, Teller addressed the Joint AEC Weapons Laboratory Symposium on Nonmilitary Uses of Nuclear and Thermonuclear Explosions, appealing to the attendees to reach for new ideas in civilian nuclear applications. He thus planted the seeds that led to Project Plowshare—a national research program established to explore peaceful application of nuclear explosions, such as excavating mines and harbors or enhancing productivity of oil and gas wells.

Public concern about the environmental consequences of nuclear explosions brought an end to Project Plowshare. Nonetheless, the program's legacy is visible in many of the Laboratory's accomplishments, from an underground coal and oil gasification process to computer codes that model nuclear waste containment at the proposed Yucca Mountain repository.

Teller's enthusiasm for peaceful applications of nuclear power was predicated on the belief that sound solutions could be found to address four key issues: containing nuclear material in the event of an accident, simplifying a reactor's operation so that it is close to automatic, preventing the diversion of fuel for military use, and disposing of spent fuel safely and reliably. In 1972, he was

In 1962, Edward Teller received the Enrico Fermi Award from President John F. Kennedy (far right) in a White House ceremony attended by Glenn T. Seaborg (far left), chairman of the Atomic Energy Commission, and Teller's wife, Mici (second from right).



In 1956, Teller challenged scientists at General Atomics to design an inherently safe nuclear reactor. That effort led to the TRIGA® reactor. This photograph looks down into the pool of a TRIGA Mark I reactor. (Reprinted courtesy of General Atomics, San Diego, California.)

further intrigued when French physicists discovered evidence of a naturally occurring nuclear reactor in Oklo, Gabon. The reactor had burned itself out about 1.7 billion years ago after operating for 1 million years. Teller was certain this model from nature would lend answers to today's nuclear waste management questions.

In particular, Teller saw parallels between Oklo and the next generation of underground reactors being designed by Livermore scientists. The new fission reactors had no moving parts and could operate without human intervention for 30 years. Residual radioactivity would be sealed within the reactor's core and allowed to decay in place. An underground location would also limit the amount of radioactivity that could reach the surface in the event of an accident or earthquake.

Teller envisioned reactors sited 200 meters underground delivering 1,000 megawatts of power. Generally speaking, fission reactors, if widely adopted, could offset perhaps one-third of the projected increase in carbon emissions during the next century.

The 1979 reactor accident at Three Mile Island curtailed the nation's efforts to establish a thriving nuclear power program. However, in September, New Jersey–based NRG Energy filed an application with the Nuclear Regulatory Commission to build two advanced reactors in South Texas—the first such request in more than 30 years. The Tennessee Valley Authority followed in October with an application to build a new plant at its Bellefonte site in Alabama.

Teller continued to think about nuclear power until the end of his life. In 2003, he wrote a paper with Livermore physicist Ralph Moir, putting forward new ideas on building thorium-burning reactors underground. This paper, Teller's last, appeared in *Nuclear Technology* in 2005.

Today, Lawrence Livermore is part of a Department of Energy collaboration developing a small, sealed, transportable, autonomous reactor (SSTAR) housed in a tamper-resistant container. SSTAR addresses the concerns of nuclear proliferation and the growing need for clean, reliable, and cost-effective energy. (See *S&TR*, July/August 2004, pp. 20–22.)

Teller maintained his optimism that, despite the obstacles, nuclear power could be used to further the good of humanity. He was confident that an improved reactor design could safely provide energy to developing nations and thus reduce the chasm that exists between poverty and wealth.

—Maurina S. Sherman

Key Words: fission; fusion; nuclear power; nuclear reactor; Project Plowshare; small, sealed, transportable, autonomous reactor (SSTAR); TRIGA® reactor.

For further information contact Stephen B. Libby (925) 422-9785 (libby1@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

Graphitized-Carbon Fiber/Carbon Char Fuel
John F. Cooper
U.S. Patent 7,261,804 B2
August 28, 2007
This method recovers intact graphitic fibers from fiber–polymer composites. The graphite fiber–polymer composite mixture is pyrolyzed, and the graphite fibers are separated by molten salt electrochemical oxidation.

Serpentine and Corduroy Circuits to Enhance the Stretchability of a Stretchable Electronic Device
Mariam N. Maghribi, Peter A. Krulevitch, Thomas S. Wilson, Julie K. Hamilton, Christina Park
U.S. Patent 7,265,298 B2
September 4, 2007
This electronic apparatus can be stretched in a longitudinal direction generally aligned with its central axis. The apparatus has at least one circuit line connected to a stretchable polymer body. The circuit lines and their longitudinal components extend in the longitudinal direction, and an offset component is at an angle to the longitudinal direction. The longitudinal and offset components allow the apparatus to stretch in the longitudinal direction while maintaining the integrity of the circuit lines.

Solar Thermal Aircraft
Charles L. Bennett
U.S. Patent 7,270,295 B2
September 18, 2007
This aircraft is powered by heat energy from the Sun. The aircraft body carries a heat engine, such as a Stirling engine, that produces power for a propulsion mechanism, such as a propeller. A thermal battery supplies heat to the engine. A solar concentrator, such as a reflective parabolic trough, concentrates solar energy from within the aircraft and is connected to an optically transparent section of the aircraft body. A conduit collects the concentrated energy and transports heat to the thermal battery. A solar tracker uses a heliostat to determine the optimal alignment with the Sun. A drive motor then actuates the solar concentrator based on the heliostat readings.

Protein Crystallography Prescreen Kit
Brent W. Segelke, Heike I. Krupka, Bernhard Rupp
U.S. Patent 7,276,216 B2
October 2, 2007
This kit for prescreening protein concentration for crystallization includes several vials, reagents, and sample plates. Protein samples in solutions of varying concentrations are placed on sample plates with the reagents. After the sample plates are incubated, they are examined to determine which concentrations are too low or too high. The concentrations that are optimal for protein crystallization are selected and used.

System for the Co-Production of Electricity and Hydrogen
Ai Quoc Pham, Brian Lee Anderson
U.S. Patent 7,276,306 B2
October 2, 2007
This system for generating hydrogen gas and electricity can adjust the proportion of hydrogen to electricity from 0 to 100 percent. The system integrates fuel-cell technology for power generation with fuel-assisted steam electrolysis. A hydrocarbon fuel or a reformed or partially reformed hydrocarbon fuel can be fed into the system.

Silicon Fiber Optic Sensors
Michael D. Pocha, Steve P. Swierkowski, Billy E. Wood
U.S. Patent 7,277,605 B2
October 2, 2007
A Fabry–Perot cavity is formed by a reflective surface on the free end of an integrated elongate channel or an integrated bounding wall of a chip. Either configuration includes a partially reflective surface on the end of an optical fiber. Such a device can detect one or more physical parameters, such as strain, through the optical fiber. An optical detection system provides measuring accuracies of less than about 0.1 percent.

Fade-Resistant Forward Error Correction Method for Free-Space Optical Communications Systems
Gary W. Johnson, Farid U. Dowla, Anthony J. Ruggiero
U.S. Patent 7,277,644 B2
October 2, 2007
Free-space optical laser communication systems offer exceptionally wide bandwidth and secure connections between platforms that cannot be physically connected by an optical fiber or cable. However, these links are subject to strong channel fading from atmospheric turbulence and beam-pointing errors, limiting performance and reliability. A fade-tolerant architecture based on forward error-correcting codes is combined with delayed, redundant subchannels to solve this problem. The redundancy is feasible through dense wavelength division multiplexing or high-order modulation. Experiments and simulations show that error-free communication is feasible even with fades that last for tens of milliseconds. The system is designed to operate at 2.5 gigabits per second.

Awards

David Keyes, a scientist in Livermore's Institute for Scientific Computing Research and the Fu Foundation professor at Columbia University, received the **2007 Sidney Fernbach Memorial Award** from the **Institute for Electrical and Electronics Engineers** (IEEE) **Computer Society**. Keyes was recognized for his contributions in developing scalable numerical algorithms to solve nonlinear partial differential equations and for his leadership in high-performance computation. IEEE established the award in 1992 in memory of Livermore computer scientist Sidney Fernbach.

Fusion Power Associates honored former Laboratory associate director **David Baldwin** with its **2007 Distinguished Career Award**. Established in 1987, the award is given to individuals who have made important contributions to fusion development. Baldwin was recognized for his scientific contributions to fusion research, his leadership roles in the fusion programs at Livermore and General Atomics, and the policy roles he played in guiding national and international fusion efforts.

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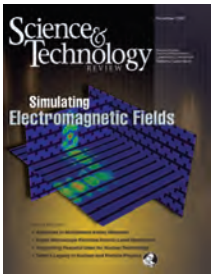

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Abstracts

Out of Harm's Way

The system for securing Russia's stockpiles of nuclear warheads and materials was in jeopardy of failing when the Soviet Union collapsed in 1991. The Department of Energy (DOE) stepped in with a program to protect Russian nuclear material and keep it out of the hands of terrorists. Originally called the Material Protection, Control, and Accountability Program, it is now the International Material Protection and Cooperation (IMPC) Program and is operated by the National Nuclear Security Administration (NNSA). In support of this program, Livermore and other national laboratories have trained Russian technical personnel to perform vulnerability analyses of nuclear sites based on a system developed at the Laboratory. This analysis is followed by the installation of such physical protection devices as new fences and other barriers, closed-circuit television monitoring systems, tamper-indicating devices, alarms, access controls, vehicle inspection facilities, and portal monitors. Livermore leads a project to help implement a rigorous approach to accounting for nuclear materials in Russia's civilian sector. The Federal Information System is based on a system used by DOE, NNSA, and the U.S. Nuclear Regulatory Commission to track and monitor nuclear materials. Livermore is also helping the Russians sustain the protection improvements by developing comprehensive regulations, building new training facilities, conducting training programs, and establishing systematic inspections. The IMPC Program is also exploring areas of cooperation with China, Ukraine, and Kazakhstan.

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U.S. Government Printing Office: 2007/770-075-70002

Edward Teller's Centennial

January 2008 marks the 100th anniversary of the birth of Edward Teller—cofounder of Lawrence Livermore, adviser to U.S. presidents, and physicist extraordinaire.

Also in January/February

- *Thanks to the power of BlueGene/L, Livermore has become a center for theoretical advances in particle physics.*
- *Researchers are investigating the mechanism by which teeth become more brittle with age.*

Coming Next Month

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