A DECADE OF DISCOVERY

U.S. DEPARTMENT OF ENERGY

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IN RECOGNITION OF THE MEN AND WOMEN WORKING IN THE U.S. DEPARTMENT OF ENERGY'S SEVENTEEN NATIONAL LABORATORIES ACROSS THE COUNTRY.

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Hundreds of particle tracks streaming from a collision of gold ions traveling near the speed of light in the STAR detector at Brookhaven Lab's Relativistic Heavy Ion Collider (RHIC). Evidence suggests that gold-gold collisions at RHIC are creating a new state of hot, dense matter—a "perfect" liquid that is quite different and even more remarkable than the gas that had been predicted by theory. Image has been artistically modified. See story, page 116.

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A DECADE OF DISCOVERY

INTRODUCTION

A lot has changed since the U.S. Department of Energy (DOE) was founded more than three decades ago. But one thing certainly has not: the vital importance of our National Laboratories.

Today, the DOE's mission is broad, with our programs and people responsible for promoting our nation's energy security through the development and promotion of reliable, clean and affordable energy; ensuring our national security and maintaining a safe, reliable and secure nuclear stockpile; providing a responsible cleanup of the environmental legacy of nuclear weapons production; and promoting scientific excellence and innovation.

In all these areas and so many more, the role of our National Laboratories is absolutely central. Today, as throughout their history, the men and women of our National Laboratories are discovering solutions to our greatest environmental, energy and national security challenges.

Though much has been written about the trail-blazing history of the Manhattan Project–era work conducted at places such as Los Alamos National Laboratory and Oak Ridge National Laboratory, the unfortunate reality is that not as much is known about the current work of those labs, or the efforts of their sister labs that comprise our modern-day complex. And therefore this book provides a 10-year retrospective of the National Laboratories' most significant accomplishments.

As this book makes clear, collectively the DOE's 17 National Laboratories remain the single greatest scientific enterprise in the world. This is true for a whole host of reasons—not least of which is the quality of the people who make the enterprise run. In fact, since the founding of the first DOE lab more than 60 years ago, the complex has been associated with the recipients of more than 80 Nobel Prizes.

To put it simply, this is a book about the transformational science and engineering that occurs at our National Laboratories. It is on a scale that is absolutely unique in the world. As the book describes in vivid detail, over the past decade, the National Laboratories have been responsible for developing new, cleaner and sustainable fuels and technologies to power our vehicles and our homes; for making conventional fuels more efficient and clean; for developing new technologies that are protecting our troops and thwarting terrorism here and around the world; for finding new and better ways to detect and treat cancer, Parkinson's disease and other debilitating diseases; and, using the world's most advanced supercomputers and technologies, for better enabling our ability to certify the reliability of the U.S. nuclear weapons stockpile without conducting underground nuclear tests.

As a nation, we will continue to depend on the power of science and engineering to push back the boundaries of what is possible. And therefore we will continue to depend on our National Laboratories and the remarkable men and women who work there.

As this splendid book illustrates, they have a record of success that will only be matched by what we know they will accomplish in the future.

James Schlesinger
U.S. SECRETARY OF ENERGY, 1977–1979

Samuel W. Bodman
U.S. SECRETARY OF ENERGY, 2005–2009

THE U.S. DEPARTMENT OF ENERGY'S

NATIONAL LABORATORIES

1 Ames Laboratory

The Ames Laboratory, located on the campus of Iowa State University in Ames, Iowa, is a national center for the synthesis, analysis and engineering of rare earth metals and their compounds. The laboratory was formally established in 1947 by the U.S. Atomic Energy Commission as a result of the Ames Project's ability to produce high-grade uranium in large quantities. That project supplied one-third of the uranium used in the successful demonstration of the first chain-reaction pile at the University of Chicago on Dec. 2, 1942, and more than two million pounds for the Manhattan Project. Today Ames conducts fundamental research in the physical, chemical and mathematical sciences associated with energy generation and storage, high-speed computer design and environmental cleanup and restoration. Ames researchers have produced a number of breakthroughs in fields such as magnetism, optics, biomaterials and environmental science.

2 Argonne National Laboratory

The Argonne National Laboratory is one of DOE's largest multidisciplinary research centers and is located on 1,700 acres, 25 miles southwest of Chicago, Illinois. Argonne research falls into five broad categories: energy sources and storage, environmental biology and climate, materials discovery and design, national security, and scientific facilities. Argonne manages national user facilities supporting hard X-ray science, leadership computing, nanoscale materials science, structural biology, heavy ion physics, electron microscopy and transportation research. When established in 1942, it was known as the University of Chicago's Metallurgical Laboratory, or Met Lab. It's here where, on Dec. 2, 1942, Enrico Fermi and his colleagues created the world's first controlled nuclear chain reaction in a squash court, thereby ushering in the atomic age.

3 Brookhaven National Laboratory

Brookhaven National Laboratory (Brookhaven) in Upton, New York, conducts research in nuclear and high-energy physics, physics and chemistry of materials, environment and energy research, nonproliferation, neurosciences and medical imaging, and structural biology. It also builds and operates major scientific facilities available to university, industry and government researchers. Established by the Atomic Energy Commission in 1947, today Brookhaven is owned by its successor, DOE, which subcontracts the actual research and operation to universities and research organizations. Discoveries at the lab have earned six Nobel Prizes. Brookhaven is also home to the Relativistic Heavy Ion Collider, which continues to provide insights into the nature of matter from atoms to stars.

4 Fermi National Accelerator Laboratory

Research at Fermi National Accelerator Laboratoray (Fermilab) in Batavia, Illinois, centers on the fundamentals of matter and energy. Contributing to Fermilab's many breakthroughs in physical science research is the Tevatron, the world's highest-energy particle accelerator and collider. Tevatron is second in size only to the European Laboratory for Particle Physics, CERN. In 1995, both the collider detector and D0 (D-Zero) experiments (detectors that utilize the Tevatron) announced the discovery of the top quark. This is just one example of how Fermilab scientists from around the world have played a significant role in understanding nature's particle zoo.

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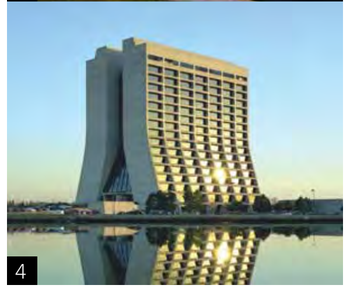
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5 Idaho National Laboratory

The Idaho National Laboratory (INL) located in Idaho Falls is a science-based, applied engineering laboratory dedicated to supporting DOE's research programs in nuclear energy, national and homeland security and clean energy. Established in 1949 as the "National Reactor Testing Station," work at INL has included initial development and testing of nuclear reactor designs, developing prototype reactors for use by the U.S. Navy and developing technologies to manage nuclear waste. INL is conducting research supporting the advanced fuel cycle initiative and nuclear energy demonstration and deployment, as well as specialized national and homeland applications and clean energy technologies.

6 Lawrence Berkeley National Laboratory

The Lawrence Berkeley National Laboratory (Berkeley Lab) conducts research across a wide range of scientific disciplines, with an emphasis in fundamental studies of the universe: quantitative biology, nanoscience, new energy systems and environmental solutions, and the use of integrated computing as a discovery tool. Located on 200 acres in the hills overlooking the central campus of the University of California, Berkeley, Berkeley Lab was founded in 1931 by Ernest Orlando Lawrence, inventor of the cyclotron. Berkeley Lab has the distinction of being the oldest DOE National Laboratory. Its 17 science divisions are organized within the areas of computing sciences, physical sciences, life and environmental sciences and general sciences. Many research projects are staffed and supported by multiple divisions, with computational and engineering integrated across the biosciences, general sciences and energy sciences. This approach reflects Berkeley Lab's mantra that scientific research is best done by collaborating with teams in different fields of expertise.

7 Lawrence Livermore National Laboratory

The Lawrence Livermore National Laboratory (Livermore Lab) near Livermore, California, was founded in September 1952 as a second nuclear weapons design laboratory to promote innovation in the design of the nation's nuclear stockpile through creative science and engineering. Its principal responsibility is ensuring the safety, security and reliability of the nation's nuclear weapons by applying advanced science, engineering and technology. Livermore Lab also applies its special expertise and multidisciplinary capabilities to preventing the proliferation and use of weapons of mass destruction, bolstering homeland security, and solving other important problems, including energy and environmental security, basic science and economic competitiveness. Livermore Lab is now home to the National Ignition Facility, which, when completed in 2009, will be the world's largest laser.

8 Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) in New Mexico was founded in 1943 as a secret facility specifically dedicated to developing the atomic bomb. It since has had a long record of groundbreaking science and technology that fosters national security. As part of the National Nuclear Security Administration, LANL contributes to meeting the nation's nuclear deterrence capability and other security needs. The laboratory is also one of the world's largest science and technology institutions, conducting multidisciplinary research for fields such as astronomy, renewable energy, health, nanotechnology and supercomputing. Research conducted at LANL helps mitigate a wide variety of threats to U.S. interests from the proliferation of nuclear weapons and the spread of deadly diseases to inadequate energy supplies and the effects of climate change.

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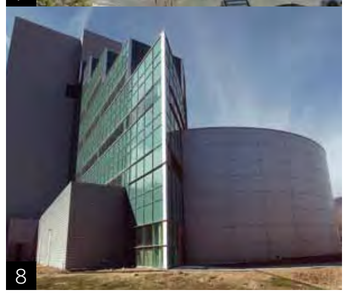
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9 National Energy Technology Laboratory

The National Energy Technology Laboratory (NETL), which is dedicated to advancing national, economic and energy security, can trace its origins back to the early 20th century. Over the years, it gradually emerged from an amalgam of fuel and energy facilities. NETL assures that U.S. fossil energy resources can meet increasing demand for affordable energy without compromising quality of life for future generations. Through onsite and contracted research, NETL develops technologies to resolve the environmental, supply and reliability constraints of producing and using fossil resources. Whether producing steel armor to protect soldiers from the blast effects of improvised explosive devices (IEDs), or devising a new method for cleaning coal – the nation's most plentiful and affordable fossil fuel – NETL is on the cutting edge of energy research and technology.

10 National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL), located in Golden, Colorado, develops renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovations to address the nation's energy and environmental goals. Founded in 1974, NREL started out as the Solar Energy Research Institute. In September 1991, its name was changed to the NREL upon being designated a national DOE lab. NREL is at the forefront of biofuels research, raising the efficiency of wind turbines and solar cells, and advancing the use of clean, renewable energy.

11 Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) is a multifaceted science and technology laboratory that conducts basic and applied research in several key areas of science. The laboratory is home of the Spallation Neutron Source, the world's leading producer of neutrons for scientific research, and the Jaguar, the most powerful supercomputer ever built for open science.
Originally known as Clinton Laboratories, ORNL was established as part of the Manhattan Project in 1943. Both the laboratory and the nearby city of Oak Ridge were built by the Army Corps of Engineers on former farmland in the mountains of East Tennessee. Within two years, Oak Ridge housed more than 75,000 residents. The laboratory's wide range of research and development activities are organized and conducted under six scientific themes: advanced materials, biological systems, energy, high-performance computing, national security and neutron science.

12 Pacific Northwest National Laboratory

The Pacific Northwest National Laboratory (PNNL) delivers science and solutions to the country's most complex challenges of developing energy and environmental solutions, heightening national security, and advancing mission-driven science through an outstanding staff and research and development capabilities. Established in 1965, the lab's original mission was focused on nuclear technology and the environmental and health effects of radiation. PNNL gradually evolved into a national laboratory with a diversified, multiprogram mission. PNNL's six core research disciplines include microbial and cellular biology, environmental sciences, analytical and interfacial chemical sciences, radiological sciences, sensing and measuring technologies, and computational sciences and information analytics. PNNL is not only concerned with expanding energy technology, it strives to preserve and strengthen the vast energy network that is part of the nation's electric power grid.

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13 Princeton Plasma Physics Laboratory

The Princeton Plasma Physics Laboratory (PPPL), located near Princeton University's main campus, is a national center dedicated to plasma (ionized gas that forms at high temperature) and fusion science with a leading international role in developing the theoretical, experimental and technological innovations needed to make fusion practical and affordable. The facility originated in 1951 when it conducted classified magnetic fusion research under the name Project Matterhorn. PPPL researchers are now leading work on an advanced fusion device, the National Spherical Torus Experiment, and are developing other innovative concepts that they hope will lead to an attractive fusion energy source. Laboratory scientists collaborate with researchers on fusion science and technology at other facilities, both domestic and foreign.

14 Sandia National Laboratories

Sandia National Laboratories (Sandia) develops technologies that prevent the use and spread of weapons of mass destruction, protect our national infrastructure, defend the nation against terrorism, and ensure the stability of our energy and water supplies. Sandia is a major DOE research and development laboratory with two primary locations: Albuquerque, New Mexico, and Livermore, California. Sandia's primary mission is to develop, engineer and test the non-nuclear components of nuclear weapons, maintain the reliability of nuclear weapon systems, and research and develop arms control and nonproliferation technologies. Like several other National Laboratories, Sandia was initially a product of World War II's Manhattan Project.

15 Savannah River National Laboratory

The Savannah River National Laboratory (SRNL), located near Aiken, South Carolina, is recognized as a world-class applied research and development laboratory, delivering unique and innovative science and technology solutions. SRNL was engaged in early work on design and utilization of facilities for production of nuclear materials for the nation's defense. Today, the laboratory puts science to work in the fields of environmental management, national and homeland security, and energy security, and serves as the corporate laboratory for DOE's Office of Environmental Management. Work includes applied R & D in environmental remediation, hydrogen as a fuel source, handling of hazardous materials and technologies for preventing nuclear proliferation. The laboratory has specific experience in vitrification of nuclear waste and hydrogen storage that was initially developed to support production of tritium and plutonium at the Savannah River Site during the Cold War.

16 SLAC National Accelerator Laboratory

SLAC National Accelerator Laboratory designs, constructs and operates state-of-the-art accelerators and related experimental facilities to explore the frontiers of photon science, astrophysics and particle physics. Established in 1962 as the Stanford Linear Accelerator Center, the facility is located on 426 acres of Stanford University-owned land in Menlo Park, California. The main two-mile-long linear accelerator speeds electrons and positrons up to 50 GeV and has been operational since 1966. The laboratory's BABAR detector played a pivotal role in the research leading to the 2008 Nobel Prize in Physics, and six scientists have been awarded Nobel Prizes for their research at SLAC.

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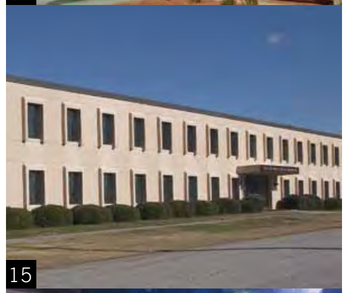
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17 Thomas Jefferson National Accelerator Facility

The Thomas Jefferson National Accelerator Facility conducts nuclear science research using continuous beams of high-energy electrons to discover the underlying structure of the atom's nucleus at the level of quarks and gluons. Founded in 1984, its stated mission is "to provide forefront scientific facilities, opportunities and leadership essential for discovering the fundamental structure of nuclear matter; to partner in industry to apply its advanced technology; and to serve the nation and its communities through education and public outreach." The laboratory's main research facility is the Continuous Electron Beam Accelerator Facility (CEBAF), which is built 25 feet below the ground. The CEBAF enables scientists to detect matter a million times smaller than an atom. This phenomenal reach into the subatomic world provides scientists with deeper insight into the particles and forces that make up the universe.

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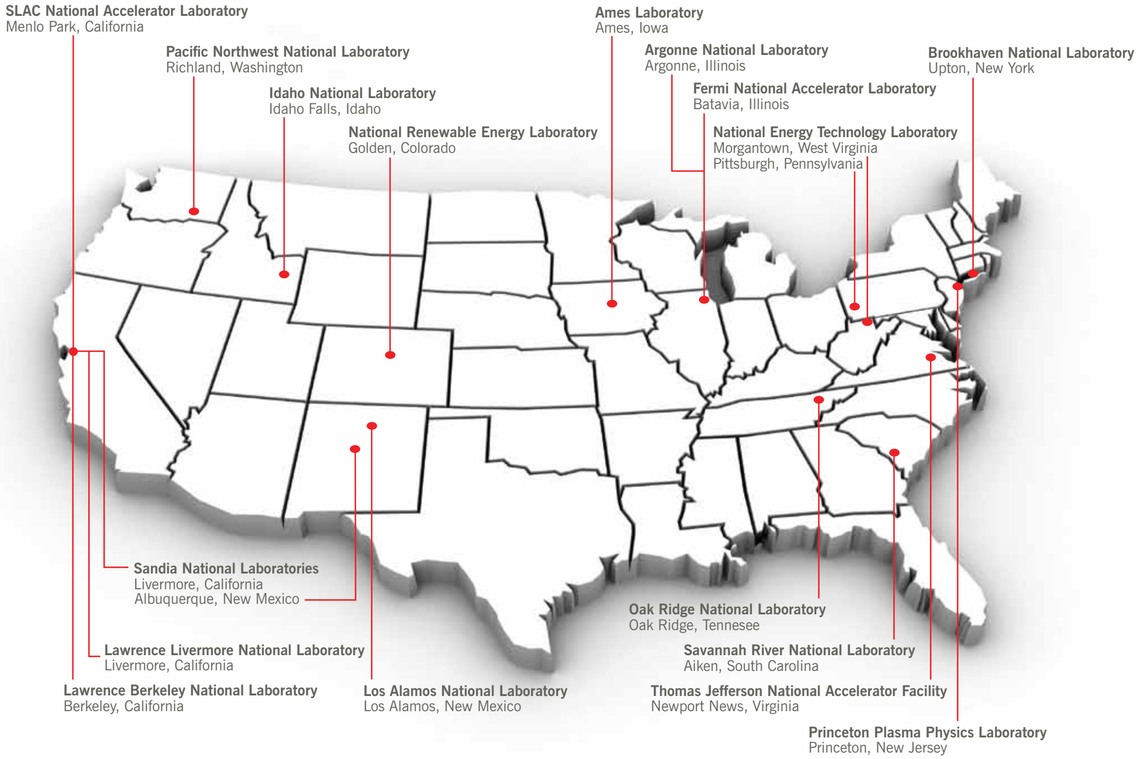
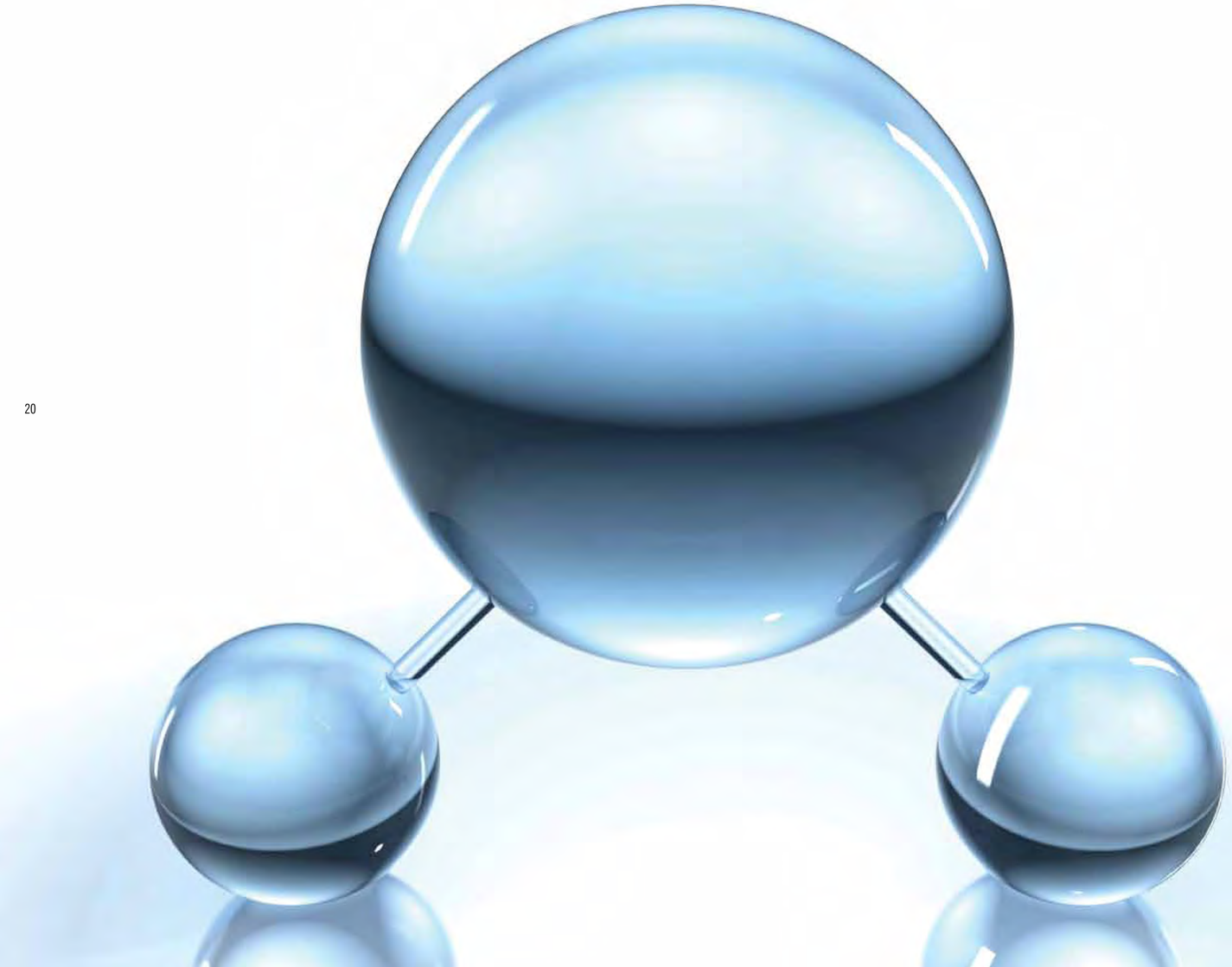


ENERGY AND ENVIRONMENT

EFFICIENT BATTERIES · U.S. DEPARTMENT OF ENERGY · CELLULOSIC BIOFUELS · U.S. DEPARTMENT OF ENERGY · CLEAN COAL U.S. DEPARTMENT OF ENERGY · HYDROGEN FUEL CELLS · U.S. DEPARTMENT OF ENERGY · GREENHOUSE GAS EMISSIONS · U.S. DEPARTMENT OF ENERGY · NUCLEAR ENERGY · U.S. DEPARTMENT OF ENERGY · NUCLEAR WASTE U.S. DEPARTMENT OF ENERGY · FUSION · U.S. DEPARTMENT OF ENERGY · SOLAR ENERGY · U.S. DEPARTMENT OF ENERGY · ENERGY EFFICIENT BUILDINGS · U.S. DEPARTMENT OF ENERGY · WIND TURBINE EFFICIENCY · U.S. DEPARTMENT OF ENERGY · POWER GRID MONITORING · U.S. DEPARTMENT OF ENERGY · CLEAN TRANSPORTATION

INTRODUCTION

Perhaps no other scientific endeavor is as pivotal to our nation's future as research conducted in the fields of energy and the environment. The last 10 years have seen many astonishing advances in these disciplines, pushed on by a number of imperatives: the need to reduce greenhouse gas emissions, to develop and make use of cleaner sources of energy, and to clean up those environments that have been polluted or made hazardous. The research projects profiled in this section show how far scientists at the National Laboratories have come toward resolving these issues. Research is making great strides toward improving waste-treatment technologies, increasing the efficiency of solar cells, investigating ways to harness fusion energy and developing technologies that will make hydrogen-powered vehicles more commonplace on our highways. These are the kinds of scientific and technological innovations that, in the long run, will help preserve our planet's ecosystems and ensure our future energy needs.



MEET THE NEXT GENERATION

OF ENVIRONMENTALLY FRIENDLY (AND VERSATILE) NUCLEAR REACTORS

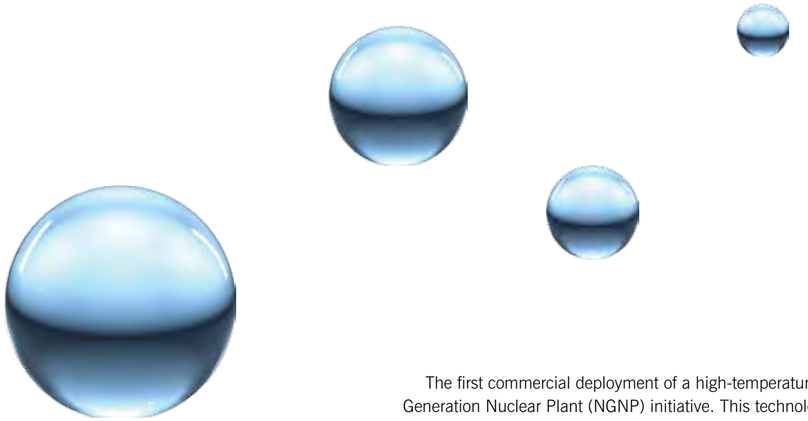
Idaho National Laboratory scientists envision nuclear reactors that will work more efficiently, produce less waste, and can be used for other industrial applications.

Significantly avoiding carbon dioxide (CO_2) emissions on a global scale has become a goal for nearly every industrialized nation. Generation IV nuclear reactors, which have been under development since 2000, offer promising new technologies that will help the United States reach this goal. "Nuclear energy is already the biggest noncarbon-emitting source of electricity we have in the United States," said Ralph Bennett, a nuclear engineer and director of international and regional partnerships at Idaho National Laboratory (INL) in Idaho Falls, Idaho. "Advances to a fourth generation of nuclear energy will take 20 years or more, but hold tremendous potential for helping meet CO_2 reductions at mid-century."

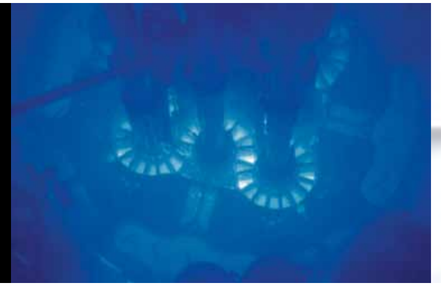
U.S. Department of Energy (DOE) laboratories and universities are at the forefront of research and development on Generation IV—the name for the effort to advance the next generation of commercial nuclear reactor designs. Generation IV reactors are considered to be a revolutionary departure from previous designs. Advanced light water reactors are on the verge of deployment around the world. They are evolutionary designs with improved safety and performance features derived from more than 40 years of experience with commercial light water reactors. Generation IV designs employ technologies that extend performance and fuel efficiency beyond that which can ordinarily be achieved with light water reactors. These new designs will allow clean, safe nuclear power to play a larger role in our nation's energy mix and support hybrid systems that include clean coal and renewable energy sources.

Generation IV reactors are considered to be a revolutionary departure from previous reactor designs.

Six reactor concepts are currently being studied by teams of international experts as part of the Generation IV International Forum. The DOE will likely narrow these down to two Generation IV designs over the next 15 to 20 years to serve as models for the next reactor fleet. In the near term, the most promising new design appears to be a gas-cooled reactor dubbed the Very High Temperature Reactor. It could ultimately reach operating temperatures of 1000 degrees Celsius, hot enough to power many industrial processes. Today's existing reactors use water as a coolant and heat to just over 300 degrees Celsius. Despite these high temperatures, gas reactors are extremely safe. Among other features, they employ a fuel design that is incredibly resistant to heat and radiation damage.



ARTIST'S CONCEPT of household hydrogen fuel cells.



ADVANCED TEST REACTOR

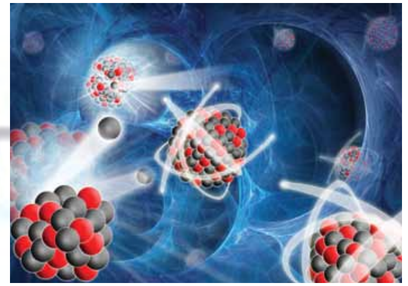
The first commercial deployment of a high-temperature gas reactor is the goal of the DOE's Next Generation Nuclear Plant (NGNP) initiative. This technology will provide industries with a clean source of process heat to power most product applications. Many conventional industrial processes, such as oil refining, water treatment, fertilizer production and plastics manufacturing, require large amounts of hydrogen and very high temperatures. Hydrogen and heat are produced by burning natural gas that could be more effectively used to heat homes and power low-emission vehicles. Today hydrogen production alone accounts for about 7 percent of the natural gas used in the United States. About half of that hydrogen is used to produce ammonia for fertilizers, the other half to sweeten crude oil. Hydrogen fuel cells may be years away from large-scale deployment, but hydrogen production has always been an essential process in modern manufacturing and the production of agricultural products.

Nuclear generation is proven and ready to meet carbon dioxide reduction goals in 2020 and beyond.

Finally, and perhaps most importantly, high-temperature reactors can also be used to cleanly extract our nation's enormous oil reserves that are trapped in rock formations and cleanly convert even the most unattractive coal forms into high-quality transportation fuels, gas and the full spectrum of petroleum-based products. All of this, Bennett explained, could go a long way toward meeting the country's goal for CO_2 reductions, assuring energy independence and creating millions of new jobs in domestic energy supply and manufacturing.

NGNP is a deployment-oriented project that will enable commercialization of this technology within 8 to 10 years. Already in late 2008, an engineering team from INL, Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, Argonne National Laboratory in DuPage County, Illinois; and associated universities has achieved significant milestones in testing the fuel forms used in high-temperature gas-cooled reactor designs. Using multiple encapsulated fuel particles that were designed and manufactured in the United States and irradiated in INL's Advanced Test Reactor, a record-setting 13 percent fuel burn up was achieved without any fuel failures. This greatly exceeds the 3 to 4 percent burnup currently experienced in existing light water reactors. INL, ORNL and commercial fuel fabricators are also working on carbon-based fuel cladding that is extremely resistant to heat damage.

FUTURE CARS will use the most cutting edge technology.



FISSION Current technology uses fission of Uranium-235.

"We could be getting about three times the energy out of the uranium with these new fuel forms," said David Petti, a nuclear engineer and INL director of the Very High Temperature Reactor Technology Development. "The integrity of the individual fuel particle in the reactor has historically been the first line of defense in reactor safety so for us, these new 'super fuels' are very exciting developments with enormous potential to improve power, efficiency and lifetime of our new and operating commercial reactors. What's more satisfying is that they were developed in the United States by teams of experts from the DOE, the National Laboratories, universities and the commercial nuclear industry."

Also key to the Generation IV program are reactor designs that extract the residual energy of used light water fuel to make power, produce new fuel and render the original fuel far less radioactive than when it went into the reactor. This form of fuel recycling is clearly the focus of all responsible nations capable of advanced nuclear power systems design. It effectively turns today's nuclear waste into tomorrow's clean energy supply and makes nuclear power an almost endlessly renewable energy source.

Significant international research collaborations for Generation IV technology are ongoing, with more than half a billion dollars in collaborations committed over the next 5 years. France is pushing to have a Generation IV reactor built and operating as early as 2020; Japan, China and Russia have similar objectives. The United States may be ready to deploy a Generation IV reactor within 20 years; however, the level of support for this program is significantly less in the United States than in any of these other major program contributors.

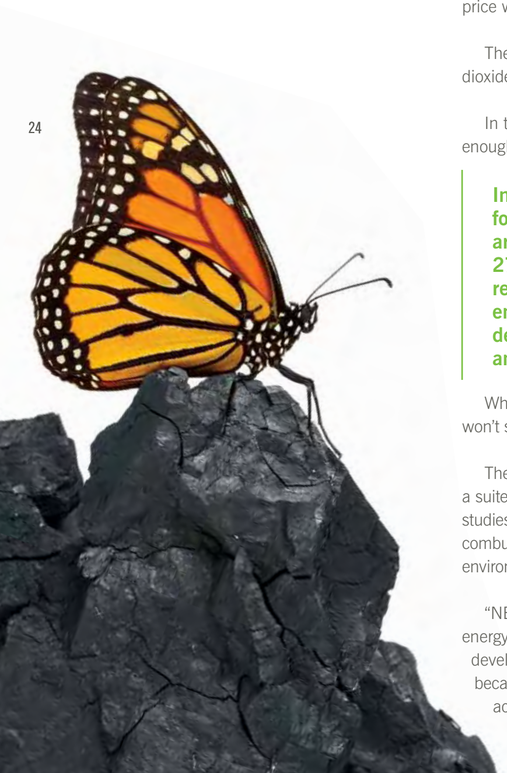
It is frequently noted that there is no single answer to meeting our nation's energy needs. This reflects the fact that unlike many nations, the United States has many options from which to choose. Technology advancements, hybrid energy systems that integrate historically competitive technologies, smart grid, distributed generation and conservation all must be part of the solution. However, any realistically achievable energy policy must include nuclear power as a base-load energy source. Almost 40 years of operating experience has unquestionably demonstrated nuclear power's safety, reliability and efficiency.

MAKING COAL CLEANER FOR THE FUTURE

Because of its abundance and low cost, scientists at the National Energy Technology Laboratory are looking for ways to make coal a cleaner energy resource.

Energy use always comes at a price—not just in dollars and cents, but in land use, air and water emissions, impact on wildlife and national security. Whether tapping the energy in the sun or wind, a reservoir, an atom's nucleus or the chemical bonds in the world's fossil resources, we must consider the price we pay for energy's considerable benefits.

The coal conundrum is how to minimize its environmental impacts—including the release of carbon dioxide, the major greenhouse gas—while taking advantage of its abundance and low price.



In the United States, for instance, there are an estimated 275 billion tons of recoverable coal—enough to meet current demand levels for another 250 years. Most is used for electricity generation. While coal currently accounts for some 37 percent of installed generation capacity, it actually supplies just over half of the country's power.

In the United States, for instance, there are an estimated 275 billion tons of recoverable coal—enough to meet current demand levels for another 250 years.

The situation is similar in Russia, China, India and Australia where, collectively, there are close to another 400 billion tons of recoverable coal reserves. China is building coal-fired power stations at an average of one a week to feed its booming economy.

While the global recession may dent demand and, therefore, the rate of coal-use expansion, its use won't stop or reverse. Consequently, the race is on to find ways to make coal use cleaner than ever before.

The National Energy Technology Laboratory (NETL) is zeroing in on the problem and developing a suite of technologies to capture carbon dioxide, mercury and sulfur from flue gases. The laboratory studies both pre- and post-combustion solutions since, while new plants may be fitted with pre-combustion capture, old plants can be fitted for post-combustion capture equipment to lessen their environmental impact. NETL is having notable success.

"NETL has an impressive history developing science and engineering solutions to solve America's energy problems. Three quarters of the Nation's coal-fired power plants already employ technologies developed with NETL support," said NETL Director Carl O. Bauer. "The laboratory is successful because its research addresses energy supply, cost and the environment concurrently, helping to achieve greater energy security at lower cost while reducing our environmental footprint."

Among NETL's research interests are the effects of the ionic liquid membrane, sorbents, aqueous ammonia, integrated pollutant removal, chemical looping and oxyfuel demonstration of re-heat combustion—all of which have a role in either making coal combustion more efficient or cleaning the exhaust gases. Ionic liquids, for example, are used as solvents to aid carbon dioxide capture from coal-derived flue gases. They are also converted into membranes to enable removal of carbon dioxide from flue gas.

The race is on to find ways to make coal use cleaner than ever before.

Once carbon dioxide is captured from flue gases, it can be stored or "sequestered" in terrestrial ecosystems and geologic formations such as depleted oil and gas wells, unmineable coal seams and deep saline formations. In the United States alone, the latest DOE Carbon Sequestration Atlas of the United States and Canada suggests that there is storage space for more than 1,100 years of carbon dioxide production.

One of NETL's goals is to develop technologies to capture, transport and store carbon from flue gases for less than a 10 percent rise in energy's cost. The carbon sequestration program, which started in 1997 with funding of just $1 million, has now grown to $150 million a year, indicating the degree of importance now placed on the key issue.

Another NETL goal has been to make the capture of mercury—which is released by coal combustion—effective and affordable. NETL has achieved this goal.

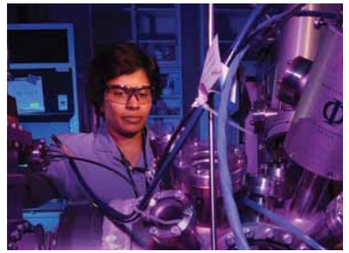
For 15 years, starting in the early 1990s, NETL conducted a comprehensive program to develop cost-effective technologies to control mercury emitted from coal-fired power plants. By 2007, NETL technologies were being implemented on a commercial scale and the program was deemed a success.

In 2008, researchers Hank Pennline and Evan Granite won an R&D 100 award—known as the "Oscars of Invention"—for the development of mercury control technology. Future mercury research has transitioned from government to private sector leadership.

Yet another environmental concern is the sulfur that is released by burning coal, which can contribute to the formation of acid rain. NETL has more than two decades of experience developing scrubbers, sorbents and other technologies to strip the sulfur from the flue gases at coal-fired power plants.

In one example, NETL's Ranjani Siriwardane and Dan Cicero won an R&D 100 award in 2001 for devising, developing and commercializing a method using sorbents to remove sulfur from the gas stream of coal gasification plants down to the parts-per-million level from as high as 4 percent.

With plentiful and inexpensive worldwide coal supplies, coal is almost certain to be used for heat and power for decades—if not centuries—to come. Technologies developed at NETL will help solve the coal conundrum and ensure that it is used cleanly and efficiently.



RANJANI SIRIWARDANE with NETL's spectrometer

RESEARCHERS HANK PENNLINE AND EVAN GRANITE won an R&D 100 award

ONE OF THE MOST ADVANCED, and cleanest, coal power plants in the world is Tampa Electric's Polk Power Station in Florida. Rather than burning coal, it turns coal into a gas that can be cleaned of almost all pollutants.

SOON AT THE PUMP:

CELLULOSIC BIOFUELS

Consumers will have more than gasoline and diesel to choose from when they pull up to the pump.

When talk turns to the need for alternative fuels, ethanol made from corn often comes to mind. But for 25-some years, researchers at a pilot facility at National Renewable Energy Laboratory (NREL) in Golden, Colorado, have been quietly and steadily working on developing biofuels made from nonedible plants like prairie grasses, wood chips and harvested corn and wheat leftovers. They're close to achieving a DOE goal: producing by 2012 "cellulosic" ethanol cheap enough to compete with conventional gasoline.

NREL researchers refer to the facility as a "glorified brewery." Here corn husks and stalks and switchgrass are fed into giant vats and churned into a tarry sludge that smells like molasses. After this "pretreatment," which releases sugars locked in cellulose, the sugary paste is mixed with fermenting microorganisms and water, then left to "brew" for several days in giant fermentation tanks.

ANDY ADEN, a biomass group engineer

The facility, constructed in 1995, produces primarily liter-sized portions of ethanol and operates in intermittent runs. Its capacity is about one ton of biomass per day. If run around the clock, it would produce some 75 gallons of ethanol for every ton of feedstock. In contrast, a commercial-scale plant could process some 700 to 1,000 tons of biomass daily.

The goal of NREL's pilot plant is to perform the research and development necessary to make cellulosic ethanol production cost-effective and to demonstrate how it could be produced on an industrial scale.

Currently, cellulosic ethanol produced for commercial markets would sell for roughly $2.43 per gallon compared to the approximate $1.33 per gallon price needed to be commercially viable by 2012, reported Andy Aden, a biomass group engineer. Consequently, NREL researchers are working to overcome significant hurdles, such as dismantling cellulose molecules, that require enzymes (natural proteins), to help the process. But these enzymes are expensive and drive up ethanol production costs. Unlike corn kernels, which are made up of starches that readily dissolve into simple sugars, cellulose does not release sugars easily. It's the part of the plant that gives cell walls their structure, and nature has made it especially hard to break down.

FERMENTOR

Cellulosic ethanol has the potential to offset a significant portion of gasoline use and make the U.S. energy portfolio more sustainable.

"Nobody really knows the magic that goes on when these enzymes break down material into sugars," said George Douglas, NREL spokesman. But NREL is working with industry partners to find out.

Also necessary for lowering cellulosic ethanol production costs is improving the efficiency of the fermentation process. Cellulose breaks down into five different sugars, all of which must be fermented by different microorganisms. NREL and its industry partners are engineering microorganisms that can ferment several sugars simultaneously and with higher yields. They are also experimenting with temperature ranges and nutrients to find the most suitable conditions to speed up the process.

Another NREL goal is to quadruple today's current production by producing 36 billion gallons of renewable fuels per year by 2022. While corn-based ethanol currently meets most of the U.S. demand for biofuels, important drawbacks include the fact that corn is a staple of the world's food supply. Its use for fuel has an impact on food prices. In addition, corn is grown on valuable agricultural land and involves energy-intensive processes for growth and harvesting.

Soon at the Pump: Cellulosic Biofuels

PROPELLER inside fermentation tank

FERMENTATION TANK and controls

In contrast, most cellulosic biomass, like sawdust and corn stover, is a byproduct of other processes. So-called "energy crops," such as switchgrass, thrive in marginal soils, use much less water and yield about 7 tons more per acre than corn. Another benefit, cellulosic biomass contains the molecule lignin, which acts as glue for the plant's cells and, as a byproduct of the fermentation process, can be used as a combustion fuel. Cellulosic ethanol produced on a commercial scale produces sufficient lignin residue to provide heat and electricity for the entire production and refining process.

To meet both goals, NREL is in the process of expanding its biofuels plant to double its geographic footprint and expand its research capabilities. After 2012, when the goal of producing cost-effective cellulosic ethanol is met, the industry will likely expand to other "green" fuels, such as butanol, Aden said.

For cellulosic ethanol to be commercially viable by 2012, the cost needs to come down to about $1.33 per gallon.

In the meantime, cellulosic ethanol has the potential of curtailing gasoline use significantly and making the U.S. energy portfolio much more sustainable. "Right now, when you pull up to most pumps, you've got two choices: gasoline and diesel," Aden said. "But in the not-too-distant future, consumers will have more choices, and that's exciting."

BUILDING BETTER BATTERIES
WITH NEW MATERIALS AND IMAGINATION

Batteries that are more compact, more powerful and longer lasting promise to reduce the cost and increase the practicality of tomorrow's hybrid-electric vehicles.

Researchers at Argonne National Laboratory (Argonne) near Chicago, Illinois, have for decades envisioned the car of the future, one that is fuel-efficient, high-performing, safe and affordable. Such advancements will be aided by patented innovations and ongoing work by scientists and engineers at Argonne, who are revolutionizing the lithium-ion batteries used in hybrid-electric vehicles. Argonne researchers are zeroing in on the materials used in electrodes, where fundamental improvements can make a significant impact. "Our research is addressing limitations of commercial lithium-ion materials on the market," said Gary Henriksen, manager of Argonne's Electrochemical Energy Storage Department, citing the relatively short life, high cost and safety issues associated with the current generation of batteries.

One new approach, patented by Argonne, involves a new family of composite cathode materials for lithium-ion batteries. Its research was funded by the U.S. Department of Energy's (DOE) Vehicle Technology Program. The technology replaces a lithium cobalt oxide electrode with a new electrode that consists of a combination of lithium and manganese-rich mixed-metal oxides. The new composite electrodes are more stable and can be charged to higher voltages. "We can almost double the amount of energy out of the same volume or weight of cathode material," Henriksen explained. These high-energy materials are being developed for use in plug-in hybrid-electric vehicles. Batteries that use these more stable composites are less prone to safety concerns, such as overheating and fires, which plague current lithium-ion batteries.

Argonne has developed different electrode materials for use in high-power batteries for conventional hybrid-electric cars. This technology promises to make the batteries more compact, more powerful, longer-lasting and safer. It also could drastically cut the cost of hybrid-electric vehicles for consumers.

Hybrid-electric vehicles currently on the market cost more than their gas-only counterparts. Plus, if gasoline prices are high, it would take years for consumers to recoup their extra investment. "If you can replace the battery with one that does the same job—but is smaller, more lightweight and less expensive—you can get your return on investment much more quickly," Henriksen said.

Argonne's patented work with composite cathode materials should hit the marketplace soon. In early 2008, Japan's Toda Kogyo Corp. entered into an agreement with the lab to take the technology to Detroit, Michigan. Toda is gearing up to start production at a manufacturing facility not far from the auto hub.

Our number-one goal is to reduce our dependence on oil.

Argonne licenses its advanced battery technologies on a nonexclusive basis. While it charges for these licensing rights, it's a good deal for industry. Argonne has been working on advanced battery R&D for about 40 years and on advanced lithium-ion batteries for about 10 years. "About 10 or 15 years ago, Argonne started to grow a really strong team of people from whom this success has been derived," said Mike Thackeray, group leader and Argonne Distinguished Fellow in the lab's Battery Technology Department.

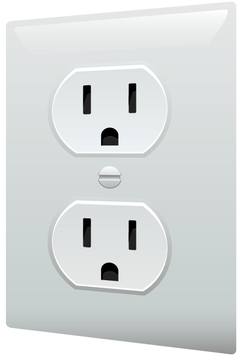
Currently, a team of about 35 scientists and engineers is spearheading the effort to build a better battery. Its lithium-ion battery research is funded by the DOE's Vehicle Technology Program. Argonne's approach is holistic, from basic research through engineering to testing complete battery systems. "We're trying to cover the breadth—to take materials from their infancy to prototype production and into industry much faster," Henriksen said.

The goal is to move successful technology into the marketplace as soon as possible.

Each time the United States faces an energy crisis, such as in the 1970s and more recently when gasoline prices topped $4 a gallon nationally, Argonne's work receives new emphasis and attention. "Our number one goal is to reduce our dependence on oil," said David Howell, acting team leader for Hybrid Electric Systems at DOE headquarters in Washington, D.C.

But the technologies developed at Argonne are positioned to spread beyond automotive batteries to consumer electronics such as cell phones and laptops, and the aerospace, defense and medical sectors. For example, more energy is needed for the ever-increasing array of features packed in sleek, lightweight cell phones. Argonne's battery technology may help electronics makers meet those demands.

Argonne scientists predict their technology could migrate into broader electronics applications quickly. "We believe our materials could be available within the next couple of years," Henriksen predicted. "Then it's basically up to the industrial battery community to introduce them into their products."



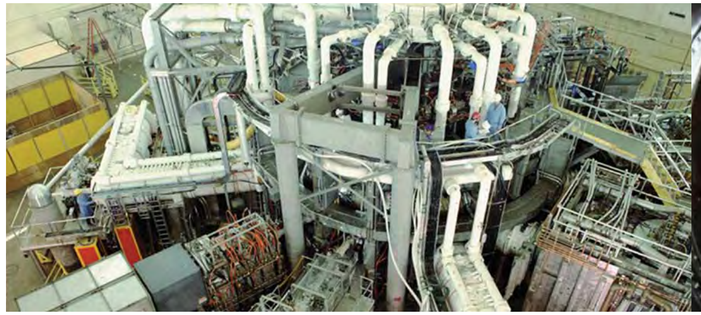
FUSION ENERGY: TRUE STAR POWER

Fusion, no longer exclusive to the sun and stars, provides means for endless energy on earth.

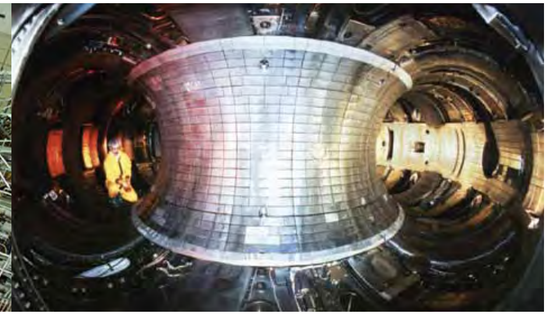
The challenge is to find the right conditions under which a fusion power plant can produce more energy.

Nuclear fusion, the process that powers the sun and stars, offers the dream of a safe, inexhaustible and environmentally friendly source of energy. Producing practical amounts of fusion energy on earth requires the confinement of a very hot, ionized fuel known as plasma, akin to a small sun. ITER (originally the International Thermonuclear Experimental Reactor), which is expected to go online in Cadarache, France, in 2018, will be the first facility capable of achieving sustained burning plasma, a necessary next step in developing the promise of fusion energy. Dr. Ned Sauthoff, who runs the U.S. ITER project office at the Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tennessee, remarked that "ITER will give us greater assurance that fusion is capable of providing abundant, economical and environmentally benign energy in the future." To succeed, ITER will require a significant parallel research effort to "enhance understanding of the operating characteristics of tokamaks (doughnut-shaped chambers used in fusion research in which a plasma is heated and confined by magnetic fields).

ITER will be 56 feet in diameter. Inside, nuclear fusion, in just half a gram of tritium-deuterium fuel, will produce 500 million watts of power—ten times greater than the external power required to heat the plasma. (Tritium and deuterium are heavy isotopes of hydrogen that fuse together to form helium).



TOKAMAK FUSION test reactor



INSIDE THE TFTR vacuum vessel

ITER will begin to approach the power output and energy gain required for a practical power plant, but as a whole, it will not be a power generator. The United States has joined the European Union, Japan, China, Russia, India and South Korea in supporting the effort.

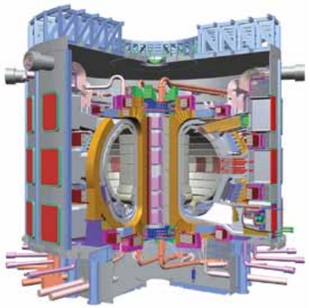
One area of potential concern for large-scale tokamaks is the dissipation of energy from the plasma. Understanding what causes heat to stay in such fuel, and what causes it to leak out, has been a long-standing problem. But now researchers at the Princeton Plasma Physics Laboratory (PPPL) in Princeton, New Jersey, have shown that tiny eddies generated in the plasma stream, like swirls in a fast-flowing river, may be one cause of heat loss from the plasma. "This is a breakthrough in the understanding of turbulence in these plasmas," said PPPL director Rob Goldston.

Nuclear fusion offers the dream of a safe, inexhaustible and environmentally friendly energy source.

Fusion reactions occur at high temperatures when two light nuclei, atoms stripped of their negatively-charged electrons, slam into each other and fuse to create a heavier nucleus. In the process matter is converted to energy, which in principle can be harnessed to operate a steam turbine and generate electricity. The challenge is to find the right conditions under which a fusion power plant can produce more energy than is needed to heat the roiling plasma.

PPPL broke the world record for fusion power generation in 1994 with its Tokamak Fusion Test Reactor (TFTR) by producing momentarily a whopping 10.7 million watts. If converted to electricity, this amount of power could satisfy the needs of about 3,000 average-size homes.

But the doughnut-shaped TFTR, like all conventional tokamaks, requires powerful and expensive magnets to produce the high pressures needed for perpetuating fusion reactions. In 1984, physicist Martin Peng in ORNL's Fusion Energy Division realized that it might be possible to reduce the energy



ITER diagram

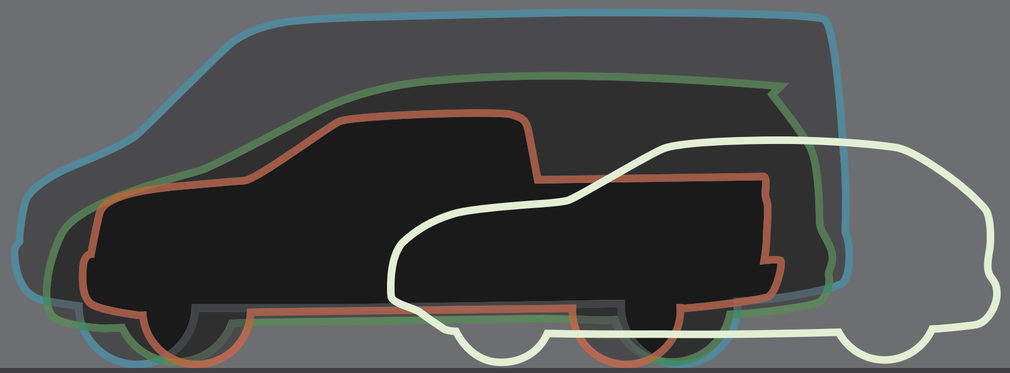
in those magnets with a novel design that confined plasmas to a ball with a hole in its center—more like a cored apple than a doughnut. This simpler, more efficient spherical torus design, which has more modest magnets, would also give scientists an unprecedented wide-angle view of the swirling of ions and electrons inside. And so with great enthusiasm, in February, 1999, physicists flipped the switch on PPPL's 20-foot diameter National Spherical Torus Experiment (NSTX).

Typically in NSTX, the plasma core reaches about 20 million degrees Celsius. However, like other magnetic fusion devices, the NSTX plasma is much cooler at its edge where it comes in contact with the high-purity carbon tiles that surround it—or what Goldston calls "the physical world." The plasma edge temperature in NSTX is only 1 million degrees Celsius. The tremendous temperature difference between the core and the edge can create turbulence in the plasma as energetic particles, both atomic nuclei and electrons, collide and swing around the magnetic fields that are supposed to keep them in line. Physicists had previously measured the centimeter-sized turbulence created by the nuclei, but none had confirmed the existence of the tiny, but long-theorized form of electron turbulence.

To tackle this problem, the PPPL team directed microwave beams at the plasma and measured how they scattered by the turbulence, a trick that was only possible due to NSTX's very open design. "This is a totally cool technique," Goldston said of the methodology. "We have extremely good spatial resolution, plus or minus 5 percent of the radius of the plasma." These precise measurements allowed a team led by PPPL physicist Ernesto Mazzucato to confirm the existence of those pesky electron eddies, about 1 millimeter in diameter.

"We now have the suspect under the spotlight, but we don't know for sure how strongly this turbulence is causing the heat to leak out," Goldston said. By varying a number of parameters, including the drop in electron temperature and the variation of magnetic fields across the plasma, the physicists may even have learned how to eliminate this electron turbulence. Their results, in very good agreement with theoretical predictions, were published in 2008 in Physical Review Letters.

MAPPING ENERGY FROM THE SOURCE TO YOUR CAR'S TAILPIPE AND BEYOND



Just how much energy goes into a sports utility vehicle versus a hybrid vehicle? GREET can tell you exactly.

There are spreadsheets and then there are spreadsheets. Taking up 15 megabytes of hard disk space and with 28 separate tabs, Argonne National Laboratory's publicly available GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Transportation) model can answer just about any question that a company, government agency or academic researcher has about greenhouse gas emissions and energy consumption of vehicles powered by everything from Brazilian sugarcane to hydrogen fuel cells. For any given vehicle technology and fuel system, GREET separately calculates the energy consumption by energy type; the emissions of greenhouse gases, including carbon dioxide, methane and nitrous oxide; and the outputs of six critical pollutants, including nitrogen oxides and soot.

In the last two years, project leader Michael Wang and his five-person team have updated GREET to model even the energy it takes to produce a vehicle's fuel and get it to the pump; how much energy is used in driving the vehicle; and how much energy is required to manufacture the vehicle and recycle or dispose it at the end of its cycle. "That gives a real comprehensive life-cycle approach to looking at conventional and advanced vehicles," said team member Andrew Burnham.

Wang, who hails from China, began this massive spreadsheet model in 1995. Upon earning his doctorate in environmental science at the University of California-Davis and joining Argonne, in DuPage County, Illinois, he wanted to compare conventional vehicle impacts with electric vehicles. "But that's like comparing apples to oranges," said Wang. "It's easy to measure the emissions of a gasoline-powered combustion engine as it rumbles away, but looking at only the quiet whirr of an electric motor may not show its true impact on the environment. Its electricity, which is generated at a power plant far from where the vehicle was operated, has to be taken into account."

GREET can simulate more than 82 vehicle-fuel combinations and has more than 9,000 registered users worldwide.

Consequently, Wang's model asks, how was that power generated? Was it produced in a coal-fired plant in Arkansas or at a wind-energy farm in California? How was it transported to the electric wall outlet? How much energy did it take to produce the aluminum used in the car's engine? While Wang initially made his calculations by hand, he soon realized he could build a spreadsheet that would make this task easier for him and, ultimately, the transportation community.

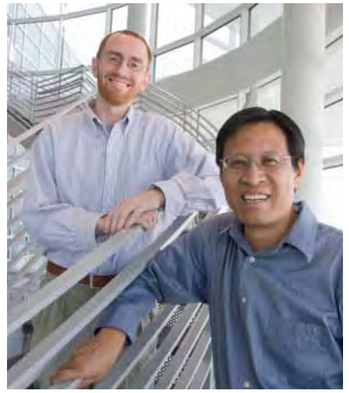
The project took off just as the federally sponsored Partnership for a New Generation of Vehicles—collaborative research between National Laboratories—federal agencies and major automakers on how to bring highly fuel-efficient cars to the marketplace, got rolling in the early 1990s. The partnership impelled people to think about fuel-cycle analysis.

Today, GREET can simulate more than 82 vehicle-fuel combinations. It has more than 9,000 registered users worldwide. To address technology improvements, GREET simulates fuel production pathways and vehicle systems over a period from 1990 to 2020 in five-year intervals. Since the biggest challenge is acquiring accurate data, Wang is constantly tinkering with parameters. Most recently, his team used survey data just released from the Energy Information Administration to update his efficiency estimates for petroleum refining operations.

For any given vehicle technology and fuel system, GREET separately calculates the energy consumption by energy type such as gas, oil or coal.

Just as Wang realized that a vehicle's impact can extend beyond its tailpipe, researchers began challenging how far those impacts spiral out. For instance, when corn is grown on a farm recently cleared of native vegetation, this land-use change and its direct impact on greenhouse gas emissions are relatively easy to calculate. More contentious is how farming in the United States might indirectly affect greenhouse gas emissions in international economic channels. If the United States exports less corn, or U.S. corn prices increase, some maintain that other countries may expand their corn-growing operations.

Wang and his group at Argonne are still grappling with the issue, and working with other organizations to address the indirect effects of large-scale biofuels production with economic general equilibrium models. But more comprehensive models will be needed to take into account the supply and demand of agricultural commodities, land-use patterns and global land availability.



PROJECT LEADER MICHEAL WANG (right), and team member Andrew Burnham

PENNSYLVANIA might rely on silver maple for its biofuels crop.

CELLULOSIC BIOFUELS Bioenergy Research Center scientists envision a more diverse portfolio of future bioenergy nonfood crops, including woody waste, grass and other cellulosic biofuels. Current biofuels are made of food crops such as corn and sugar cane.

BIOENERGY RESEARCH CENTERS AT THE

FOREFRONT OF GREENER FUELS

A joint effort by several research laboratories is working to make biofuels a viable and sustainable energy resource.

As greenhouse gas emissions grow and world oil fields potentially pass their peak production, the search is on for future fuels that literally grow on trees. The U.S. Department of Energy (DOE) has established three Bioenergy Research Centers that will lay the foundation for a plant-based energy economy. Consisting of uniquely structured partnerships among National Laboratories, universities, nonprofit research centers and private companies, each center is receiving $25 million in annual federal funding. The plan is to provide each with up to $135 million through 2012. Results of fundamental research performed by the centers will provide the nascent bioenergy industry with the critical new techniques and tools needed to make production of cellulosic biofuels (biofuels made from nonfood plant fiber) efficient, economical and sustainable.

> **We are bringing to the table different approaches and ways of thinking that increase our chances of success.**

Although the three centers share the common goal of achieving new breakthroughs in the transformation of plant matter into biofuels, each center has a unique perspective and approaches the problem from a variety of different angles. “We are bringing to the table different approaches and ways of thinking that increase our chances of success,” said Tim Donohue, director of DOE’s Great Lakes Bioenergy Research Center (GLBRC) in Madison, Wisconsin, and a professor of bacteriology at the University of Wisconsin-Madison. “It increases the probability that society is going to reap the benefit of this investment by putting their eggs in several baskets.”

The centers have their work cut out for them. At present, converting plants into fuels is a costly, multistep process that must be made cheaper and more efficient before it can compete with fossil fuels in the marketplace. “We are focusing on the major problem of why biofuels are not a sustainable industry,” commented Martin Keller, director of the DOE’s BioEnergy Science Center (BESC) based at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee.

The structures of plants themselves pose the first hurdle. Plant cells are built of interwoven large polymeric molecules. The breakdown of these molecules leads to sugars that microbes can ferment into fuels such as ethanol. These polymeric molecules are very sturdy and resist both chemical and mechanical breakdown, necessary to get access to the sugars.To overcome this problem, called recalcitrance, BESC researchers are working to identify the thousands of genes involved in plant cell

Refineries in **HAWAII** could use eucalyptus.

wall construction and how they interact to build stems, trunks and leaves. “Once we know the genes, we can start examining how we can change them to make the plant easier to digest,” said Keller. That includes the automation of the screening of plant samples for desirable traits with methods commonly found in the pharmaceutical industry, which routinely tests vast libraries of chemical compounds for potential drugs.

But sugars aren’t the only viable source of plant energy. Plants also store their biochemical energy in energy-rich molecules such as oils and starches. GLBRC is studying how to maximize the oil and starch yield in leaves and other nonedible portions of plants. “If we could breed plants to accumulate as much as 20 percent oils, we could double the energy produced per acre of land,” Donohue said.

If we could breed plants to accumulate 20 percent oils, we could double the energy produced per acre of land.

An area that bioenergy scientists are working to streamline is the laborious process required to refine green plants into biofuels. At present, breakdown enzymes produced by one set of microbes must be grown and purified before being added to harvested plants. A second set of microbes is then used to ferment the plant sugars into biofuels such as ethanol. BESC aims to collapse these three steps into one with a single organism that can both manufacture catalyst enzymes and ferment the sugars into biofuels. “This type of consolidated bioprocessing provides the biggest savings and could completely change the economics of biofuels,” Keller said. His researchers have already identified one such multitalented microbe and are using a combination of genetic and genomic tools to optimize its performance.

To further speed the breakdown of raw plant biomass process, scientists at the DOE’s Joint Bioenergy Institute (JBEI) in Emeryville, California, are studying how to pretreat plants with ionic liquids before they are added to fermenters. Ionic liquids are made of ions similar to table salt, but are liquid rather than solid at room temperature. Early results show that ionic liquid pretreatment can break down plant cell walls more rapidly and effectively than current treatments using acid or ammonia. Ionic liquids also do not cause downstream problems, such as inhibition of microbial fermentation, which can decrease the efficiency of biofuel synthesis.

Switchgrass could be the preferred biofuels crop in **NEBRASKA AND FLORIDA.**

At the same time, JBEI scientists are building a better biofuels manufacturing microbe from scratch. “We view all these enzymes and metabolic pathways as parts. We want to put them onto the chassis of a microbe and modify the parts to get the greatest benefits from them,” said JBEI scientist Blake Simmons. Leading their efforts is synthetic biology pioneer and JBEI director Jay Keasling, who is also a professor of bioengineering and chemical engineering at the University of California-Berkeley, and the director of the Physical Biosciences Division at Lawrence Berkeley National Laboratory (Berkeley Lab) in Berkeley, California.

While current biofuels are made of food crops, such as corn and sugar cane, scientists working at the Bioenergy Research Centers envision a far more diverse portfolio of bioenergy crops. The centers are examining a wide range of fast-growing perennial plants that are already found in abundance in different regions of the country. Switchgrass might be the preferred biofuels crop in Nebraska and Florida, refineries in Hawaii might use eucalyptus while those in Pennsylvania might use silver maple. Excess biomass produced by forests and farms also could contribute. “It’s not so much a silver bullet that we need but a silver shotgun,” remarked Berkeley Lab scientist Blake Simmons. “We’ll have tens if not hundreds of solutions that make the most of our diverse geographical climate, growing conditions and water availability.”

Biofuel crops will have an impact on soil fertility, water and air quality, animal migration patterns and land use, as well as local and global economies. To that end, GLBRC scientists are developing tools with economists, engineers and others to maximize the environmental benefits of a biofuels economy. “We want to enter this new world with our eyes open,” Donohue said. Researchers at Berkeley Lab are looking even further ahead by developing third-generation biofuels that are chemically equivalent to gasoline, diesel or jet fuel.

Other experts say the DOE Bioenergy Research Centers will play a critical role in jump-starting the nascent biofuels industry. “These government centers are working at a basic research level on questions of practical importance that private companies can pick up and move with,” said Doug Cameron, chief science advisor for Piper Jaffray, a global investment bank headquartered in Minneapolis, Minnesota, and a member of the GLBRC external advisory board. Although all private companies involved in alternative fuels need to understand the detailed physical composition of plants and how best to deconstruct their scaffolding, “almost none of them can afford to have people working on it at the level you have at these government-funded centers,” according to Cameron.

REDUCING ENERGY DEMANDS
BEGINS AT HOME

Building an affordable, comfortable home that produces as much energy as it uses is no longer the home of the future, but the home we need now.

One of the timeliest initiatives emerging recently from Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tennessee, began with a collaboration with Habitat for Humanity to develop energy-efficient technologies for five homes in Lenoir City, Tennessee. To date, results of this effort, championed by ORNL researcher Jeff Christian, have shown great promise and have now expanded to include seven more commercially built homes in Oak Ridge and Knoxville, Tennessee.

It all started in 2002, when all of ORNL's building research projects were consolidated and challenged to develop "the zero-energy house"—one that would use only the energy it produced. Believing that energy-efficient homes should be affordable for working families, Christian quickly seized this challenge and argued that unless the issue of residential energy consumption is addressed now, it will likely grow by 1 percent per year until 2025. Even more alarming, the annual rate of consumption for commercial energy is forecast to be twice that figure in the same period.

"Yes, we must replace oil with biofuels. Yes, we must pursue other supply-side solutions in an environmentally acceptable manner," Christian said. "But there's enormous potential to reduce energy demand in our homes and offices. That's by far the cheapest solution to address this problem."

Consequently, five low-energy homes were built in a Tennessee community between 2002 and 2005, the result of the Habitat for Humanity partnership and funds from the Tennessee Valley Authority. The community became a "living laboratory" for ORNL researchers studying the impact of energy-efficient building practices and technologies. Their work has so far produced impressive real-world results. In some homes, electric bills declined to less than 50 cents a day. "Creating more energy-efficient buildings is not only part of the overall solution, it's the most cost-effective opportunity to reduce the nation's energy consumption and affect climate change," Christian stated.

Low-energy homes resulted in some electric bills of less than 50 cents a day.

The latest project involves three research houses built in 2008 at Campbell Creek in Knoxville. The first is a typical Energy Star "builder house" with an energy efficiency score of 85 Home Energy Rating System (HERS). The second "retrofit house" with energy-efficient upgrades has a HERS rating of 64 (the lower the better). The third, a "high performance" house with technologies pushes the HERS rating to 30, or about 55 percent savings compared to the "builder house." Both the second and third houses, because they have HERS ratings of less than 70, were awarded EnergySmart Home Certificates for their reduced energy use under the DOE Building America Builders Challenge Program.

ZERO-ENERGY HOMES Jeff Christian at one of the Habitat for Humanity near-zero-energy homes in Lenoir City, Tennessee.

STRUCTURAL INSULATED PANELS The secret behind each house's exceptional energy efficiency lies in a well-insulated airtight envelope.

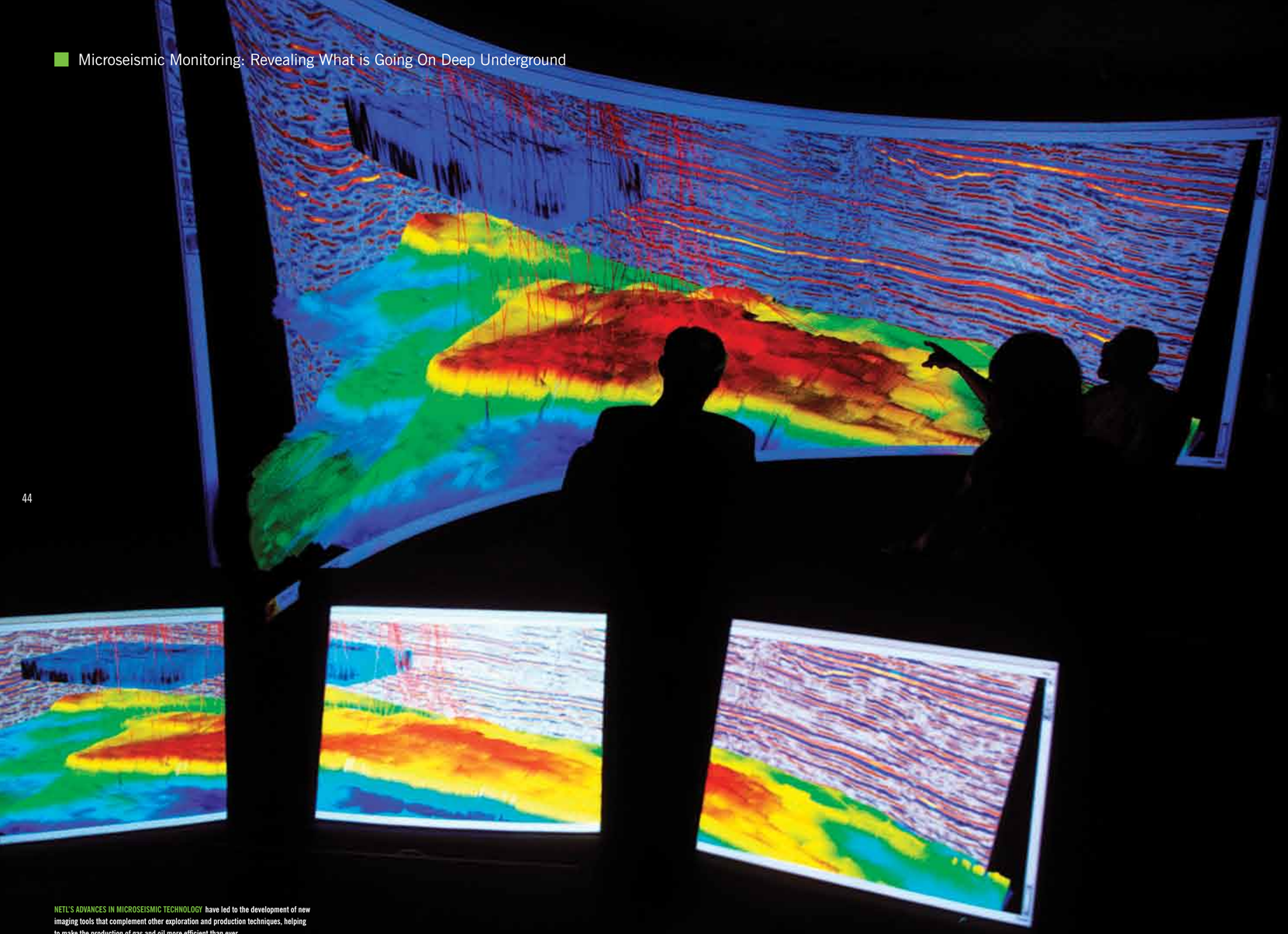
"With these three houses in a typical residential setting we will have research capabilities that are world-unique," Christian said. "And the really exciting thing is that these houses will be available for research for seven years, so we will be able to replace, test and accelerate the development of even more efficient component technologies." In the United States buildings command 40 percent of the country's overall energy use, outstripping industry at 32 percent and transportation at 28 percent. Buildings also produce 43 percent of U.S. carbon emissions, using 38.8 quadrillion British thermal units (BTUs) of energy each year for heating, cooling, ventilation, lighting, water heating, refrigeration and other energy demands. Obviously, a residential housing community is the logical place to launch a zero-energy project.

ORNL works with industry partners to develop the construction materials and technologies needed to build greener homes. Researchers have tested solar-reflective roofing, insulation materials, structural insulated panels, solar technologies and foundation systems. The laboratory has developed software tools to assess moisture-resistant construction materials, provide energy efficiency ratings for buildings, design more efficient heat pumps and other equipment and guide development of standards for building insulation, materials and moisture design.

Creating more energy-efficient buildings is the number-one most cost-effective way to reduce the nation's energy consumption.

Meanwhile, Christian and his team are carrying out their work in support of an ambitious U.S. Department of Energy program to develop affordable, net-zero-energy housing by 2020 and zero-energy commercial buildings by 2025. The Habitat homes feature renewable energy sources to minimize demand for fossil fuels, such as heat pump systems that tap geothermal energy in the ground and solar panels to provide electricity and water heating capabilities. Energy-efficient construction and technologies are incorporated, including roofs with "cool-color" coatings to deflect heat, utility walls that consolidate most of the homes' major plumbing (alone providing an energy saving of 15 percent) and virtually airtight construction with advanced ventilation systems to keep the homes comfortable.

"I've noticed that when I tell people that these new houses have energy costs of approximately 50 cents a day, they tend to think about their own homes," Christian commented. "People respond to the idea. They just need education and awareness."



NETL'S ADVANCES IN MICROSEISMIC TECHNOLOGY have led to the development of new imaging tools that complement other exploration and production techniques, helping to make the production of gas and oil more efficient than ever.

MICROSEISMIC MONITORING:

REVEALING WHAT IS GOING ON DEEP UNDERGROUND

A new technology will get the most out of our nation's oil and gas resources by helping engineers and geologists "see" how a well connects with an oil reservoir below the surface of the earth.

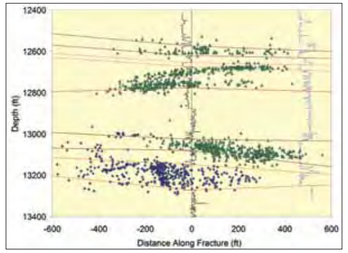
The National Energy Technology Laboratory (NETL) and other National Laboratories have partnered with industry to develop a breakthrough technology that is helping oil and gas producers connect their wells with the hydrocarbons stored in networks of fractures found in many of today's most promising domestic oil and gas accumulations. Also known as "plays," these accumulations exhibit complex geological characteristics. The technology combines subsurface sensors with powerful data collection and analysis software, to record the myriad of tiny microseisms (or microearthquakes) that occur as fluid is pumped into a well bore, creating a split or fracture in a subsurface rock formation holding natural gas or oil. The individual locations of these microseismic events are mapped to create an image of the fracture.

This image, which reveals both the direction and extent of the fracture resulting from a specific pumping procedure, can be used to optimize the placement of such fractures and their connection with networks of natural fractures within hydrocarbon-bearing rock formations, increasing the recovery of domestic natural gas and oil resources. Before this technique was developed, engineers could use computer models to indirectly infer the dimensions of the hydraulic fractures they were creating downhole, but had little direct evidence of their extent and orientation.

These unconventional reservoirs could provide a major component of our domestic energy production over the next two decades.

This new technology, called microseismic monitoring, is important because the United States' national energy security is dependent on our ability to economically extract as much of our own hydrocarbon resources as possible. A growing portion of our domestic production is from "unconventional" reservoirs—underground formations that require hydraulic fracturing to release their oil and gas—and developing technologies that enable us to efficiently produce these resources is critical to any effort to reduce America's need to import energy.

For example, the recent rapid expansion of natural gas production from the Barnett Shale play in central Texas has been made possible by large, multiple-stage hydraulic fracturing treatments



MICROSEISMIC MAP **The dots on the map represent Microseismic events occurring deep in the earth that represent where the hydraulic fracture is going, and provide industry the ability to "see" the hydraulic stimulation event in great detail that previously could only be modeled. In addition, the technology is now being used not only to map the hydraulically induced fracture (needed for reservoir stimulation), it can also be used to "illuminate" the existing natural fractured network where the unconventional gas resides. This allows for a much better understanding of these reservoirs and improves understanding of stress fields in the rock that were previously only estimated. All of this information allows operators to be more efficient in developing today's unconventional gas.**

MULTI-WELL SITE **in Colorado**

(i.e., more than one created fracture per well bore) performed in horizontally drilled wells. Microseismic monitoring of these stimulations has played an important role in optimizing well performance and ensuring that each well produces at its full potential. Operators are now using this technology to overcome the complexities of similar shale reservoirs across North America, including the Bakken, Caney, Fayetteville, Marcellus, Muskwa and Woodford shale plays.

These unconventional reservoirs are seen by industry and government experts as providing a major component of our domestic energy production over the next two decades. The Barnett Shale play currently produces about 4 billion cubic feet of gas per day and production is expected to grow to as much as twice that amount over the next five years. Barnett's Newark East Field is thought to be the largest gas field in the United States. The more recently explored Marcellus Shale play of West Virginia, Pennsylvania and New York has been described by some as having the potential to provide as much as 50 trillion cubic feet of technically recoverable gas. The Bakken Shale, an oil play in North Dakota and Montana, contains more than 3.6 billion barrels of recoverable oil, according to the U.S. Geological Survey. All of these geologically complicated reservoirs can be developed more efficiently through the application of microseismic monitoring technology.

The roots of this technological breakthrough stretch back to research and development funded by the U.S. Department of Energy (DOE) in the late 1970s. Additional R & D funded by DOE through NETL in the 1980s and 1990s enabled enhancements to the tools and techniques that were subsequently commercialized by Pinnacle Technologies, Inc.

During the past 10 years NETL has continued to work with Pinnacle and others parties to push the envelope by funding new R & D to refine and enhance the application of microseismic mapping technology. One project focused on the development of a hybrid technique that combines information from downhole seismic sensors with that from surface tiltmeters, to provide a more accurate depiction of the fracture being created underground. A second project with the University of Texas and Anadarko Petroleum employed Pinnacle's microseismic monitoring to map fractures in East Texas' Bossier formation and identified places where hydraulic fractures intersected faults and grew in unexpected directions. Another project, sponsored by NETL through the Stripper Well Consortium, introduced microseismic monitoring to smaller independent producers seeking to improve recovery from Appalachian shale gas reservoirs.

A fourth effort, currently underway, is helping to develop the technology needed to make "designer seismic" monitoring possible. This approach involves the drilling of multiple, strategically placed, small diameter, inexpensive microholes with permanently installed seismic receivers to enable high-resolution and relatively inexpensive seismic monitoring of a reservoir over an extended period of time. The sensors are used to record seismic events resulting from fluid movements within the reservoir at successive points in time, enabling the mapping of injected fluid fronts moving through the reservoir. Such time-lapse monitoring will be a valuable tool as the oil and gas industry increases the application

of enhanced oil recovery techniques to sweep residual oil from mature fields. This R & D project, sponsored by NETL in partnership with Lawrence Berkeley National Laboratory in Berkeley, California, and Lumedyne Technologies Inc. of San Diego, California, is focused on developing the small-sized, inexpensive geophones needed to make this possible.

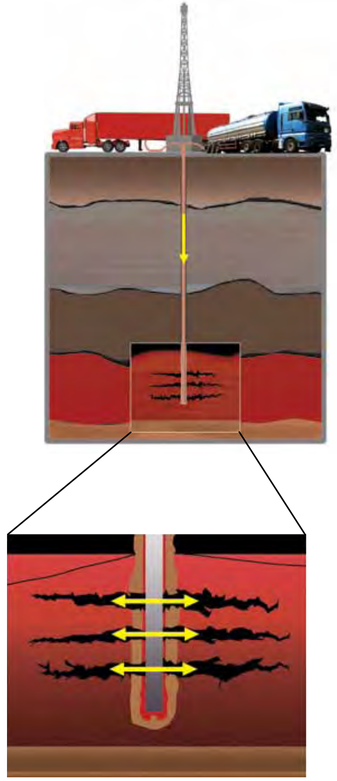
The first systematic research into microseismic fracture mapping, done by Los Alamos National Lab (LANL) in Los Alamos, New Mexico, in the 1970s, was related to fractures in geothermal wells. Somewhat later, NETL collaborated with Sandia National Laboratories to build and deploy receivers for testing similar mapping technology. In the 1980s, this system was used at the NETL Multiwell Site experiment in Colorado, where major fracture experiments were successfully monitored.

When it became clear that single receivers would not be adequate for microseismic monitoring because of their limited accuracy, NETL sponsored a project to develop a multilevel receiver system that became the first generation of a number of successive systems. Pinnacle Technologies began using these receivers and developed a business that quickly grew to several hundred mapped fractures per year. NETL sponsored an additional research project with Pinnacle to help the company refine and enhance its technology. Recently the company has employed its microseismic and tiltmeter technology to monitor more than 12,000 hydraulic fracture treatments.

The development and application of microseismic imaging technology… will continue to play an important role in facilitating more efficient production of natural gas and oil from the nation's unconventional resource base.

The important thread in this story is the significant role played by DOE, and in particular NETL, in helping to develop this technology over the more than two decades required to make it commercially workable for normal oil and gas activities. DOE's early investment in basic research and NETL's long-term support were critical to the development of microseismic monitoring as a modern tool for oil and gas producers. According to NETL director Carl Bauer, "The development and application of microseismic imaging technology has played and will continue to play an important role in facilitating more efficient production of natural gas and oil from the nation's unconventional resource base."

It is particularly timely that this technology is available for commercial application just as producers are looking for ways to improve their efficiency in developing unconventional reservoirs. Microseismic monitoring is a way to more precisely characterize reservoirs and related flow dynamics, enabling fewer wells to produce more oil and gas, more quickly, at lower cost and with fewer environmental impacts. This technology, which enhances the high-density drilling approach of conventional domestic oil and gas field development, will be an important element of future methodologies for developing our nation's energy resources.



NETL'S ADVANCES IN MICROSEISMIC TECHNOLOGY **have led to the development of imaging techniques that help improve the efficiency of fracturing treatments (illustrated above) designed to produce more of our domestic oil and natural gas resources.**

THE FUTURE OF FUEL

Scientists are making significant headway in finding alternatives to power automobiles without polluting the atmosphere.

Great hopes have been vested in hydrogen fuel cells since their use in spacecraft in the 1960s. They are now being used for stationary power generation and material handling equipment, and the prospect of a commercially viable system for powering automobiles has moved a significant step closer, thanks to advances in applied research and development at the U.S. Department of Energy's (DOE) National Laboratories. Novel fuel-cell technologies, including advanced catalysts and membrane electrode assemblies (MEAs) have been developed over the past few years, offering a major option for a clean alternative to gasoline engines. Next-generation catalysts are yielding improved activity and durability, making fuel cells suitable for a mass market.

According to senior researchers, the new catalysts give high performance with a big enough reduction in cost per kilowatt to make fuel cells potentially competitive with conventional technologies used in automobiles. The biggest cost item is the catalyst, reflecting the high price of platinum, so far found to be the most suitable material.

The biggest cost item is the catalyst, reflecting the high price of platinum.

Three National Laboratories—Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico; Lawrence Berkeley National Laboratory (Berkeley Lab) in Berkeley, California; and Brookhaven National Laboratory (Brookhaven), in Upton, New York—have been pioneers in the advancing the state of the art of fuel-cell catalysts and moving the technology toward the mass consumer market. Most recently, Brookhaven has pioneered a method using much smaller quantities of platinum with improved results. This involves working with nanoparticles of a support material and coating them with a skin-like layer of platinum. Compared with current-generation fuel cells using pure platinum, this approach reduces platinum content by 90 percent.

This advancement would not be possible without prior work carried out at Berkeley Lab and LANL. Berkeley Lab prepared catalysts with platinum on the surface of platinum alloys and discovered that catalysts with this structure perform better than conventional platinum catalyst particles, due to the effects of layering and alloying.

LANL researchers incorporated an ionomer into the electrode, increasing proton conductivity, and pioneered an approach to catalyst deposition on thin-film electrodes. These improvements mean that less platinum (by more than a factor of 20) is necessary for the same or better performance, which enables the use of nanoscale particle catalysts. The new catalysts have been incorporated into MEAs and tested with encouraging results at LANL and some private companies.

Catalysts are used in both electrodes of a fuel cell to maximize the electrochemical reactions, in which hydrogen and oxygen combine to produce not just water but also—by making hydrogen's electrons pass through an external circuit—an electric current. The Brookhaven team first created a catalyst using the new approach for the positive anode terminal, where hydrogen enters the fuel cell. An alloy of platinum and ruthenium, a metal of the same group, had already proved efficient. Under the new approach, an ultrathin platinum monolayer was deposited on ruthenium particles, making almost all the platinum atoms available to react with the hydrogen.

The combination is useful in dealing with one of the factors impairing the performance of fuel cells—the accumulation of tiny traces of carbon monoxide, which are expensive to remove, are poisonous and bond to the platinum, preventing hydrogen oxidation. Ruthenium catalyzes the oxidation of this carbon monoxide into carbon dioxide, which is harmless to the cell.

The tendency of platinum to lose its activity and affect fuel-cell performance in stop-and-go driving conditions has been one of the big obstacles to a satisfactory automobile system.

The team has worked on similar techniques using other core materials and developing more elaborate combinations, with one outer shell on top of another. One of the most promising involves a core of palladium coated with platinum, which is then sprinkled with gold clusters. Gold has been shown to be effective in making the catalyst at the negative cathode more resistant to corrosion, keeping the platinum intact. The tendency of platinum to lose its activity and affect fuel-cell performance in stop-and-go driving conditions has been one of the big obstacles to a satisfactory automobile system. Another promising combination is an alloy of platinum with nickel and copper. Under certain operating conditions, this alloy performs three times better than standard catalysts.

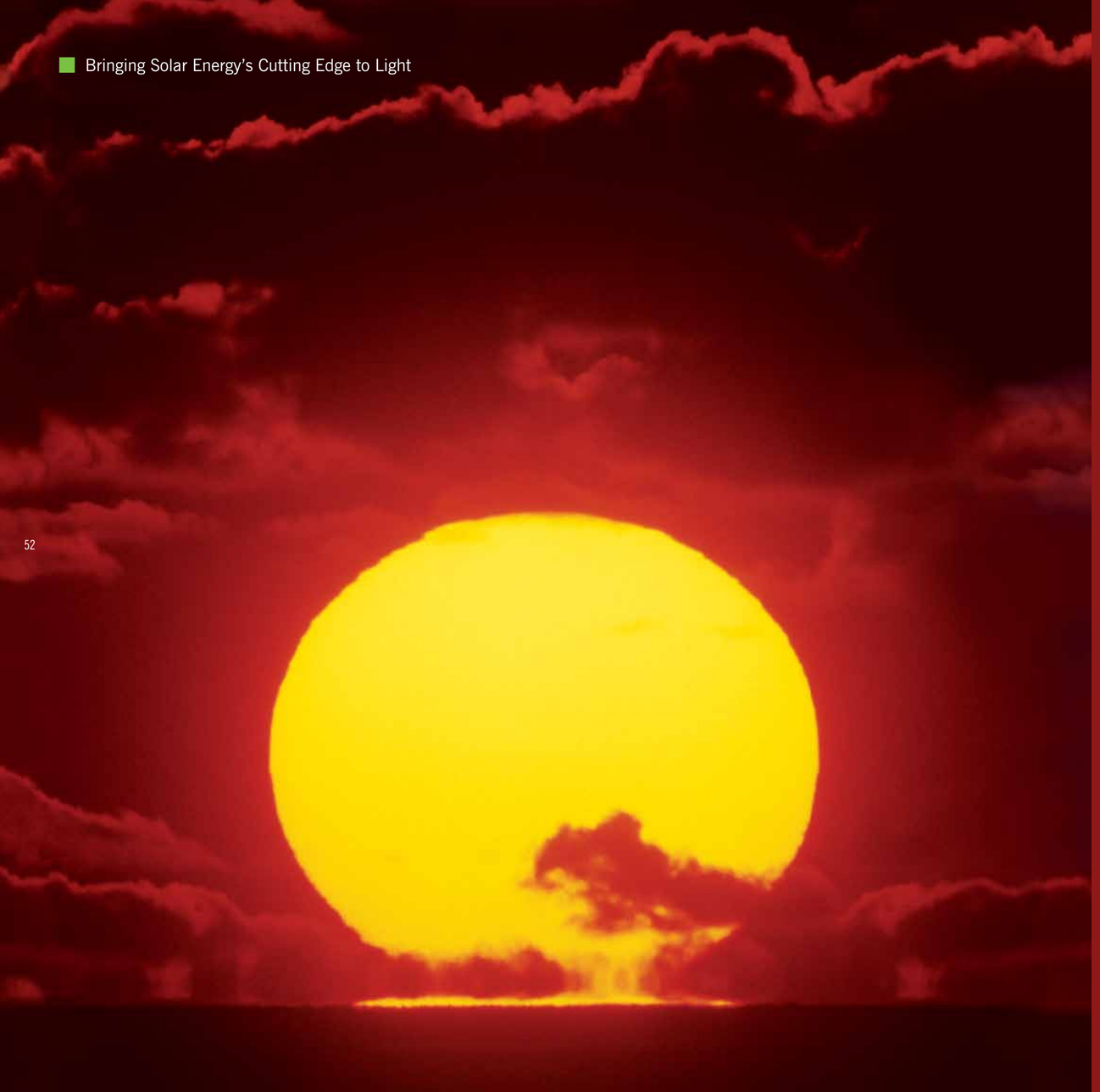
The DOE Hydrogen Program's goal, to overcome obstacles to taking hydrogen fuel-cell vehicles from the laboratory to the showroom, now appears to be within reach. In 2004, the program began implementing a $1.2 billion Hydrogen Fuel Initiative, with the goal of reducing both petroleum dependence and greenhouse gas emissions. The principal emphasis has been on personal transportation, the sector with the greatest potential on both counts. U.S. transportation is responsible for about one third of carbon dioxide emissions and two thirds of petroleum use, and light-duty vehicles account for most of that.

Priority has been given to fuel cells using polymer electrolyte membranes. These solid electrolytes can operate at reasonably low temperatures, avoiding long startup times, and provide the power density needed for automobiles. Other uses include forklifts and back-up power for telecommunications.

But the search for a low-platinum, high-performance catalyst has been a long one. "It's not something that happens overnight," said JoAnn Milliken, manager of the Hydrogen Program. To be sure, similar cost and reliability hurdles exist for the competing option of rechargeable batteries.

Fuel cell costs have already come down from $275 per kilowatt in 2002 to around $75 per kilowatt, with a 2015 target of $30 per kilowatt, which would be competitive with conventional gasoline engines. System durability has reached almost 2,000 hours, on the way to a target life of 5,000 hours, equivalent to 150,000 miles. Higher durability has already been demonstrated in single laboratory cells.

If technical targets are reached by 2015, it is expected to be another five years before affordable hydrogen cars enter the market, although automobile manufacturers say they can introduce the cars sooner—if, that is, hydrogen is available for fueling. "I think it's the logistics of providing the fuel—building the infrastructure—that will determine whether hydrogen fuel cells will make it." Milliken said. But scientists are confident that fuel-cell technology will pass the test.



BRINGING SOLAR ENERGY'S CUTTING EDGE TO LIGHT

Growing public demand for solar electric energy ensures that it will become a significant part of our clean energy needs in the near future.

Generating electricity from the sun's power has always been clean energy's Holy Grail, and researchers at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, produced in August 2008 an experimental new photovoltaic (PV) cell that set a record 40.8 percent conversion rate from light to power. The current commercial norm for silicon solar PV arrays is around 12 to 15 percent conversion.

The inverted metamorphic triple-junction solar cell is cutting-edge and offers a glimpse of what might be on the horizon. The design that produced the 40.8 percent cell has room for improvement, and could approach 45 percent with further development.

The new cell uses a germanium wafer as the bottom junction and compositions of gallium indium phosphide and gallium indium arsenide to split the solar spectrum into three equal parts that are absorbed by each of the cell's three junctions for higher potential efficiencies. The cell is grown on a gallium arsenide wafer, then flipped over and the wafer removed. By removing the wafer, the cell is a natural candidate for space or terrestrial arrays using inexpensive lenses or mirrors to concentrate sunlight onto the surface, with the whole array

NREL scientists are researching nanotechnology, where the theoretical potential for light-to-power conversion efficiencies is huge.

Bringing Solar Energy's Cutting Edge to Light

THE ROOF of the U.S. Department of Energy building in Washington, D.C.

RESEARCHER examining NREL's organic polymer solar cell.

SOLAR PANELS on the roof of your home can decrease your energy bill.

ROLAND HULSTROM, NREL Solar Program Manager.

rotating to follow the sun. The inexpensive light-gathering optics reduces the cell cost to a fraction of the system cost, giving "concentrating photovoltaics" the potential for very inexpensive electricity.

Meanwhile, NREL scientists are researching nanotechnology where the theoretical potential for light-to-power conversion efficiency is huge. They are also collaborating with industry on the potential to produce at commercial scale thin-film copper indium gallium diselenide PV devices that could be rolled out in vast quantities. Such material could be used to clad a building cheaply and not only provide its own electricity, but export surplus to the power grid.

"Efficiencies are lower, but you would also have somewhat lower costs to offset the lower efficiencies," said NREL Solar Program Manager Roland Hulstrom.

Already production of PV power has roughly doubled every year this century. Recent estimates put PV peak electricity output around 12.4 gigawatts a year. Most installations have been in Germany, Japan, the United States and Spain, which collectively account for about 90 percent of the global total. In some projections, PV could produce enough electricity to meet the needs of 14 percent of the world's population by 2030.

Interest in the technology has been boosted in recent years as the threat of climate change becomes more evident. However, the technology is not without its challenges. PV cells produce direct current—fine for satellite usage where power-to-weight ratios are critical. But for most terrestrial uses, it must be converted to alternating current, which involves a slight but important loss of power.

Another challenge is that solar, by definition, works best in intense sunlight, which is limited in some countries and climates. Its power, like most renewable energy, must be used immediately or stored. Generally, this is not an issue in the United States where, on a hot summer day when generation from solar PV is peaking, demand for electricity for air conditioning is also peaking. Storage is another issue, and one on which NREL is working.

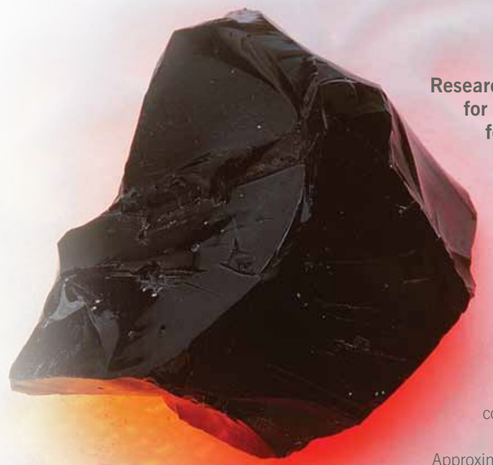
Consequently, Hulstrom sees a future where solar PV and a sister technology, concentrated solar-thermal electric, could produce significant amounts of the electricity in the United States. In addition, low-carbon solar PV could play a major role in electrolyzing water into its constituent atoms hydrogen and oxygen, freeing hydrogen for fuel cells and hydrogen engines.

There's a tremendous opportunity beyond the challenges.

"The challenge is to continue to lower costs, ensure reliability and integrate solar electric power plants with the grid in an optimal fashion," Hulstrom said. "When, not if, we are able to do this, then the potential is very attractive. In short, there is a tremendous opportunity beyond the challenges."

FROM SLUDGE TO GLASS:

MAKING NUCLEAR WASTE SAFER FOR THE FUTURE



Research and development work continues to improve a proven method for storing high-level radioactive waste, and explore other applications for the future.

During the Cold War, the United States produced materials for nuclear weapons by extracting uranium and plutonium from materials assemblies irradiated in government-owned nuclear production reactors. The extraction process left behind a highly radioactive liquid waste, commonly known as sludge. Savannah River Site (SRS), in Aiken, South Carolina, is home to the Defense Waste Processing Facility (DWPF), the world's largest operation dedicated to disposing of radioactive waste in the safest known manner. "The DOE Office of Environmental Management is charged with remediating the legacy waste left from the defense nuclear mission," said John Marra, associate laboratory director at the Savannah River National Laboratory (SRNL), the environmental office's corporate lab that developed the processing facility's waste remediation methods.

Approximately 37 million gallons of radioactive waste are stored in the SRS tank farms. Of that, all the sludge and the high-activity portion of the "salt" waste are sent to DWPF to be converted into a stable glass product by processing it with frit, a tailored glass crushed to the consistency of sand. Through this process, called vitrification, the facility has already poured more than 10 million pounds of glass containing more than 16 million curies since operations began in 1996.

"The waste is blended with the frit and the mixture is processed through a high temperature melter—nominally 1,150 degrees Celsius—to produce a homogeneous borosilicate [silica and boric oxide] glass," said David Peeler, a research scientist in the lab's glass formulation group. "It becomes molten and is then poured into stainless steel canisters."

As the newly created mixture hardens in the two feet by ten feet canisters, it becomes a glossy black glass that has chemically bonded with the radioactive species. This finished glass product is the result of complex calculations, testing and retesting. The frit composition is at the heart of a successful effort.

The waste glass must meet a multitude of criteria. Constraints include viscosity (how thick or thin the glass is) and the "liquidus" temperature (the temperature above which the glass is completely melted). If the glass' viscosity is too low, it can corrode parts in the melter; too high and it could slow down the melt rate and in turn slow down the mission. Viscosity also can affect the glass' ability to pour into the canister.

Of course, not all sludge is the same. So the glass formulation team must adjust the frit composition for each batch of waste. Carol Jantzen, an internationally known ceramics expert at the laboratory, developed models that predict glass properties such as durability, liquidus temperature and viscosity based on glass composition.

Personnel at the tank farms work with the lab to determine which tanks of sludge are due for processing next. Using Jantzen's models, the glass formulation group identifies frit candidates to combine with the next batches of sludge. "We as a lab utilize those models and, working a year or two ahead of the processing facility, evaluate different tank blending strategies for the next sludge batch," said Peeler.

Vitrification keeps nuclear waste in a safe, stable form over long periods of time.

After the tank farm and lab scientists agree on a blending strategy, SRNL's glass formulation team enters an experimental phase. To validate model predictions, the laboratory produces and characterizes nonradioactive glasses using simulated sludge, and radioactive glasses to ensure measured properties are in line with the model predictions. The team also runs melt-rate tests to see which candidate frit will convert the waste into glass fastest. Based on model predictions, glass characterization and melt-rate testing, the laboratory recommends a frit suitable for processing a specific sludge batch. A separate SRNL team receives samples of radioactive sludge from the tank farms and runs that sample through the entire process to prove its viability before the sludge is moved to the waste processing facility.

The remediation mission is scheduled to run into the late 2020s. With every batch of sludge, the teams at Savannah River fine-tune the process with an eye on minimizing mission life, and in turn, minimizing costs. One popular term among the scientists and management is "waste loading," getting as much waste into each canister as possible. "If you have 4,000 pounds of glass in a canister and you're at 25 percent waste loading, you have approximately 1,000 pounds of waste and 3,000 pounds of frit in each canister," said Peeler. "Targeting a higher waste loading will yield fewer canisters for a given sludge batch."

DOE eventually will store the canisters in a national repository, where canister storage space will be limited. SRNL's model development and the laboratory's refinements to the glass formulation, along with other collaborations between SRNL and DWPF, have enabled the facility to process specific sludge batches with as much as 38 percent waste loading, up from 25 to 28 percent when the mission started.

The technology has direct application to commercial reprocessing.

Developments at SRNL have applications that extend beyond this remediation effort. "If you look at a country like France that uses nuclear power, as well as Japan and the United Kingdom, they reprocess spent nuclear fuel," Marra said. "The technology has direct application to commercial reprocessing. Also, the vitrification process has been used for low-level nuclear waste and other difficult-to-deal-with waste."

VITRIFICATION Pouring glass to immobilize radioactive waste.

NEW TECHNOLOGY
FORESEES POWER BLACKOUTS
BEFORE THEY OCCUR

"Phasors" have nothing to do with *Star Trek;* they're the way of the future for monitoring the nation's power grid.

On August 14, 2003, a cascading power failure left 50 million people in the northeastern United States and eastern Canada in the dark. It was the largest blackout in American history and prompted calls for better ways to monitor the nation's electrical power system.

Now new measurements, called phasors, provide simultaneous measurements of voltage, current and frequency across a wide area of the grid. Phasors provide operators with a faster means to take the pulse of the nation's electrical power grid. Phasors describe the differences in timing between the crests of the waveforms that characterize electrical power as it travels through the lines.

"If we had phasors in place then, we would have been able to see very clearly at least 30 minutes before that event that we were in trouble," said Stan Johnson, a manager at the North American Electric Reliability Corp. (NERC), which is responsible for situation awareness and security of electrical infrastructure. NERC sets standards for how electrical grids are managed and ensures that grid operators comply.

If we had phasors in place then, we would have been able to see very clearly that we were in trouble.

Thirty minutes would have been enough time to take corrective action. "We probably would have wound up shutting the lights off in the Cleveland, Ohio, area, but at least [the blackout] would not have steamrolled all the way across the Northeast," Johnson said.

Power once came from relatively local sources. Now that new markets have opened, electricity from inexpensive or renewable sources that can be located in remote areas can be transmitted over long distances to densely populated regions with high power demands. As a result, Johnson contends, bulk power systems are operating much closer to their limits.

New Technology Foresees Power Blackouts Before they Occur

RELIABLE ELECTRICAL SUPPLIES ensure our way of life.

THE VIEW from the inside of an electrical pylon.

ONE OF EIGHT hydroelectric dams on the Columbia-Snake Waterway.

MEASURING POWER TRANSMISSION at transforming stations helps keep America's electric grid efficient.

NERC is working with the U.S. Department of Energy (DOE) to implement the use of phasor measurements throughout the hundreds of thousands of lines that supply most of the country with power. "Ideally those measures hold steady," said electrical engineer Jeff Dagle of Pacific Northwest National Laboratory, who supports DOE's transmission reliability program. Rapid changes in the phasor measurements signal instabilities in the system.

Synchronized measurement devices placed directly on the lines can provide an instantaneous picture of the state of the grid.

"What you'd do is cut schedules," Dagle said. Because considerable power is sent around the grid for economic convenience, the cheapest resource, which might be further away than an expensive resource, is most likely to be tapped. "If you know that the grid can handle it, then there's no problem," he said. "But when you either know or suspect that the grid is going to have problems, you can fire up generation that's closer to the load and alleviate some of that stress."

Three separate systems transfer power in the United States. The Eastern Interconnection serves most of the Midwest, the eastern seaboard and parts of Canada. Texas has its own system, and the Western Interconnection serves the states from the Rocky Mountains west and parts of Canada and Mexico.

The western grid was the first to implement phasor measurements as a way to manage loads on the long transmission lines required by sparse populations and remote power sources. "It's like weights and springs," Dagle said. "Each generating plant might be a weight, and each transmission line is like a spring. In a steady state, everything would be nice and stable, but if there's a change, it'll bounce or oscillate."

A large part of the western grid failed on August 10, 1996, as a result of this phenomenon. Hot weather in California, combined with abundant water for hydropower in the northwest, meant that "they were pushing a lot of power through a constrained transmission infrastructure," Dagle said.

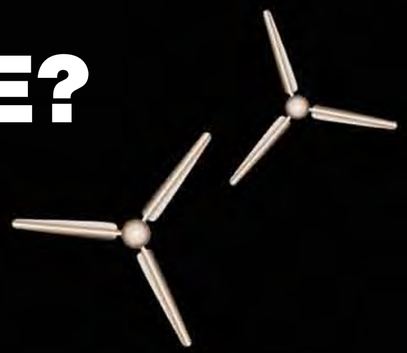
The overloaded lines began to slowly ring with a wave pattern that repeated once every three seconds superimposed on the normal 60 Hz (60 cycles per second) alternating current frequency. That destabilized the system. "It actually broke apart," Dagle said.

"With the phasor measurements, you could detect oscillations with enough precision to send a control signal to dampen them," said power engineer David Hawkins, who leads the renewable power program for not-for-profit California Independent System Operator (ISO). California ISO operates most of the wholesale power grid that links power plants with utility companies for most of California.

The technology for sending such a corrective signal is not yet in place. With enough advance warning, however, more traditional controls could head off serious problems.

Phasors have long been used to assess the health of the grid, but they were values calculated from other measurements. With synchronized measurement devices placed directly on the lines, those values can now be reported many times per second, providing an instantaneous picture of the state of the grid. Previously, operators relied on numbers that were updated once every four seconds. "Imagine driving down the highway at 65 miles per hour with your eyes closed, and every four seconds you'd open your eyes to take a peek," Hawkins said. "Very quickly you'd be in for some unpleasant surprise."

Efforts are now focused on improving computer programs that assemble the data and create graphic displays that provide grid operators with information they can easily use.



WHAT TAKES THE WIND OUT OF
A WIND TURBINE?

Building a wind turbine that is both durable and more energy efficient requires thinking outside the props.

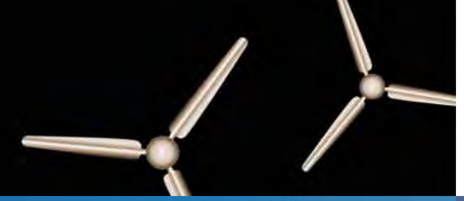
As the world races to find alternative energy sources away from depleting fossil fuels, attention focuses increasingly on the earth's limitless supply of wind. The National Renewable Energy Laboratory (NREL) in Golden, Colorado, is driving international collaborative efforts to find innovations in gigantic wind turbines to better harness this invisible and powerful force.

NREL discovered that the fatigue failings of the gear box...were caused by problems with the bearings.

Using wind power to generate electricity was developed first in the 1880s in Scotland and the United States. By the 1920s, the largest wind-driven electric generators were 79 feet high, had four 75-foot diameter rotor blades and generated 5 to 25 kilowatts. The blades, originally of sailcloth or wood, came to be made of cheap high-tensile steel placed atop open lattice towers. Today the typical utility-class–size tubular steel tower ranges between 180 to 350 feet tall and has three fiberglass blades 65 to 130 feet in length. The blades rotate at 10 to 22 revolutions per minute and normally can generate 1.5 to 3 megawatts of power. They can operate in winds up to 60 mph.

"The taller the tower the better it can access strong winds," explained Jim Johnson, a 20-year NREL Senior Engineer. "But there are tradeoffs. The bigger and taller wind turbines become, the more logistical challenges, engineering problems and costs they incur."

Problems of wind energy generation range from finding the right site in remote locations with constant high winds, a process called "micrositing," to transport problems for the huge blade, to finding new composite materials for blades and towers and improving control systems to regulate turbine power.



JIM JOHNSON, a 20-year NREL Senior Engineer.

NREL and the U.S. Department of Energy's (DOE) Wind Energy Program are making huge strides in resolving these and other issues. One groundbreaking example is the Liberty Turbine, developed by Clipper Windpower in an R&D partnership with NREL and DOE. Those combined efforts have yielded one of the most advanced, and most efficient, wind turbines ever produced.

The 2.5 Megawatt Clipper Liberty wind turbine features a new lightweight, enlarged rotor that increases power production, a revolutionary generator design that improves reliability and reduced gearbox weight and size. Because the generator is lighter, it will also cost less to produce and be easier to maintain than similar machines. Researchers believe this advanced design will become a benchmark for future turbine design in the United States and Europe.

Because the generator is lighter, it will also cost less to produce and be easier to maintain.

Not only are researchers pushing forward with revolutionary new turbine designs, they are grappling with some of the most vexing problems encountered by turbines with years of service in existing wind farms. Equipment fatigue, especially in turbine gearboxes, threatens to drive up wind power costs, just as the industry is poised to capture a greater share of U.S. generating capacity.

"The faster and harder the turbines run, the faster the ascendancy of fatigue damage," said Johnson. "It became a particular problem of the wind turbine's giant gearboxes. Instead of lasting the expected 20 years, these increasingly sophisticated and heavy boxes are found to be stressing out and stiffening after five to seven years."

TUBULAR STEEL TOWERS range between 180 to 350 feet tall and have three fiberglass blades 65 to 130 feet in length.

LIBERTY TURBINE, developed by Clipper Windpower in partnership with NREL, produces 1.5 to 3 megawatts.

The DOE Wind Energy Program focused its efforts on this breakdown in gearbox reliability. It decided to help identify improved gearbox design opportunities.

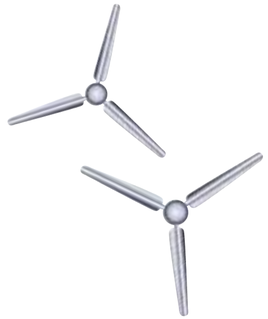
NREL sponsored a drivetrain "Wind Turbine Reliability" workshop to jointly identify research needs. Some 90 participants from wind farms, service companies, consultants, manufacturers, universities and laboratories shared information on hardware reliability, and offered perspectives on reducing operating and maintenance costs.

A WindPACT drivetrain project was developed to examine the design of gearboxes, the way components interacted and moved and the way the control systems were designed to regulate turbine power and maintain stable, closed-loop behavior (especially in the presence of turbulent winds). It tested simple gearbox designs.

In 2007 NREL initiated a long-term Gearbox Reliability Collaborative (GRC) to improve gearbox performance and durability. The collaborative validated the design process, tested extensively instrumented gearboxes to identify weakness in current design approaches and pointed out ways to improve initial designs and retrofit packages.

"We helped the collaborative write a standard to improve the level of manipulation, concentrating on the design and standards of gearboxes," said Johnson. Then came the surprise.

"NREL discovered that the fatigue failings of the gearbox were not due to its design, but were caused by problems with the bearings," said Johnson with some satisfaction. "Awareness of this has been a kind of breakthrough in the problem of wind turbine component fatigue. Now we can focus on the real cause."

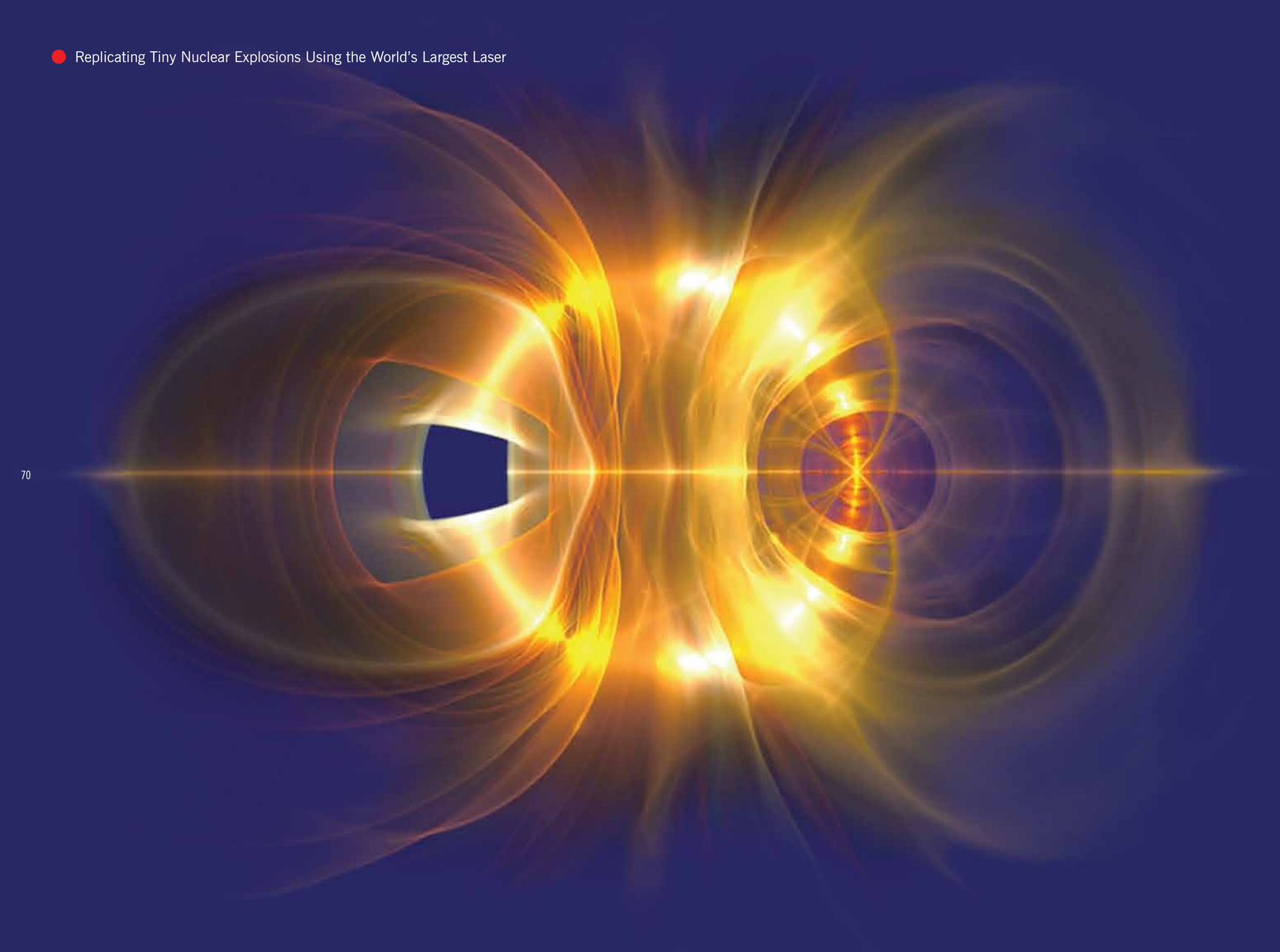


NATIONAL
SECURITY

NUCLEAR PROLIFERATION · U.S. DEPARTMENT OF ENERGY · MINIATURIZED RADAR · U.S. DEPARTMENT OF ENERGY · PANDEMIC PREVENTION · U.S. DEPARTMENT OF ENERGY · AIRPORT SECURITY · U.S. DEPARTMENT OF ENERGY · LASER FUSION · U.S. DEPARTMENT OF ENERGY · NUCLEAR ARSENAL TESTING · U.S. DEPARTMENT OF ENERGY · PROTECTIVE MILITARY TECHNOLOGY

INTRODUCTION

The realm of national security comprises a number of priorities, including thwarting terrorism here and abroad, bolstering the infrastructure of our country's power grid and ensuring the safety and reliability of our country's nuclear deterrent. Some of the research projects supporting our nation's security concerns may sound like the stuff of science fiction, but they are not. For example, leading-edge millimeter-wave scanners may not only make negotiating airport security a breeze, but could also provide a more thorough per-person search by making three-dimensional images so detailed as to reveal any concealed objects. Elsewhere, scientists have built an X-ray generator, called the Z Machine, that works to study the details of nuclear explosions and their effects without conducting underground nuclear tests. Such advances not only make us a more informed country; they also make our country more secure.



REPLICATING TINY NUCLEAR EXPLOSIONS USING THE WORLD'S LARGEST LASER

The goal of the National Ignition Facility is to create a miniature star on earth to ensure the safety of the nation's nuclear stockpile.

More than 15 years have passed since the United States last tested a nuclear device. By joining with other nations in abstaining from testing, the United States has helped slow the global arms race. But the decision has other consequences. Without testing, we need alternative ways of monitoring the nation's nuclear arsenal.

To plug the knowledge gap, nuclear scientists run computer simulations of weapon systems and explosions. That helps them understand whether the warheads are safe and working as designed. These simulations employ some of the world's most powerful computers, but like any computer model they need to be compared with real data. Which is where the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in Livermore, California, comes in.

The NIF was built to simulate much of the physics of nuclear weapons. It enables scientists to trigger and study fusion reactions—essentially tiny thermonuclear explosions. "We can study the physics of weapon performance, including how nuclear fuel is actually burned," says Livermore physicist Ed Moses. "We can look at how nuclear materials behave at extremely high pressures and temperatures."

It will be the cornerstone of the government's Stockpile Stewardship Program.

By tracking the course of these reactions, scientists can ensure that their models are accurate. "The only way to tell if the models are right is to create the conditions they simulate," Moses added. "That is what the NIF can do and it is a unique facility to do it. The goal is to ensure the safety and efficacy of our strategic stockpile without nuclear testing." It will be the cornerstone of the government's Stockpile Stewardship Program.

The work will begin in the fall of 2010. During the experiments, a thimble-sized gold target in a warehouse-sized building at Livermore will be illuminated with an array of 192 lasers. When fired up,

THE TARGET CHAMBER at the National Ignition Facility in Livermore, California, where the world's largest laser is being completed. The laser, built for fusion research, has already shown the ability to fire 4 megajoules of infrared energy for up to 20 nanoseconds.

NIF LASER BAY consists of two bays, each housing 96 beams that send laser light toward a millimeter-sized target to create conditions similar to those in a star's core and inside exploding nuclear weapons.

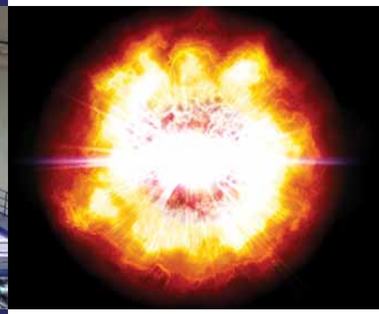
they will become the most powerful light show ever assembled in a laboratory. Briefly, they will ignite a fusion reaction similar to that which powers the sun.

In a fusion reaction, energy is released when two light nuclei are squeezed together to form a heavier one. At the sun's heart, the fuel is hydrogen and helium nuclei. To recreate a similar process on earth, physicists know that two isotopes of hydrogen—deuterium and tritium—are the best candidates. The challenge is to produce and control the terrifying temperatures and pressures needed to force the isotopes together.

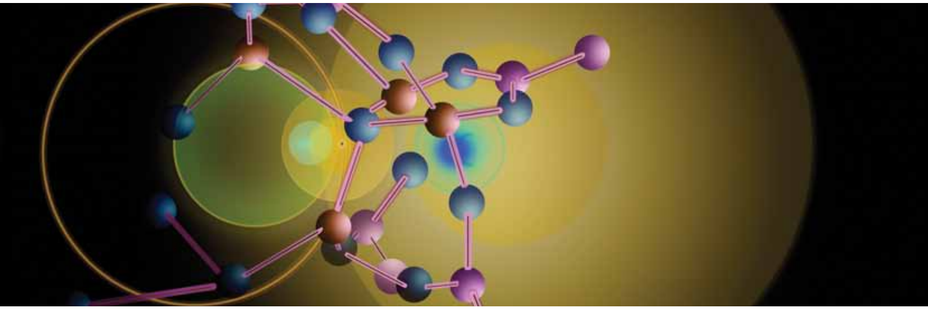
That's what the NIF is designed to do. At its heart is a cylindrical gold target. When the lasers strike the target—96 from below, the others from above—the gold casing soaks up the light and emits high-energy X-rays, bathing the inside of the cylinder in intense radiation.

The fuel itself will be stored inside a small ball of beryllium held within the cylinder. When the X-rays hit the ball, the outer surface will blow off at high speeds, driving the target inward at about a million miles per hour. The resulting shock wave will then compress the hydrogen isotopes at pressures of up to 100 billion atmospheres. That's enough to fuse the deuterium and tritium into helium nuclei. Very briefly, a tiny star will burn inside Livermore.

Weapons researchers will learn about the behavior of fusion detonations, and energy researchers will probe the reactions in a bid to build a future generation of power stations. Fusion reactions release



THE FUSION REACTIONS that will take place at Livermore essentially will be tiny nuclear explosions.



BERYLLIUM is a nonradioactive metal that is extremely light and very stable. It is lighter than aluminum, yet one and a half times stiffer than steel. Beryllium is used in satellite guidance systems, spacecraft, optical instruments, nuclear reactors and golf clubs.

no greenhouse gases and the hydrogen isotopes needed to power the process can be extracted from seawater. If the process can be safely controlled, it could form the basis of a limitless supply of carbon-free energy for fueling our future without pollution or global warming.

While this will not be the first time that fusion will have been triggered by scientists, the Livermore reaction will be unique in one important respect. In other fusion experiments, researchers have watched the reaction flare and then die out. The ignition facility will deliver a far bigger spark than previous experiments, enough for the nuclear fire to burn by itself. The fusion reaction will last less than a billionth of a second, but for that short time it will be self-sustaining. Previously, this has only been achieved in nuclear weapons explosions.

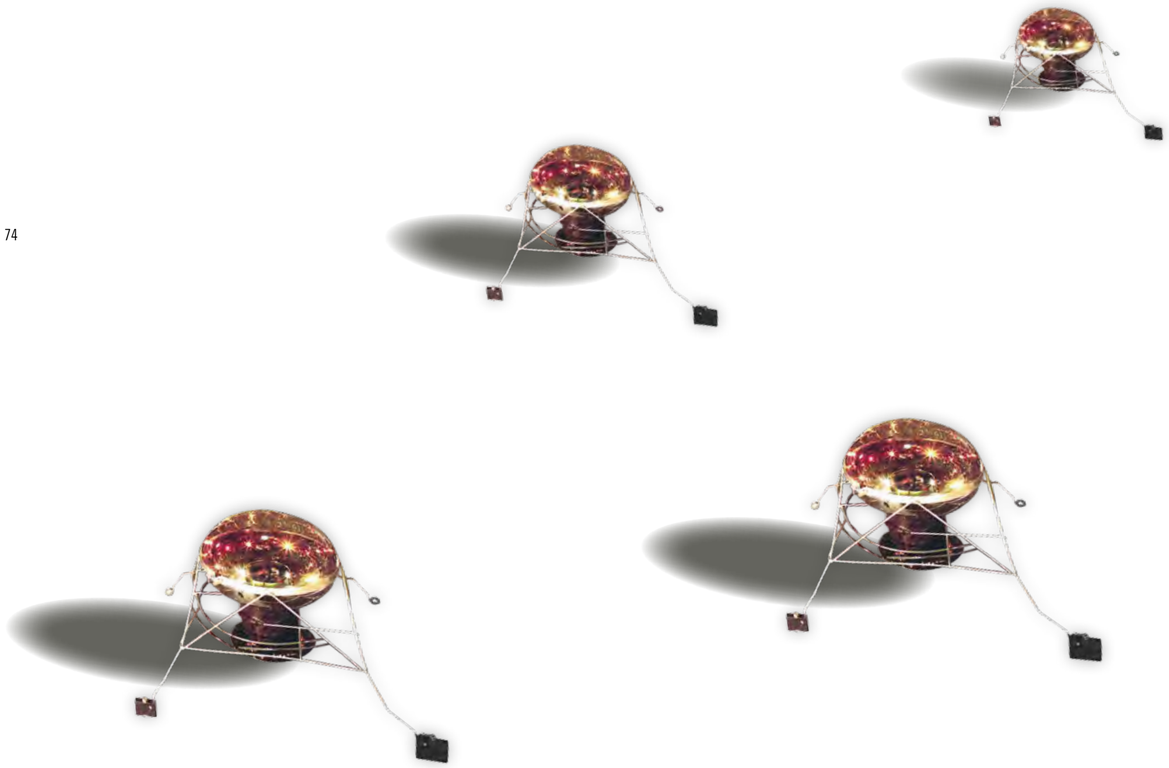
Laser fusion at NIF, and the basic science behind it, is one of the most interesting results that could come from this facility.

The Livermore device is not designed to maintain the kind of high repetition rate needed to produce electricity. Other efforts have developed technologies for this purpose. Livermore researchers plan to vary the laser and target conditions to work out which configuration produces the most energetic reaction.

"One of the holy grails of 21st-century science is harnessing fusion as an energy source," said Barry Walker, a laser researcher at the University of Delaware, Newark. "Laser fusion at NIF, and the basic science behind it, is one of the most interesting results that could come from this facility."

ANTINEUTRINOS REVEAL

THE INNER WORKINGS OF NUCLEAR REACTORS



Antineutrino detectors can potentially achieve the important goal of tracking fissile materials, such as plutonium, to ensure they are not being diverted into weapons.

Ghostly particles streaming from nuclear reactors can reveal from a distance events within the core. Prototype detectors buried near a commercial nuclear power plant are helping physicists develop new ways to independently peer inside and monitor the activity of nuclear reactors. The idea has captured the interest of the International Atomic Energy Agency (IAEA), which works to prevent diversion of fuel that could be used to make weapons.

The nuclear fission that provides power also generates abundant subatomic particles called antineutrinos, which rarely interact with other forms of matter. Antineutrinos fly right through radiation shields in numbers directly proportional to the operating power of the plant, which makes them potentially valuable indicators of the nuclear reactions inside.

We can really tell what's going on inside the reactor core.

"This is something fundamentally new. We can really tell what's going on inside the reactor core," said physicist David Reyna, who leads a project to design better detectors at Sandia National Laboratories in Livermore, California. "That information has been so unavailable that people who monitor activities at nuclear reactors have just started to think about what they would do if they had it."

Reactors consume uranium and create plutonium. Only a few kilograms of plutonium are enough to make a nuclear weapon, so the IAEA closely tracks the material. Both uranium and plutonium produce antineutrinos, but their appearance in the detectors differs slightly.

"If you measure the energy precisely enough, you should be able to extract…the proportion of uranium and plutonium in the core at that moment," Reyna said.

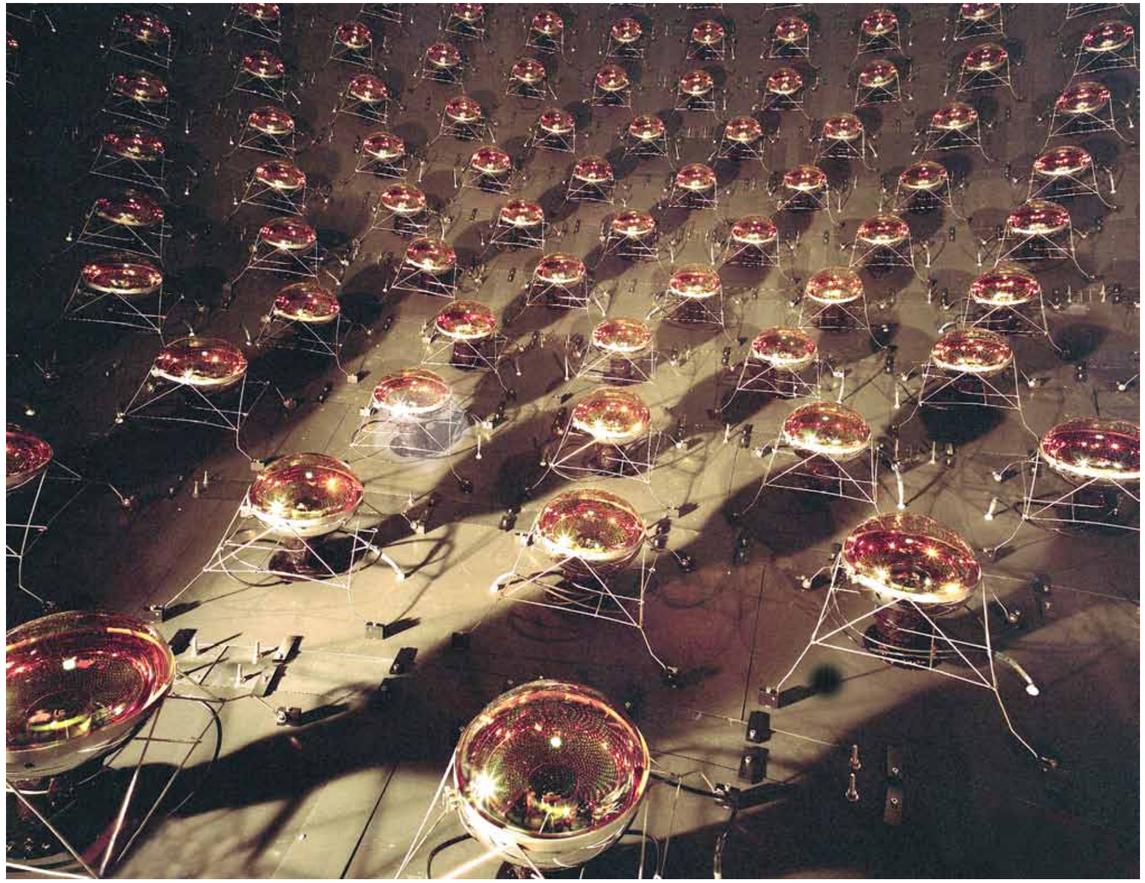
Their elusive nature makes antineutrinos notoriously difficult to catch, though the sheer numbers generated by reactors increase the chance of success.

"The antineutrino, itself, is basically impossible to see," Reyna said. "It's just passing through." But antineutrinos will interact with particles called protons to set off a brief chain of events that is easier to see. "You get particles coming out of that interaction that you can identify," Reyna added.

Each collision creates two quick flashes of bluish light in certain types of materials. The split-second timing of the flicker distinguishes an antineutrino's trail from traces left by other forms of radiation.

"We can easily distinguish between gamma rays and antineutrinos because antineutrinos have such a unique signature," said Adam Bernstein, a physicist at Lawrence Livermore National Laboratory, who leads the project to develop detectors that would be useful for safeguarding reactors. "It's extremely difficult to mimic, so it's very difficult to spoof the detector."

OUTSIDE the antineutrino/neutrino detector.



INDIVIDUAL DETECTION ELEMENTS for the antineutrino/neutrino detector

Since 2004, teams from both laboratories have tested four experimental detectors at the San Onofre Nuclear Generating Station near San Clemente, California.

The first was a set of tanks filled with proton-rich fluid. Because natural radiation from rocks and space can swamp the signal from the antineutrinos, the engineers blanketed the detection tanks with water, which will slow other signals but let antineutrinos through. Although the combination of liquid tanks and water shield made this detector too large and heavy to easily deploy, it accurately reported operations at the station, demonstrating the usefulness of this approach.

In October 2008, the IAEA invited scientists from several nations who are developing ways to detect antineutrinos to Vienna to exchange ideas with people in the agency who are looking for new ways to monitor reactors.

"One very nice thing about this detection is that it's very difficult to interfere with an antineutrino. Nothing really stops them," said Julian Whichello, head of new technologies for IAEA. "It has an inherent sort of protection in the source of information."

Antineutrinos also offer an autonomy from reactor operations that is absent from other forms of monitoring, such as measuring the flow of coolant. "It requires no connection of cabling to other parts of the reactor," said Andrew Monteith, a physicist at IAEA. "It's all self-contained. We'd like something that we could just plunk on the ground outside the reactor."

The agency doesn't quite see the need for antineutrino detectors for monitoring stations similar to San Onofre, which shut down periodically to load fresh fuel and remove spent rods. That pause gives inspectors the opportunity to directly count the fuel rods and measure the amount of plutonium.

But newer reactors, yet to be built, will operate continuously by cycling "pebbles" of fuel through the core. Antineutrino detection might be well suited for monitoring these new reactors, but they will first need to be made smaller.

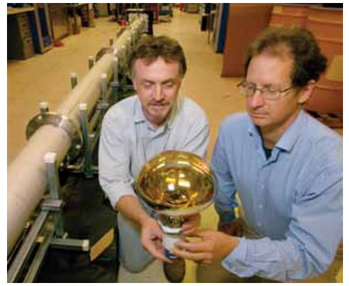
Teams from both Livermore and Sandia are collaborating with university scientists to develop smaller detectors. They recently placed one that uses crystals of germanium in a tunnel outside the containment dome at San Onofre.

It's extremely difficult to spoof the detector.

"We are already collecting data down there with this germanium detector," said Juan Collar, a physicist at the University of Chicago who helped to develop the new device.

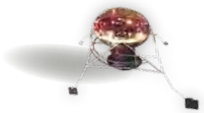
Instead of waiting for antineutrinos to interact with protons, a rare event, this latest prototype looks for evidence of atoms that have been nudged by antineutrinos, a much more common occurrence. That means the detector can be much smaller. "These germanium crystals would fit inside your fist," Collar said.

Antineutrino detection projects such as these will not only continue to contribute to basic science but to applications relevant to national security as well. They may well be elusive, ghostly particles, but antineutrinos have a substantive future in many aspects of nuclear research.



LIVERMORE PHYSICISTS Adam Bernstein (right) and Steve Dazeley

NUCLEAR REACTOR near San Onofre, California



FINE SCULPTING THE DETAILS ON

CLASSIC SYNTHETIC APERTURE RADARS

By combining small SAR systems with a unmanned aerial vehicle platform, Sandia is providing radar imaging capabilities for a variety of applications.

The outcome of World War II's Battle of Britain might have turned in favor of the Nazis and changed the course of history if Robert Watson-Watt of the British Radio Research Station had not demonstrated in the mid-1930s the capabilities of radar for aircraft detection. Significant developments in radar have been occurring since, many of which have implications for national security.

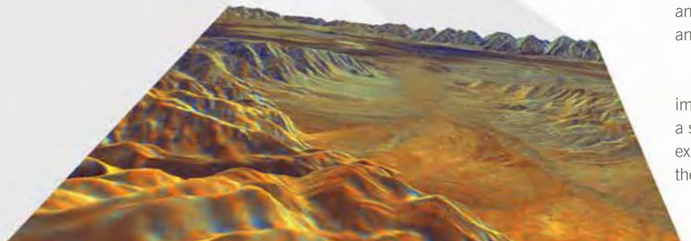
During the postwar 1950s, a significant development in the form of Synthetic Aperture Radar (SAR) occurred at the Goodyear Aircraft Co. that quickly became an alternate imaging modality to airborne photography. SAR was further developed at Sandia National Laboratories (Sandia) in Albuquerque, New Mexico, where scientists have honed in explicitly on real-time performance, physical size and image exploitation needs to drive SAR modifications.

"SAR is an all-weather (clouds, dust, rain), day or night technique that can also provide key information unavailable through traditional optical means," said Bill Hensley, manager, SAR Applications at Sandia. "Besides imagery, SAR can provide 3-D maps, reveal minute changes in terrain and be used for navigational guidance. Many national security organizations could use SAR to 'own the night' and reveal details unavailable through any other technique."

Sandia has a long history of developing components and technologies applicable to SAR. Over the last decade, Sandia's scientists have applied technologies to imaging radars to meet the needs of advanced weapon systems, verification and nonproliferation programs and environmental applications.

MiniSAR-derived systems and technologies have been engaged in a wide variety of missions, ranging from crevasse detection in Antarctica to incorporation in NASA's Lunar Reconnaissance Orbiter mission.

"SAR requires world-class expertise in nearly every engineering discipline, including system, electrical, electromechanical, mechanical and materials engineering," said Bryan Burns, senior scientist, who has been involved in Sandia's SAR development activities for well over two decades. "It also requires detailed understanding of many scientific concepts, ranging from the physics of atmospheric transmission to electromagnetic interactions to real-time embedded computing. Through a long legacy of capabilities developed under the nuclear weapons program and refined by key projects for national security, Sandia has developed the expertise in these areas to deliver a unique combination of performance, size, and image processing algorithms."



While the U.S. Army sponsored development of STARLOS (SAR Target Recognition and Location System), a real-time SAR with image-formation and automatic target recognition of multiple and simultaneous targets, between 1986 and 1991, Sandia scientists worked to reduce SAR's size from 2,000 to 500 pounds and introduced further imaging capabilities.

In 1999, Sandia worked with General Atomics, Inc. (GA) to design and develop the Lynx SAR, which further reduced SAR size and weight to less than 85 pounds. This made them capable of accommodating small unmanned aerial vehicles (UAVs) for reconnaissance and surveillance in adverse weather conditions. That same year, Sandia and GA delivered the first prototype compact SAR. The sensor offered one to ten foot resolution strip-map capability and spotlight (higher-resolution, single-area imaging) resolutions as high as four inches, with a maximum range of 25 to 85 kilometers.

Many national security organizations could use SAR to "own the night" and reveal details unavailable through other imaging techniques.

Since then, Lynx radar and subsequent designs have been successfully demonstrated on medium-payload UAVs. In fact, the Lynx SAR is now performing day-to-day border search operations onboard a Customs and Border Protection (CBP) Predator B UAV.

As sponsors worked to build more effective operational SAR systems and image-exploitation approaches, DOE's Laboratory of Directed Research and Development (LDRD) began funding SAR improvements, which led to further reducing package weight and adding multiple new imaging and image-exploitation capabilities. In 2000, a three-year LDRD project was accompanied by a supplementary LDRD to fabricate a new compact digital receiver, a miniaturized waveform synthesis prototype and an advanced application-specific integrated circuit. In FY 2004–05, LDRD developed highly modular software architecture and advanced image-formation algorithms for lower-resolution images. The efforts resulted in the MiniSAR, a functional radar weighing less than 30 pounds. Its prototype was successfully demonstrated in May, 2005, on a UAV.

"A number of key technical advances were achieved to yield a high-performance, ultra-fine resolution, all-weather, day-or-night imaging capability that can be integrated onto small, low-cost airborne platforms such as class III UAVs (nominal 50-pound payload) as well as larger aircraft, depending on the application," said Kurt W. Sorensen, manager of Sandia's SAR Sensor Technologies Department. "Since 2005, MiniSAR-derived systems and technologies have been engaged in a wide variety of missions, ranging from crevasse detection in Antarctica to incorporation in NASA's Lunar Reconnaissance Orbiter mission."

MiniSAR filled a void in remote sensing technology by providing unequaled real-time image quality and resolution for tactical warfare systems, while achieving four- to five-fold reductions in size, weight and cost. In particular, it gave even small UAVs the ability to see through smoke, dust, clouds and rain.

LDRD projects have since concentrated on developing better moving-target imaging and improved image resolution. Focus areas include Enhanced Inverse SAR (ISAR), which seeks to coherently process a set of radar-pulse echo data to image a target object whose motion is unknown. These advancements exemplify how, by combining MiniSAR-based systems with a UAV platform, Sandia today can provide the United States with capabilities that up until now would have been unachievable.

PROTECTING
OUR SOLDIERS

Improved steel armor and cutting-edge solar cell technology will soon provide soldiers with better protection and lighter loads when they venture into harm's way.

Keeping soldiers safe is a high-tech operation. Today's modern military force relies on modern technology—such as night-vision goggles, GPS, radio systems and specially equipped armored vehicles. A lot of research goes into bringing technology to today's soldiers. U.S. Department of Energy (DOE) labs have a hand in creating and improving technologies that push the boundaries of safety and performance for soldiers in the field. These often translate into advancements that will improve civilian life.

Improvised explosive devices (IEDs) pose a significant threat to soldiers on the ground, and present a challenge to engineers charged with outfitting military vehicles with armor able to withstand the deadly blasts. However, scientists at the National Energy Technology Laboratory (NETL) have developed a type of steel-cast armor that's especially designed to protect tanks and transport vehicles from IEDs.

The secret to their success is a process developed by NETL called "lost-foam casting." Lost-foam casting was originally developed for use with aluminum, but NETL scientists adapted the process to cast steel, which previously had never been attempted due to its higher density and melting temperatures. As the name implies, it starts with a model of a part, created from polystyrene foam. The foam is then dipped into a solution that coats the foam pattern and leaves a thin, heat-resistant layer. Molten metal is then poured into the mold, vaporizing the foam. When the metal cools and solidifies, all that remains is the metal part.

Scientists at NETL have developed a type of armor designed to protect tanks and transport vehicles on the ground from the impact of IEDs.

The advantage of this technique over traditional rolled and forged steel is that it allows for the creation of parts in a variety of complex sizes and shapes. This not only makes it possible to specially design armored plates for different types of vehicles, but to generate patterned steel parts that are better at deflecting IED blasts. Today's high-tech armor uses a pattern that incorporates hundreds of rows of angled slots called P-900. This armor was designed by the Army Research Laboratory, which asked NETL to develop a casting process to produce this new armor. While it may seem counterintuitive to create armor with holes, Paul Turner, who works on the project at NETL, explained that those slots serve an important function. "Essentially it fractures the projectiles into smaller pieces so they don't have the energy to penetrate the armor," Turner said.

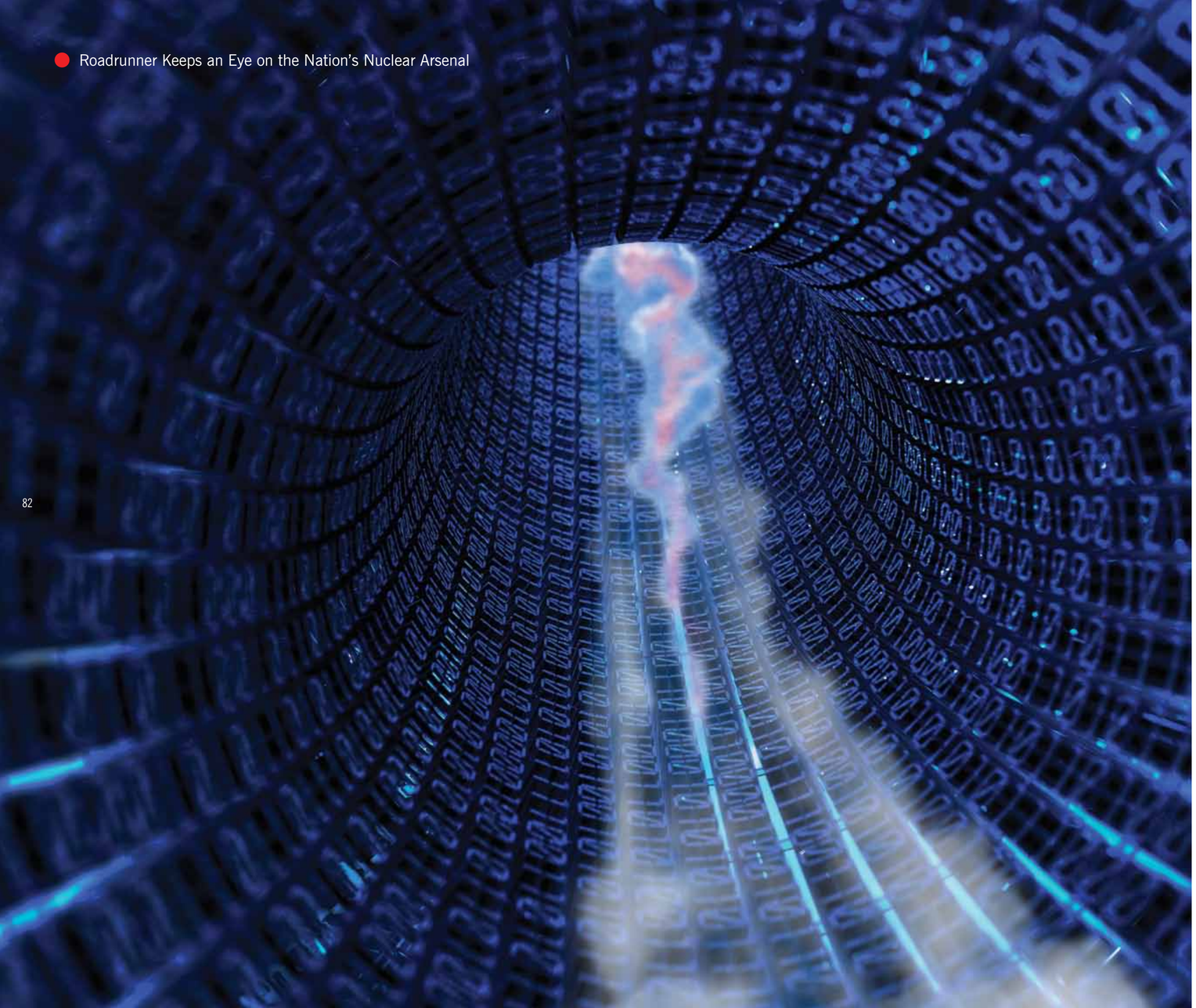
The process has been in development since the late 1980s. At least 25,000 units of armor have been tested in the field. Castings produced with the lost-foam process are up to 10 percent lighter and perform better in ballistics tests. Now the same concept is being adapted to lighter weight materials. "You can use a lot of the lessons learned from this to develop other materials," Turner said. "For example, titanium armor is being developed for aircraft applications."

But weight is an issue on the ground as much as in the air, and the National Renewable Energy Laboratory (NREL) in Golden, Colorado, is concerned about the weight that soldiers carry, not tanks. Many soldiers already carry 100 pounds or more on their backs. Electronic gadgetry can take that number even higher. Consequently, NREL is working on advanced solar-cell technology, designed to help reduce soldiers' dependence on battery power and lighten an individual's load by as much as 20 pounds. The challenge is that current solar cells are either too large or cannot generate sufficient power to reliably charge electronic devices. But NREL is working toward producing a solar cell that is small enough to integrate into portable electronics, yet efficient enough to meet modern power requirements.

NREL is working on solar cell technology designed to reduce soldiers' dependence on battery power and lighten loads by as much as 20 pounds.

To achieve these goals, researchers plan to use a specially designed lens to concentrate sunlight onto a special layer of photovoltaic materials. Instead of using just one material, they plan to combine different types of materials that convert sunlight into electric current—each optimized to specific portions of the light spectrum.

NREL believes that through new breakthroughs in materials and solar-cell design they can create a technology that will enhance the functionality of portable electronics and help push energy demands towards renewable and environmentally friendly sources. In fact, they hope that through their research, they can turn solar-cell research upside down—literally. One of their designs involves layering photovoltaic materials in reverse—from top to bottom instead of one on top of another as in most current designs. The new process has been aptly named the "inverted metamorphic multijunction" solar cell. This reverse approach, the team believes, holds the promise of advantages in performance, engineering design, operation and cost. The hope is it will lighten the battery load not only for soldiers in the field, but ultimately for the environment and technology users everywhere.



ROADRUNNER
KEEPS AN EYE ON THE NATION'S NUCLEAR ARSENAL

The Roadrunner supercomputer provides a best-in-the-world tool for enhancing our scientific understanding of nuclear weapons and ensuring the reliability and safety of the U.S. nuclear stockpile.

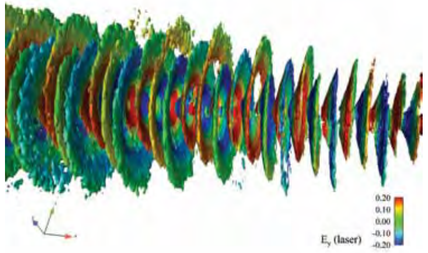
In May 2008, the Roadrunner supercomputer—a partnership between Los Alamos National Laboratory in Los Alamos, New Mexico, the National Nuclear Security Administration and IBM—became the first computer to perform one quadrillion calculations per second. That's a petaflop—1,000 times faster than the fastest supercomputer a decade ago.

Roadrunner provides the first full-scale example of the future of high-performance computing. Its innovative design uses the low-power, high-performance PowerXCell 8i processor to achieve unprecedented performance at a relatively modest energy cost. Roadrunner is more than twice as energy efficient as the Jaguar supercomputer at Oak Ridge National Laboratory in Oak Ridge, Tennessee (see "The Supercomputing Fast Lane," page 112), a more conventional design. Roadrunner was cited as one of 2008's top 10 inventions by *Time* magazine.

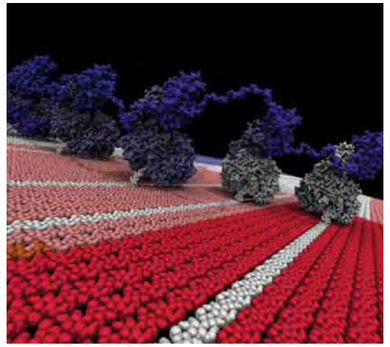
Roadrunner's fleet-footed numeric modeling capabilities will focus on classified research to maintain the nation's nuclear weapons stockpile. The supercomputer's speed will be used to increase our predictive capability and improve confidence in predicting the behavior of nuclear weapons. These efforts will include predicting and understanding the behavior of thermonuclear burning plasmas and laser-plasma interactions in experiments at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, in Livermore, California. Charles McMillan, associate director for weapons physics at Livermore, expects that "Roadrunner will provide a best-in-the-world computational tool for enhancing our understanding of nuclear weapons science and generating a science-based predictive capability for ensuring the reliability and safety of the nuclear stockpile."

Roadrunner is the first of this new generation of supercomputers.

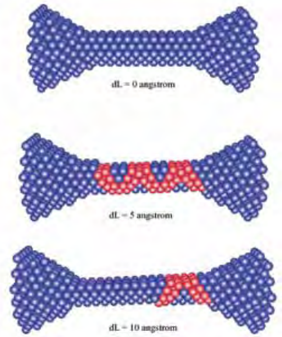
ROADRUNNER



ISOSURFACES of longitudinal electric field Ex (indicating the presence of electron plasma waves) with color indicating laser field (Ey) produced by Roadrunner.



ATOM simulation of cellulosome-cellulose interactions, produced by Roadrunner



EVOLUTION of a silver nanowire under applied stretching produced by Roadrunner

Most nuclear weapons in the U.S. stockpile were produced 30 to 40 years ago, and no new nuclear weapons have been produced since the end of the Cold War. Since underground nuclear testing ended in 1992, the United States has relied on science-based research and development to extend the lifetime of the weapons in the existing stockpile.

Roadrunner's innovative design achieves unprecedented performance at a relatively modest energy cost.

The Roadrunner supercomputer uses commercially available hardware and software, including components applicable to commercial video game platforms. The system's computational power comes from the PowerXCell 8i, an IBM-developed derivative of the Cell processor in Sony's PlayStation 3 (PS3). The PS3 Cell processor was produced as part of a collaboration between Sony, Toshiba and IBM. Early in the process scientists from Livermore and IBM recognized that the Cell design needed additional capabilities for numerically intensive computing. By adding these capabilities, the Roadrunner project leveraged the original $400 million investment.

The secret to Roadrunner's record-breaking performance is a unique hybrid design, the first of its kind. Each of more than 3,000 nodes in the system contains two different processors: two AMD Opteron dual-core processors and four PowerXCell processors. The PowerXCell also is a hybrid, having one standard IBM Power PC microprocessor core and eight vector processor cores, which provide this chip's remarkable performance and efficiency.

The full Roadrunner system occupies about 5,000 square feet and uses about 2.4 megawatts of energy while running at top speed. For future supercomputers, power consumption is potentially a limiting factor. However, Roadrunner and other systems such as the IBM's Blue Gene/P system at Argonne National Laboratory in DuPage County, Illinois, are breaking down this barrier. Roadrunner uses about the same amount of power as Livermore's most recently retired supercomputer while providing 50 times the performance.

Future generations of supercomputers will be programmed differently from those currently in operation. New algorithms and tools will be required to gain access to their incredible performance. Roadrunner is the first of this new generation. In concert with the Roadrunner project, IBM has developed the Software Development Kit for Multicore Acceleration, which provides a new set of tools for programming the system. Livermore scientists demonstrated that Roadrunner could be effectively programmed and used by focusing on several important applications: plasma physics, materials science and particle transport.

MODELING URBAN DISEASE OUTBREAKS

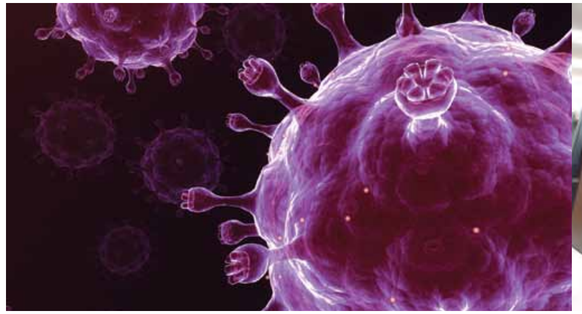
Los Alamos National Laboratory supercomputer models indicate that targeted vaccinations and early detection may provide the best way to contain the spread of a deadly virus.

If a large enough portion of the population is vaccinated, the collective benefit is pretty big.

Imagine that one day soon, a dozen travelers infected with highly contagious bird flu land in Los Angeles, California. Public health officials have fretted about this threat for years. If transmission of the deadly virus isn't stopped, thousands, hundreds of thousands or—in an absolute worst-case pandemic—millions of Americans could die. What should authorities do?

The answer, strangely enough, arrives via supercomputer programs that study the strength of metals and other materials. Developed at Los Alamos National Laboratory (LANL), in Los Alamos, New Mexico, those programs model how billions of individual atoms jostle and collide. This atomic behavior is similar to how people move and interact when they commute to work, head to school or go shopping, said Tim Germann, a LANL computer scientist. To study the issue, Germann and his colleagues teamed with influenza researchers to develop the world's most sophisticated predictions of how bird flu would spread, and how to cope with it.

During their work, they found that a multipronged strategy would best contain the virus. "Individual strategies don't work well by themselves," said Germann. No one before had looked carefully at what might happen when deploying multiple strategies. Their models showed that restricting travel and a combination of vaccination and distribution of antiviral medications would work synergistically to minimize deaths.



BIRD FLU virus

BLUE GENE/P supercomputer

"It's much more efficient to have two or three mitigation strategies that alone aren't 100 percent perfect," said Kai Kadau, another LANL computer scientist on the project. For instance, "social distancing strategies," such as closing schools, grounding commercial air travel or encouraging telecommuting, would help slow the spread of bird flu. Such measures alone, however, would not halt the disease. But by distributing antiviral medications in communities hit by the flu and vaccinating people widely, the virus would eventually stop spreading. "Restricting travel slows it down significantly and buys you some time to put some other strategies in place, such as developing a better vaccine," Kadau added.

The new models actually predict the day-to-day movements of all 300 million Americans.

The models also show that distributing even a weak vaccine can help stanch the virus, although this finding surprised a lot of infectious disease experts. "On an individual level, the vaccine isn't very effective," Germann said. "If a large enough portion of the population is vaccinated, the collective benefit is pretty big." Policymakers took note of the findings. Now vaccine developers are stockpiling a vaccine targeted to the strain of bird flu circulating mainly among poultry in Asia.

Slowing the spread of the virus among school children should also be a top priority, said Germann. Reducing transmission by closing schools or vaccinating children would play a major role in halting a burgeoning pandemic. Children's immune systems are weaker than those of adults, as evidenced by the high proportion of school kids that contract the flu strain that circulates each winter. "If you can slow or stop the spread among school children, that's your biggest benefit," said Germann.

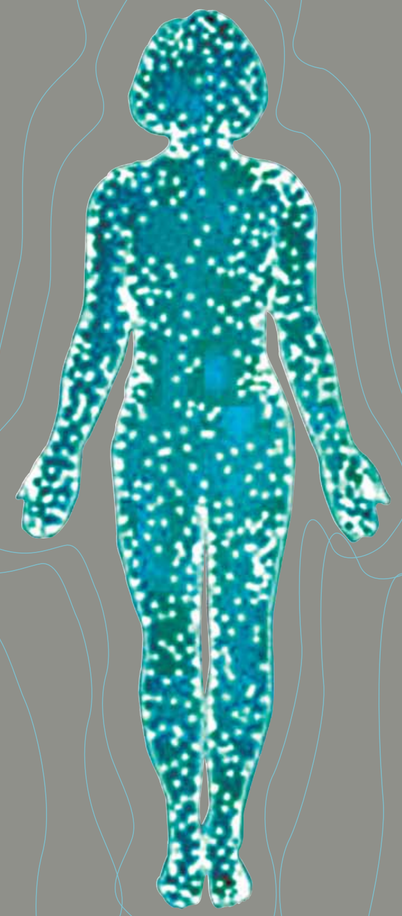
Previous attempts to model bird flu relied on crude estimates of the virus spreading from community to community. But by mining U.S. census data, the new models predict the day-to-day movements of all 300 million Americans. Such a detailed approach had never been tried before, but the supercomputers at LANL have more than enough "horsepower" to get the job done. In fact, if good census data existed for the entire world, the computer models Germann and colleagues built could even estimate how bird flu would spread across the globe. "There's no technical reason why we couldn't study the worldwide emergence of the human virus from Southeast Asia," Germann said. "But we're data-limited there. The United States has excellent census data on how people commute and travel, something you don't find in the rest of the world."

LANL researchers also have built a database of all known strains of influenza and, in another project, modeled how the flu and other viruses, such as hepatitis C, mutate and evolve. Such work is crucial for developing new antiviral medications, said Harel Dahari, a theoretical biophysicist at LANL. Together, the projects provide policymakers with hard data crucial for stopping bird flu from exploding into the deadliest pandemic of all time—a real fear among public health experts. The U.S. National Laboratories reviewed the bird flu computer models and "went in skeptical but came out saying these models are really useful," said Germann.

Subsequently, the U.S. Centers for Disease Control and Prevention (CDC) released policies on bird flu mitigation that incorporate key findings from the model. LANL researchers also are working with the U.S. Department of Homeland Security (DHS) to develop simplified computer models cities can use to build their own local plans.

MILLIMETER WAVE TECHNOLOGY

SCANS FOR MORE THAN JUST SECURITY



This new technology makes going through airport security a breeze.

What do national security, fitness and health and perfect-fit jeans have in common? Technology developed at Pacific Northwest National Laboratory (PNNL) in Richland, Washington.

In the 1990s, technology created at PNNL for airport security and sponsored by the Federal Aviation Administration (FAA) focused on millimeter wave holographic screening technology for national security applications to detect concealed metallic and nonmetallic objects. Since then, it's been deployed domestically and internationally for airport and other security applications, and spun out for unusual uses such as measuring one's body for custom-fit clothing and, under negotiation, health and fitness markets.

Terrorists are smart; September 11 profoundly demonstrated that fact.

In its current form, the space-age, phone booth–looking technology incorporates two "wands" that rotate around a person in 1.5 seconds, bouncing harmless millimeter waves off the water in the body and any objects concealed on it. The information from the scan is sent to a computer that produces a 3-D image, revealing any concealed objects.

"It's important because terrorists are smart; September 11 profoundly demonstrated that fact," said Douglas L. McMakin, staff engineer, National Security Directorate, PNNL, and a primary researcher on the technology.

The technology can detect things that current airport security technologies cannot. It's also fast and eliminates the need for physical contact between screener and passenger. The technology provides a new level of safety and security to public arenas, such as airports and subway terminals, and from potential terrorists.

"Millimeter waves readily penetrate clothing barriers and reflect off objects in or under the clothing," said McMakin. "Our patented holographic imaging software uses the reflected waves to form high-resolution imagery of the concealed threats."

The scanner uses a millimeter wave array/transceiver technology that "illuminates" the body with extremely low-powered millimeter waves—a class of nonionizing radiation not harmful to humans. More than 200,000 reflected signals are collected and sent to a high-speed image-processing computer where they form a high-resolution 3-D image of the body that is accurate to within one-quarter of an inch. The resulting image allows system operators to see objects worn in or under clothing—even nonmetallic objects. "This is just one advantage of the system," McMakin said.

Other advantages include its scanning speed (about 1.5 seconds to scan and several more seconds for the operator to screen for threats) and the fact that it does not require person-to-person contact.

For security applications, the patented technology was licensed in 2003 to SafeView Inc., a start-up company later acquired by L-3 Communications Corp., to be commercialized for noninvasive security "portals." Its commercial version of the technology, SafeScout, has been used at border crossings in Israel, international airports in Mexico City and Amsterdam, ferry landings in Singapore and railway stations in the United Kingdom. It also was used in the courthouse during Saddam Hussein's trial and has been deployed in the Green Zone in Baghdad, Iraq, to detect hidden explosives.

The technology can detect things that current airport security technologies cannot.

In 2006, L-3 Communications Corp. began selling its commercial version (called ProVision) to the U.S. Transportation Security Administration (TSA) for use in airport screening. By the end of 2008, ProVision systems were installed in 21 U.S. airports. TSA plans to purchase and install 80 more units in U.S. airports in 2009.

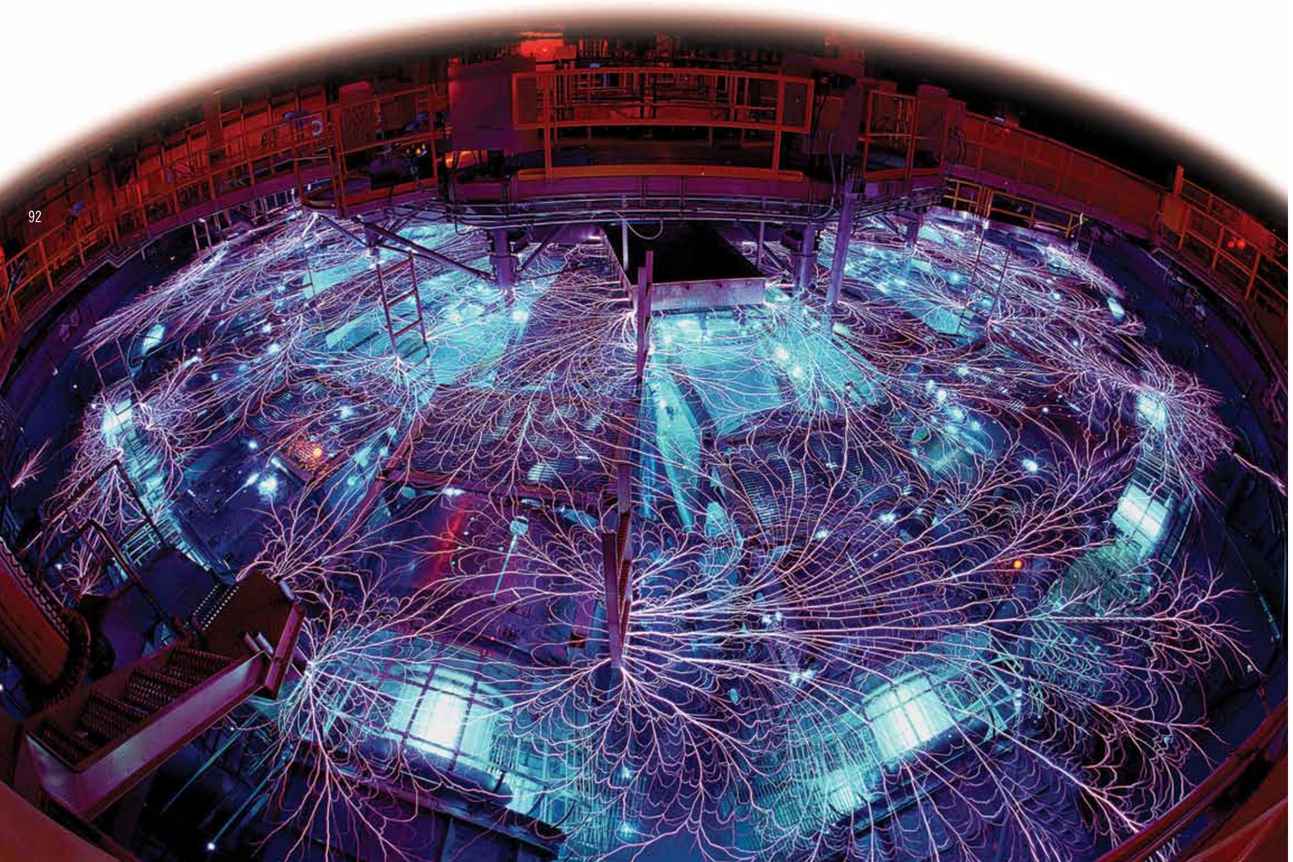
In October 2007, passengers at Phoenix Sky Harbor International Airport were the first to test the new high-tech security screener. In April 2008, the machines were rolled out at John F. Kennedy International Airport and Los Angeles International Airport. TSA reports positive feedback from passengers about the speed and ease of the technology.

In developing the machines, PNNL researchers also discovered that the technology had consumer applications. In the apparel industry, for example, companies can use it to help consumers select the perfect style and size of jeans and slacks—even wedding dresses—by collecting extremely accurate body measurements for custom-fit clothing.

"The next application we're seeking is in the fitness/health industry," said McMakin. "Because the technology can accurately measure a body, we're finding that diet centers, gyms and doctors' offices could use the technology to measure every part of a person's body and determine weight and body mass index."

PNNL was granted its first patent for the millimeter wave technology in 1995. Its roots date back to the 1960s when PNNL researchers pioneered the development of optical and acoustic holography—the foundation of the millimeter wave technology. The work for the FAA began in the late 1980s. Current funding comes from the U.S. Department of Homeland Security (DHS).

INTELLIFIT CORP. in Plymouth Meeting, Pennsylvania, licensed the technology in 2004 for what it calls the Virtual Fitting Room (VFR).



NUCLEAR TESTING

WITHOUT THE NUCLEAR EXPLOSION

The versatile Z machine helps safeguard America's nuclear arsenal while giving scientists new insights into fusion technology.

Many Albuquerque, New Mexico residents do not know it, but around 200 times a year something extraordinary happens on the outskirts of their town. On some days, the conditions of the sun are fleetingly recreated. On others, the physics at the heart of a nuclear explosion are brought momentarily to life.

These little miracles of physics take place inside Sandia National Laboratories' (Sandia) Z machine, one of the world's most powerful and sophisticated X-ray generators. Since operations began in 1996, the Z machine has helped safeguard America's nuclear arsenal, given scientists an insight into the conditions deep within stars and boosted understanding of fusion technology, which one day may prove to be an environmentally friendly power source. Not bad for a device that operates off a regular domestic power supply.

It's the very high currents and powers that make the Z machine unique.

The Z machine's secret is simple: suck in electricity slowly, and then release it in a brief burst. The outer border of the machine is a circular ring of 36 blocks of capacitors that can be charged in just under two minutes. Then, at the flick of a laser-triggered switch, each pours its electrical energy through metal cylinders and into the heart of the machine. The 36 current pulses are synchronized to within 20 nanoseconds, and when combined deliver 26 million amperes to the center of the machine.

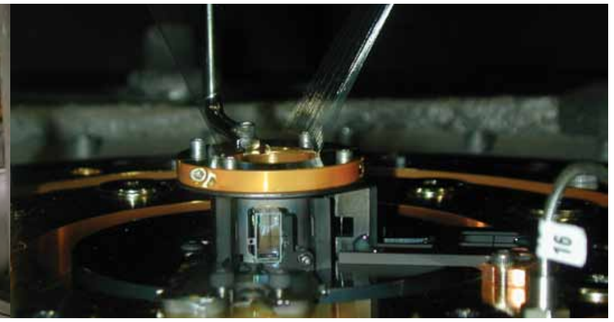
In some experiments, the Sandia team channels that current through a cylindrical array of 300 tungsten wires, each thinner than a human hair. The very large current first vaporizes the wires. Then the magnetic field created by the current pushes the tungsten particles inward, creating a brew that is so hot and dense that electrons are ripped from the atoms. This particle soup, known as plasma, collapses inward at velocities greater than 0.1 percent of the speed of light.

Nuclear Testing Without the Nuclear Explosion

INSPECTION of material samples used to test radiation effects produced by the Z machine

CIRCUITS on an LTD device able to produce large electrical impulses rapidly and repeatedly

THE Z MACHINE under renovation in 2007



JUST AFTER Z REACHES PEAK POWER, the iron inside this device reaches conditions normally only found in the immediate vicinity of neutron stars and black holes

Finally the particles collide, creating temperatures that exceed those of the sun and an X-ray pulse lasting just a few billionths of a second. The power released is immense: over 200 trillion watts, or 80 times the world's output of electricity. "It's the very high currents and powers that make the Z machine unique," said Sandia scientist John Porter. That kind of power can be very useful.

In 2003, Sandia researchers placed a small pellet containing deuterium, an isotope of hydrogen, close to the tungsten wires. When the X-ray pulse heated the pellet it pushed the deuterium atoms together until they fused into atoms of helium. The event marked the first time this method, known as pulsed power, was used to spark a fusion reaction. "It was a big breakthrough for us," Porter exclaimed.

The technique has enormous potential. Deuterium is plentiful and cheap, and releases energy when it fuses. The hope is one day the reaction could be used to run a zero-carbon power station. But it's easier to start a fusion reaction than to keep one going. Also, the Z machine lacks the needed punch to power a self-sustaining fusion reaction that produces more fusion energy output than electrical energy input. While further work at Sandia has helped its researchers ignite reactions that produce more energy, net energy gain would require a machine based on the same principles but around four times as powerful, said Porter.

Even so, Sandia researchers have already proven the Z machine's worth by demonstrating that pulsed power is a candidate for powering a future fusion plant. "They've been able to produce proof of principle," said Per Peterson, a nuclear engineer at the University of California-Berkeley.

When the Z machine is being used for nuclear weapons work, the tungsten wires are replaced with copper ones. These produce a higher-frequency X-ray pulse that mimics that given off in a nuclear explosion. That allows weapons researchers to investigate the possibility that, during military action, one of these pulses could interfere with the electronics in nearby unused nuclear devices. At Sandia, researchers monitor the effect the pulses have on materials found in electronic circuits. The results can be used to improve simulations of the effect of X-rays on circuits in real weapons.

The behavior of the bombs themselves also can be probed using the Z machine. To do so, researchers swap the wires for two sheets of copper and reverse the direction of current through one of them, so that the plates are pushed apart. When the current flows, the pressure experienced by the plates is terrifying: 8 million times greater than the atmospheric pressure at sea level and twice that at the earth's center.

The Z machine gives weapons scientists a chance to examine their theories.

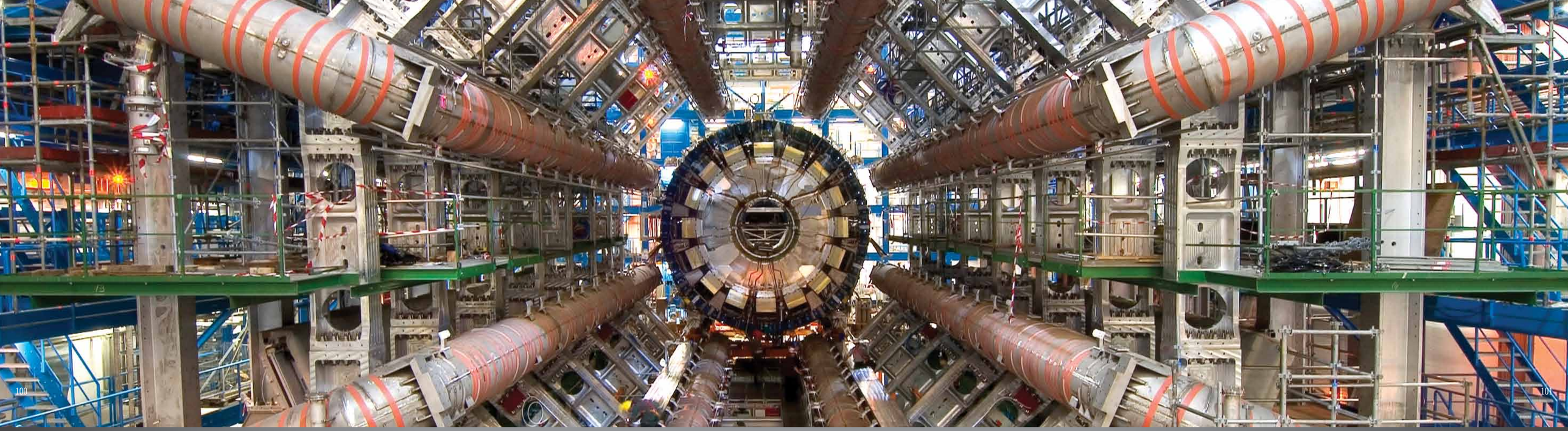
Since pressures like that also are present at the heart of a nuclear explosion, the Z machine gives weapons scientists a rare chance to examine their theories of how materials respond to these extreme pressures. To avoid detonating weapons for test purposes, scientists run computer simulations of the conditions within the nuclear components of a weapon. As with the simulation of the electrical circuits, these tests need real data to ensure accuracy. So Sandia researchers place samples of plutonium on the copper plates and observe how the material reacts to the pressure. This data gives weapons researchers a better idea of what could happen on the battlefield with respect to the safety, security and reliability of a warhead's plutonium core.

LIFE AND PHYSICAL SCIENCE

NATURE OF THE UNIVERSE · U.S. DEPARTMENT OF ENERGY · DNA TESTING · U.S. DEPARTMENT OF ENERGY · HEALTH ANALYSIS U.S. DEPARTMENT OF ENERGY · FUSION · U.S. DEPARTMENT OF ENERGY · NEUROLOGY · U.S. DEPARTMENT OF ENERGY PROTEOMICS · U.S. DEPARTMENT OF ENERGY · NANOTECHNOLOGY · U.S. DEPARTMENT OF ENERGY · NEUTRON SCATTERING U.S. DEPARTMENT OF ENERGY · CANCER TREATMENT · U.S. DEPARTMENT OF ENERGY · LASER X-RAYS · U.S. DEPARTMENT OF ENERGY · QUARK-GLUON PLASMA · U.S. DEPARTMENT OF ENERGY · PHOTOSYNTHESIS · U.S. DEPARTMENT OF ENERGY DARK ENERGY · U.S. DEPARTMENT OF ENERGY · STRANGE QUARKS · U.S. DEPARTMENT OF ENERGY · SUPERCOMPUTING

INTRODUCTION

Pick up any dictionary and you will see a laboratory defined as a building or room designed for scientific experimentation, research and analysis. Although that may be true enough for Messrs. Merriam and Webster, this section demonstrates it is far too flatland a meaning for something that clearly inhabits a multidimensional universe. One can only marvel at how researchers have been able to map the soft afterglow of the Big Bang across the sky and plan to take stop-motion pictures of atoms and molecules. Nuclear technology developed in our nation's labs is being used to combat cancer, while supercomputers are providing breakthroughs in the study of debilitating diseases such as Alzheimer's. New and remarkable forms of matter created in ion colliders are opening new doors on the nature of matter, providing insights into the creation of the universe. The National Laboratories truly surpass what their names imply: not just a collection of rooms but a place and a state of mind, where "what-ifs" become possibilities, and perhaps actualities.



CERN'S LARGE HADRON COLLIDER (LHC) is the world's largest particle accelerator.

WORLD RECORD FOR LASER WAKEFIELD ACCELERATION:

ZERO TO ONE BILLION ELECTRON VOLTS IN THREE CENTIMETERS

For 30 years, high-energy physicists have wondered about the possibility of building a laser electron accelerator that could reveal the secrets of the universe.

It took two decades and billions of Euros to develop CERN's (The European Organization for Nuclear Research) Large Hadron Collider (LHC). At 27 kilometers in circumference, it is the world's largest accelerator, big enough to fit around the country of Monaco. The LHC will soon begin testing advanced theories in physics. But given the size and cost of today's accelerator technologies, physicists are already wondering where to go next.

A group of researchers with the Lawrence Berkeley National Laboratory (Berkeley Lab) in Berkeley, California, working with colleagues from the University of Oxford, may have the answer. In 2006, the team accelerated electron beams to 1 GeV (1 giga-electron volts, or 1 billion electron volts) in a distance of just 3.3 centimeters, proving that good beams and high energies can be achieved over small distances. This baby-step approach using lasers may ultimately lead to the development of a particle accelerator no bigger than a football stadium, which could achieve the high energies needed to test the fundamental theories of the universe.

High-energy physicists have been pondering the possibilities of laser accelerators since at least 1979. The biggest hurdle was making a laser that could penetrate a gas to form a plasma with free electrons, without the laser beam dispersing along the way. Shine a flashlight on a spot nearby and the light forms a tight circle. Farther away, however, the spot becomes larger and less defined. Lasers similarly lose their focus beyond a short distance, called the Rayleigh length. If all one needs is a laser pointer, even an out-of-focus laser beam appears to make a point of light several feet away, because the beam starts out so tightly focused. A laser accelerator is more demanding.

A laser beam traveling through a plasma essentially creates a "wake" around it as it moves. Free, negatively charged electrons ride this wake in the plasma "surf" when dissociated from positively charged ions. Getting these electrons up to speeds necessary to test questions in high-energy physics requires that the electrons travel over multiple Rayleigh lengths.

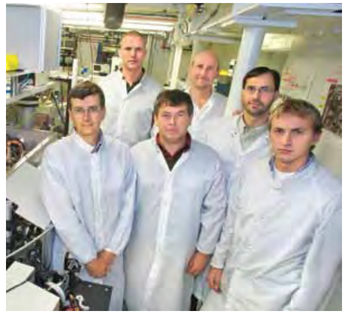
Measuring the speed of a cross-section of a laser beam reveals that the center of the beam is traveling faster than the light around the center. The solution is to slow down the light's center and speed up the light that is moving in the wake, so that both are traveling closer to the same speed.

Wim Leemans, head of the Laser Optics and Accelerator Systems Integrated Studies (L'OASIS) Program of the Accelerator and Fusion Research Division at Berkeley Lab, began testing laser wakefield acceleration with his graduate students in 1995, after Howard Milchberg from the University of Maryland developed the basic principle in the mid-1990s. Eventually, Leemans and his team took a multiple-laser approach to the problem. The first laser pulse forms a plasma channel in a plume of hydrogen gas. A second pulse from the side heats the plasma and causes it to expand, leaving a void in the center through which the third laser plows its way with a driving intensity of 10 trillion watts of power.

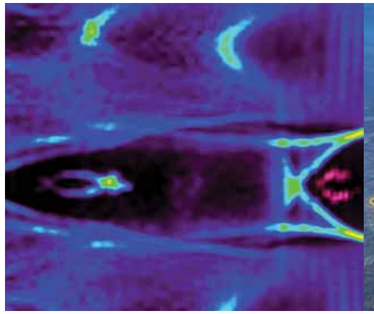
As Leemans explained, "Plasma actually has a lower index of refraction than vacuum, so the wavefront moving through the center of the channel moves slower than at the edges. This flattens the otherwise spherical laser wavefront and extends the distance over which the laser stays intense enough to excite large plasma waves."

The development of a particle accelerator the size of a football stadium could achieve the high energies needed to test the fundamental theories of the universe.

In 2004, Leemans and his Berkeley Lab team were one of three groups, including teams based at Imperial College, London, and the École Polytechnique, Paris, who achieved peak energies of 70 to 200 MeV (mega-electron volts, or million electron volts) with laser wakefield acceleration. One approach to the 1 GeV goal appeared to require using larger spot sizes for the lasers, which would dramatically increase the cost and power requirements.

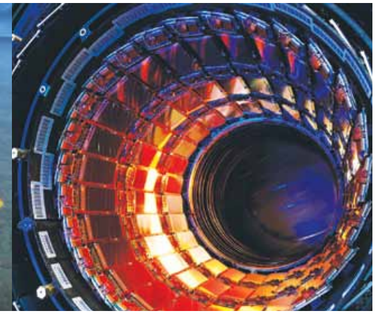


THE WORK WAS DONE BY THE L'OASIS GROUP (L'OASIS stands for Laser Optics and Accelerator Systems Integrated Studies), led by Wim Leemans (left) of the Center for Beam Physics in Berkeley Lab's Accelerator and Fusion Research Division.



A PLASMA CHANNEL, denser toward the edges, guides the laser and allows it to form high-quality electron beams. As the laser pulse travels from left to right it excites a wake in the plasma, trapping and accelerating bunches of electrons to high energies.

CERN'S LARGE HADRON COLLIDER, at 27 kilometers in circumference—is big enough to fit around the country of Monaco—is the world's largest accelerator.



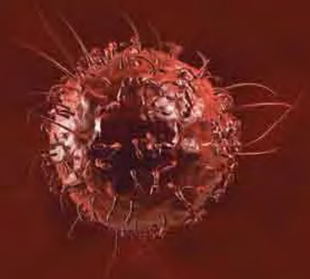
TWO PROTON BEAMS travel in opposite directions and collide at four points along the way—replicating the Big Bang conditions of "cosmic plasma," a mysterious, almost liquid state, which occurs before quarks have cooled off enough to allow atoms to form together.

Leemans and his team found a way to extend their plasma-channel approach through a collaboration with Simon Hooker at Oxford University, whose group had been able to maintain plasma channels inside blocks of synthetic sapphire. "How many laser shots can it take?" Leemans asked. "As many as you like," Hooker replied. It was a match made in stone.

In October, 2006, the physicists published a report in the journal *Nature Physics* describing their technique for getting from zero to 1 billion electron volts in 3.3 centimeters. "Billion-electron-volt beams from laser wakefield accelerators open the way to very compact high-energy experiments and superbright free-electron lasers," Leemans said. The group has proposed to DOE a 10-GeV acceleration module project called BELLA (Berkeley Lab Laser Accelerator), which could be operating in 2013. The goal is to provide a unique user facility for scientists who need advanced light sources and free-electron lasers. "Meanwhile, we'll be on the way to designing a new generation of powerful accelerators and colliders based on laser wakefield acceleration technology," Leemans says. "BELLA will help insure that the unique science U.S. Department of Energy has made possible through its leadership in advanced accelerator research will go forward into the future with laser-based technologies."

Billion electron-volt beams from laser wakefield accelerators open the way to very compact high-energy experiments and superbright free-electron lasers.

TARGETING CANCER USING NUCLEAR TECHNOLOGY



Technology that was originally designed to test nuclear weapons is now being used to kill cancer cells with minimal damage to surrounding tissues.

There was a time when the word "nuclear" conjured up images of mushroom clouds and destruction. But in recent decades, nuclear technology has been recognized as a safe, reliable and emissions-free power source, and on the scientific scene it's morphed from a force of destruction to one of healing. U.S. Department of Energy (DOE) research has made significant contributions to the growing and important field of nuclear medicine. Building on technology originally designed to test nuclear weapons, a team of scientists at Lawrence Livermore National Laboratory in Livermore, California, has designed a compact system to kill cancer cells, while doing minimal harm to the body's surrounding tissue.

It's called proton therapy, and at the present time the machines that deliver the cancer-killing proton beams are so large and costly that only six centers exist in the United States (25 throughout the world). But Livermore research has managed to come up with a design that's smaller and cheaper, that will make the therapy much more accessible to hospitals and patients who need it.

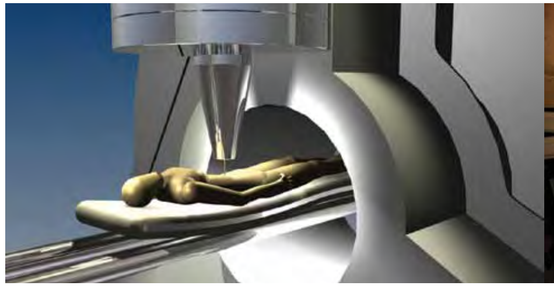
Proton therapy is a cousin to the more familiar forms of radiation therapy that use a beam of X-rays to deliver their cancer-killing blow. As X-rays enter the body they crash into the cells in their path, giving up energy as they grind to a halt. That energy kills cells, which is great for cancer cells, but not for the healthy cells that make up the surrounding skin and tissues.

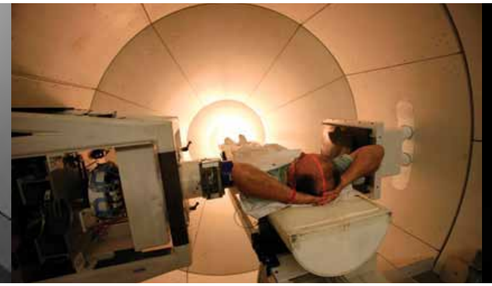
Protons do almost all their damage right when they hit the target—leaving neighboring cells virtually undisturbed.

George Caparoso, one of the investigators on the project, explained that X-rays tend to give up their energy close to the surface of the body and are hard to target at precise depths. As a result, it's often very difficult to successfully treat tumors that lie deep under the skin without inadvertently damaging other tissues and organs. As an example, a woman with breast cancer who has traditional radiation therapy likely is treating more than just the tumor in her breast. "What you'll find is that you'll get doses to the tumor, but you'll also get doses to the lung and sometimes even to the heart," Caparoso said.

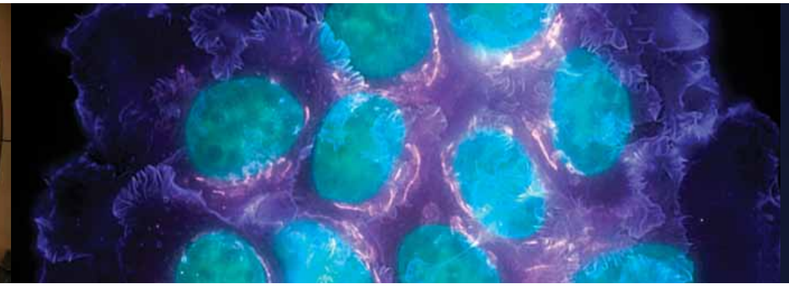
But heavy protons behave fundamentally differently than the massless photons found in X-rays. They are easier to target and control. Proton therapy machines accelerate protons to a speed that corresponds to the precise depth of the tumor cells. "By adjusting the energy of the proton, you adjust how far in it stops," said Caporoso. And what's more, the protons do almost all their damage right when they hit the target, leaving neighboring cells virtually undisturbed.

Targeting Cancer Using Nuclear Technology

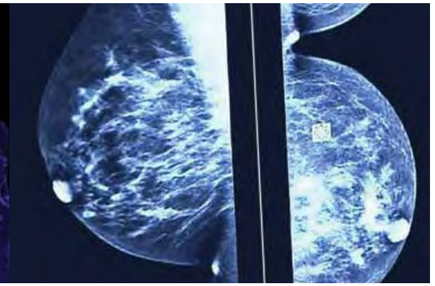




PROTON RADIATION THERAPY is potentially a better way to treat cancer because it has fewer side effects, but the technology is still very expensive.



GROWTH FACTOR STIMULATED HUMAN BREAST CANCER CELLS stained for actin (blue), nuclei (green) and the Golgi apparatus (purple).



NUCLEAR IMAGING SYSTEMS yield more reliable results than traditional mammography.

But getting those weighty protons moving fast enough requires a big accelerator, a massive superstructure that's three stories tall and costs $150 to 200 million. Caparoso and his colleagues had been working for years on reducing the size of X-ray machines used to image bombs, when he was asked by a colleague if he could do the same thing for proton machines used in medicine. A collaboration was born, and today the project is a few years away from being a commercial product that will fit into hospitals and radiation therapy treatment centers.

And while Caparoso's group would like to use nuclear technology to replace X-rays that kill cancer, scientists at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), another DOE nuclear physics lab, are developing nuclear imaging systems that in some cases are better than X-rays at finding and identifying certain tumors. A mammogram is an X-ray of the breast, and it's the standard of care for detecting breast cancer. But because mammograms only show structural differences in tissue density, they can be misleading, explained Jefferson Lab scientist Drew Weisenberger.

"A tumor may have the same density as healthy tissue, but it behaves differently," Weisenberger said. In mammograms of women's breasts that have very dense tissue, or fibroids, it is difficult to differentiate between noncancerous and cancerous masses. This can lead to false-positive results or missed tumors.

A mammogram also may miss behavior, which is key to another imaging technology used to detect tumors. The technology takes advantage of the fact that tumors are living masses of cells with metabolic requirements different from healthy cells. For instance, many tumor cells often are growing and dividing at a high rate. This behavior can be identified by the use of radioactively tagged molecules called radiopharmaceuticals. By injecting a patient with a radiopharmaceutical, doctors can monitor where it goes with nuclear medicine imaging technology. If the radiopharmaceutical accumulates in one region of the breast, there is a good chance there's a tumor, Weisenberger explained.

Jefferson Lab has improved on earlier nuclear medicine clinical devices that were not designed specifically for the breast. So why wasn't nuclear medicine imaging being used to assist in breast cancer detection? The original units were too large and bulky, and clinicians weren't convinced that they worked. "Because the resolution and sensitivity weren't high enough; the results didn't offer more than mammography," said Weisenberger.

The compact nuclear medicine imaging system developed at Jefferson Lab uses a special crystal, called a scintillator, to detect the radiopharmaceutical and generate an image. Existing clinical systems were the size of a trash-can lid and not designed to distinguish small (centimeter-sized) masses in the breast. The Jefferson Lab device is smaller and more sensitive and provides higher-resolution images, while being about the same size as a mammography machine. Dilon Technologies of Newport News, Virginia, has licensed the technology and it is in clinical use.

Weisenberger says that a mammogram is the first step for all women, with nuclear medicine imaging serving as an additional, complementary tool. If one of his loved ones had breast cancer, Weisenberger said, he would insist on using the new technology.

THE NANO FILM FESTIVAL:

ATOMS AT THE MOVIES

Ultrafast X-ray pulses will enable scientists to take stop-motion pictures of individual atoms and molecules, revealing the frenetic action of the atomic world.

SLAC National Accelerator Laboratory (SLAC) in Menlo Park, California, which possesses the world's longest linear accelerator, has been producing high-energy electrons for four decades. Starting in 2009, SLAC will use its linear accelerator to drive a new kind of laser, the Linac Coherent Light Source (LCLS), a new scientific tool for studying the world of the ultrasmall and the ultrafast.

The LCLS will produce very short flashes of X-ray light more than one billion times brighter than any other X-ray source on earth. "It can be used to measure the separation and motion of atoms in molecules, solid materials and disordered [noncrystalline] materials in a very new way," explained John Galayda, LCLS construction director. The LCLS began construction in October, 2006.

The LCLS will enable scientists to observe molecules in action and how chemical bonds form and break. It also will help explain how materials work on the quantum level.

The ultrashort LCLS X-ray pulses will enable such short measurements that atoms will not have a chance to move and blur the picture. "Rather like the way a strobe flash on a camera stops motion," Galayda explained. In addition, the pulses are so intense single images can achieve atomic resolution.

The ultrafast LCLS X-ray's "shutter speed" will be about 100 femtoseconds—one-tenth of a trillionth of a second, or the time it takes light to traverse the width of a human hair. Stop-action imaging has a long history at Stanford University: Eadweard Muybridge developed early stop-motion photography in the 1870s on the future site of Stanford. He photographed a horse galloping to resolve the long-debated topic of whether all four of a horse's feet came off the ground at once (they do).

The LCLS represents a major advance in the use of large electron accelerators to produce X-rays. Many synchrotron radiation facilities are in operation around the world today, using accelerators to produce X-rays millions of times brighter than the X-rays used for medical purposes, enabling scientists to understand the arrangement of atoms in a range of materials including metals, semiconductors, ceramics, polymers, catalysts, plastics and biological molecules. In contrast with the intense, ultrashort pulses of X-rays from the LCLS, the X-rays from synchrotron sources come as a more continuous stream. They are more useful for static structure measurements than for studies of ultrafast atomic motions.

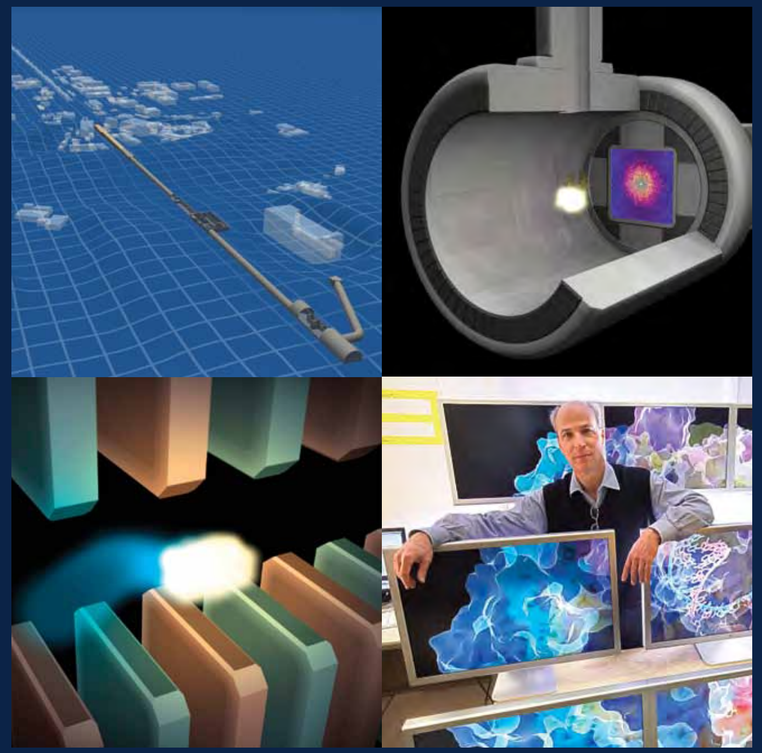
A new kind of laser will open our eyes to the world of the ultrasmall.

Synchrotron sources have been highly productive. In 2006, Stanford University researcher Roger Kornberg won the Nobel Prize for Chemistry for his research using X-ray crystallography at SLAC's Stanford Synchrotron Radiation Lightsource to study proteins important in the transcription of DNA. By exposing crystallized samples of protein molecules, usually the size of a grain of salt or smaller, to highly focused X-ray beams and creating characteristic patterns on a detector, scientists could calculate the locations of the atoms within the protein molecules. The technique enabled Kornberg and colleagues to investigate the structure of RNA polymerase, key to understanding how information held in DNA translates into the proteins of life.

The LCLS's ultrafast, ultrabright X-ray pulses will enable scientists to move beyond the study of static atomic structures and take stop-motion pictures of atoms and molecules, revealing the frenetic action of the atomic world. This will lead to better understanding of not only what atomic structures look like, but how they move and interact with each other.

The shutter speed will be about 100 femtoseconds, or the time it takes light to traverse the width of a human hair.

EADWEARD MUYBRIDGE is famous for showing that all four of a horse's feet leave the ground during a gallop. The ultrafast LCLS X-ray's "shutter speed" will be just short of 100 femtoseconds—one-tenth of a trillionth of a second, or the time it takes light to traverse the width of a human hair.



CLOCKWISE FROM TOP LEFT

LCLS CONSTRUCTION PROJECT SLAC's original two-mile linac is extended by an additional half mile, which includes X-ray transport tunnels and two experimental halls.

HOLOGRAPHIC IMAGES The X-rays pass through the molecule and leave a distinctive pattern of rings and spots on the surface of the detector at the back of the chamber.

STANFORD UNIVERSITY Researcher Roger Kornberg won the 2006 Nobel Prize for Chemistry.

UNDULATOR MAGNETS The LCLS creates intense pulses of hard X-rays using tightly packed bunches of electrons travelling through arrays of undulator magnets.

THE SUPERCOMPUTING FAST LANE

Cray's XT Jaguar has raced ahead of its competitors and promises to accelerate the pace open scientific research.

Supercomputing has never been any more super than it is now at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. In November 2008, ORNL researchers announced that the recently upgraded Cray XT Jaguar supercomputer offered a peak performance of 1.64 quadrillion calculations per second—or 1.64 petaflops—making it the most powerful computer ever seen for open scientific research.

Jaguar is the second supercomputer to break the "petaflop barrier," the first being the IBM Roadrunner system installed at Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico (see "Roadrunner Keeps an Eye on the Nation's Nuclear Arsenal," page 82). The new Jaguar uses 45,376 of the latest quad-core Opteron processors from AMD and features 362 trillion bytes (362 terabytes) of memory and a 10-petabyte file system. The machine has 578 terabytes per second of memory bandwidth and an unprecedented input/output bandwidth of 284 gigabytes per second to greatly facilitate the movement of data into and out of processors.

The system has already demonstrated its prowess, boasting the only two real (i.e., nonbenchmark) scientific applications to date that have exceeded a petaflop. One, which investigates high-temperature superconductors, achieved an unprecedented 1.35 petaflops to win the prestigious Gordon Bell Prize, awarded to recognize the world's fastest scientific computing application. The second, which simulates the electronic structure of systems such as magnetic hard drives, achieved 1.05 petaflops. Both achievements came from teams led by ORNL's Thomas Schulthess.

Jaguar also took top honors in the annual High-Performance Computing (HPC) Challenge awards, which recognize excellence in handling computing workloads. Jaguar took first place in two of the four categories (speed in solving a dense matrix of linear algebra equations and sustainable memory bandwidth) and third place in another (speed in executing the Global-Fast Fourier Transformation, a common algorithm used in many scientific applications).

Jaguar also recently has been aiding in the search for new drugs against Alzheimer's disease. In 2007, ORNL researchers Edward Uberbacher and Phil LoCascio used 100,000 processor-hours on Jaguar to investigate the mechanisms by which a new class of drugs acts. The drugs, called caprospinols, may stop

JAGUAR, the world's fastest computer for science.

the growth of Alzheimer's fibrils and even disassemble the threadlike fibers. According to Uberbacher, it's the first time molecular dynamics has been used to simulate the mechanisms these drugs use to interact with Alzheimer's fibrils and reduce their growth. The findings, he adds, will provide researchers with new ideas about how to improve the drugs that treat the disease.

ORNL originally contracted with Cray in 2004 to build a supercomputer for the researchers and scientists who use the laboratory's national supercomputing user facility. Since then, Cray and ORNL researchers have rapidly upgraded Jaguar, and it is now the undisputed leader of the pack for open scientific research. Jaguar has been put to work on a variety of petascale research, including designing more efficient car engines, probing the mysterious dark matter pervading the universe, reproducing propagating shockwaves in a supernova and simulating new superconducting materials.

Jaguar is so off-the-scale from what an average computer can do that it's really difficult to relate to in terms of raw speed.

The supercomputer may play a key role in handling the simulations required for the next report from the Intergovernmental Panel on Climate Change, the vanguard organization that predicts the climate's future. "Climate change is one area where you don't want to do the experiments," explained Thomas Zacharia, ORNL's associate laboratory director for computing and computational sciences. "Instead, you want to model

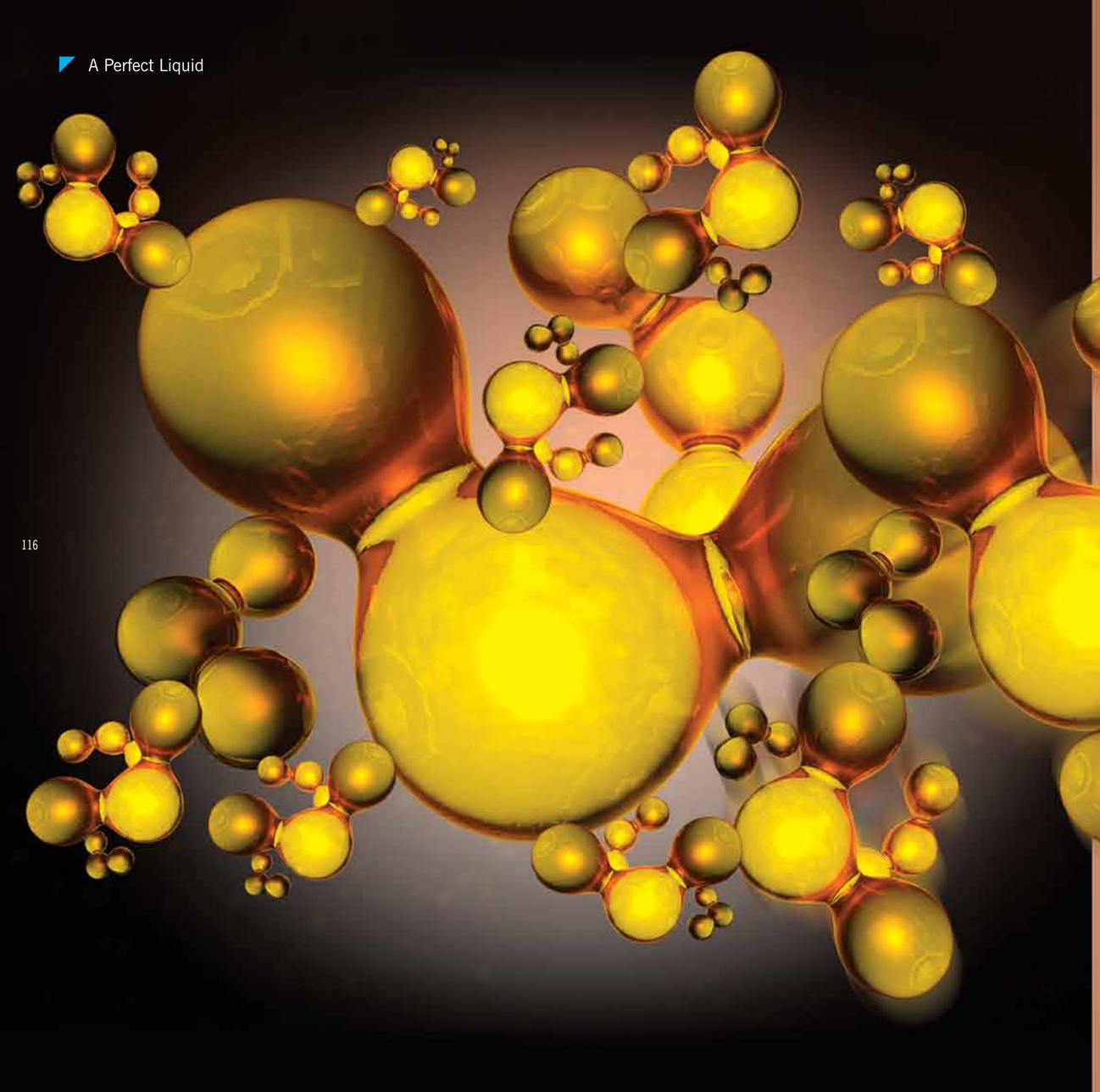
EXAMINING ALZHEIMER'S proteins on the world's fastest computer for science.

and simulate what's happening. And you want the highest-fidelity calculations to minimize uncertainty. That way, the policy decisions that have to be made are based on the most comprehensive, most sound scientific calculations."

Petascale Earth climate simulations enable scientists to incorporate increasingly complex global models that take into consideration such parameters as atmospheric wind flow, ocean currents and land and sea ice melt. The models help scientists better understand the ebb and flow of climate processes and feedback, such as the global water cycle, which in turn produces information on the timescales useful to resource managers and planners. Only supercomputers on a par with Jaguar can provide models with the kind of predictive skill needed for making decisions about the future of Earth's climate.

Supercomputing touches all aspects of humanity and has great power to accelerate progress.

Supercomputer experts predict that Jaguar and other petascale systems will transform science, acting as a "third pillar" to discovery, one that complements the centuries-old pillars of theory and experimentation. That is, supercomputers and their ability to simulate complexity now offer another broad avenue toward understanding the universe. "Supercomputing, in many ways, touches all aspects of humanity," Zacharia reflected. "It has great power to accelerate progress. In fact, I think of supercomputers as time machines. For the first time, they allow us to predict the future."



A PERFECT LIQUID

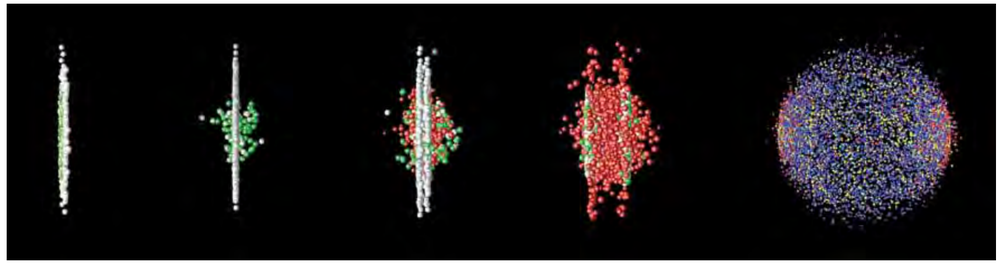
The Relativistic Heavy Ion Collider at Brookhaven National Laboratory has revealed evidence of a remarkable new state of hot, dense matter that behaves more like a viscous-free liquid than gas.

It's a simple question: What happens to matter when it's crammed into the smallest volumes and heated to the highest temperatures? We're not talking a mere few thousand degrees here, such as the temperature of the earth's core, or a few million degrees, as found in the sun's center. To reach the most extreme temperatures of a searing thousand billion degrees Celsius, physicists must smash atomic nuclei into one another to replicate the conditions present a few microseconds after the Big Bang itself, 13.7 billion years ago.

Enter the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (Brookhaven) on Long Island, New York. Since 2000, this machine, 2.4 miles in circumference, has been accelerating gold and other heavy nuclei close to the speed of light in opposite directions before smashing them head-on inside house-sized detectors positioned at four points around the ring. Under these wild conditions, the protons and neutrons inside nuclei melt, laying bare the fundamental constituents of matter: quarks and gluons.

"From the viewpoint of the man on the street, measuring the properties of these extreme forms of matter is a crucial aspect of understanding how our universe has evolved," said Brookhaven associate director Steven Vigdor.

RHIC physicists aim to study an elusive form of matter called quark-gluon plasma (QGP). The strong nuclear force normally confines quarks in tight bundles such as protons and neutrons. But



INSIDE BROOKHAVEN'S HEAVY-ION COLLIDER Two gold nuclei approach one another at almost the speed of light. As the two nuclei collide and pass through each other, some of the energy they had before the collision is transformed into intense heat and new particles. The collision liberates the quarks and gluons in the nuclei to form a quark–gluon plasma. As the area cools off, thousands more particles form. Many of these new particles will travel to a detector where their distinctive signatures give physicists clues about what occurred inside the collision zone.

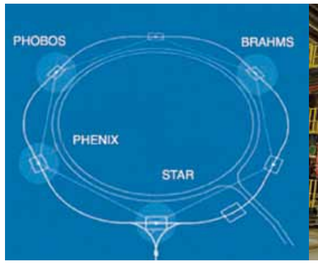
unlike gravity and electromagnetism, which get stronger as the distance between particles shrinks, the strong force counterintuitively gets very weak. This property, known as "asymptotic freedom," would appear to keep quarks and gluons from interacting with each other when the temperature is hot enough to melt many protons and neutrons inside a volume as small as a nucleus, producing a dense gas of free particles—the QGP. Were RHIC's collisions hostile enough to allow this exotic phase of matter to be studied in the lab?

Brookhaven's quest for the QGP began in 1986 with experiments at the Alternating Gradient Synchrotron, in tandem with similar experiments in Europe at CERN's (The European Organization for Nuclear Research) Super Proton Synchrotron. Just as RHIC fired up in 2000, CERN announced hints of an unusual QGP-like state. But by colliding beams of heavy nuclei head-on at much higher energies, three years later RHIC's detectors had found the most compelling evidence to date that a new form of quark-gluon matter exists at extreme temperatures.

While it may seem as though the search for the QGP is simply a matter of banging things together at high energies and waiting for the "eureka moment" when the detectors pick it up, nothing could be farther from the truth. To understand what is happening in the microscopic fireball that exists for a mere trillionth of a trillionth of a second when the gold nuclei pile through one another, RHIC's researchers have to work backwards from the debris recorded by RHIC's four giant detectors—STAR, PHENIX, PHOBOS and BRAHMS—and meticulously compare this data to sophisticated theoretical models.

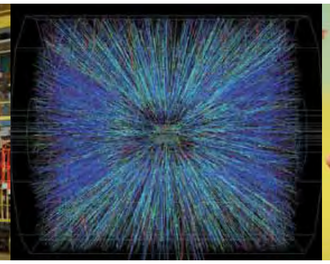
In 2005, this painstaking process produced a stunning surprise. Instead of behaving like a gas of free particles, the fleeting RHIC state behaved more like a liquid. It got even better. The patterns among the thousands of emerging particles revealed that the liquid flows with almost zero resistance or viscosity, making it the most "perfect" liquid ever observed.

Brookhaven's announcement of the perfect liquid at the 2005 American Physical Society meeting in Tampa was the first time string theory—a candidate "theory of everything" that invokes six or



STAR, PHENIX, PHOBOS & BRAHMS The layout of the detectors around the RHIC tunnel.

STAR DETECTOR The STAR detector at the Relativistic Heavy Ion Collider.



COLLIDING GOLD IONS A side view of one of the first high-energy collisions captured by STAR.

FRANK WILCZEK Co-winner of the 2004 Nobel Prize in Physics.

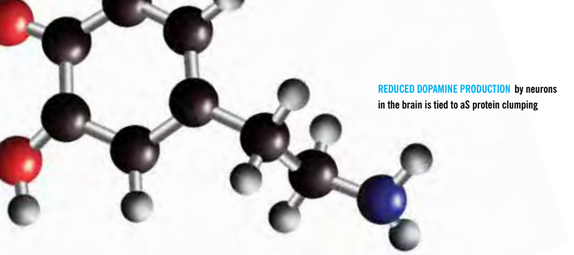
seven extra dimensions to unite all nature's forces, including gravity—had been linked to a hard experimental result. Although the strong force is described beautifully by a 35-year old theory called quantum chromodynamics (QCD), its equations are extremely difficult to solve in situations where the interactions between quarks and gluons are strong—as they must be to produce the perfect liquid behavior observed at RHIC. Bizarrely, the mathematics of string theory has offered a complementary approach by connecting strongly coupled QCD-like forces to weakly coupled gravitational forces, correctly predicting the almost zero viscosity measured in the RHIC collisions.

"String theory may provide a method for extracting predictions in a regime where traditional field theory approaches are difficult to use," said Thomas Schaefer of North Carolina State University. "But currently its predictions are for a supersymmetric cousin of QCD, so it cannot really be quantitative."

Measuring the properties of these extreme forms of matter is a crucial aspect of understanding how our universe has evolved.

Claiming outright discovery of the QGP is difficult, since it is now clear that the constituents of extreme nuclear matter behave much more cooperatively than expected. An upgrade to RHIC will see the collision rate increase ten-fold by 2012, by which time CERN's Large Hadron Collider will be colliding heavy ions at even higher energies, to reach higher temperatures. The story of how ordinary matter transforms under these wild conditions, and therefore how the first instants of the universe unfolded, is far from over. RHIC remains optimally positioned to characterize this transformation in detail.

"The 'perfect liquid' is a very interesting result that came as a surprise to most—perhaps all—theorists on the subject," said Frank Wilczek of the Massachusetts Institute of Technology, who shared the 2004 Nobel Prize for the discovery of asymptotic freedom. "The RHIC results don't in any way undermine the validity of QCD as the theory of the strong interaction, but they challenge us to understand how the theory behaves at high temperatures."



REDUCED DOPAMINE PRODUCTION by neurons in the brain is tied to aS protein clumping

HOPE FOR PARKINSON'S VICTIMS

For the first time, scientists are closing in on the molecular mechanism that causes Parkinson's disease, giving sufferers of that debilitating disease new hope.

The tremors, rigid posture and shuffling gait of Parkinson's disease have been associated for decades with the die-off of dopamine-producing neurons in the brain. These neurons tend to be riddled with suspicious protein clumps. What scientists haven't known, until recently, was how these protein plaques were connected to the disease. Now a team of scientists led by Igor Tsigelny, a project scientist in chemistry and biochemistry at the San Diego Supercomputer Center at the University of California-San Diego (UCSD), has demonstrated the molecular mechanism behind Parkinson's disease for the first time. Their modeling work, performed on supercomputers at Argonne National Laboratory in DuPage County, Illinois, has already yielded a promising treatment for Parkinson's disease. At the same time, it has provided other researchers with tools to aid the study of other disorders associated with abnormally aggregated proteins, including Alzheimer's and prion diseases.

We couldn't have done this without the supercomputers. They gave us the power to track enough molecules over time to see the interactions we were looking for.

The protein clumps in Parkinson's disease consist primarily of a protein called alpha synuclein (aS). Long a prime target for Parkinson's research, aS has resisted conventional protein analysis because it won't stand still. "It doesn't have a stable conformation," Tsigelny said. "Like Alice in Wonderland, it's changing shape all the time." Undaunted, Tsigelny decided to study aS in motion. A computer modeling approach known as molecular dynamics enabled him to track the twists, spins and gyrations of every atom in a solution of aS proteins and solvent molecules. His goal: to catch a close-up look at aS proteins in the act of aggregating.

However, tracking the motions of so many particles is too taxing for today's fastest desktop computers. So Tsigelny requested an allocation of supercomputing time through the U.S. Department of Energy's Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. His proposal was granted 1.2 million hours of processor time on Argonne's Leadership Computing Facility's IBM Blue Gene/P system, which debuted in June as the world's fastest computer dedicated to unclassified research.

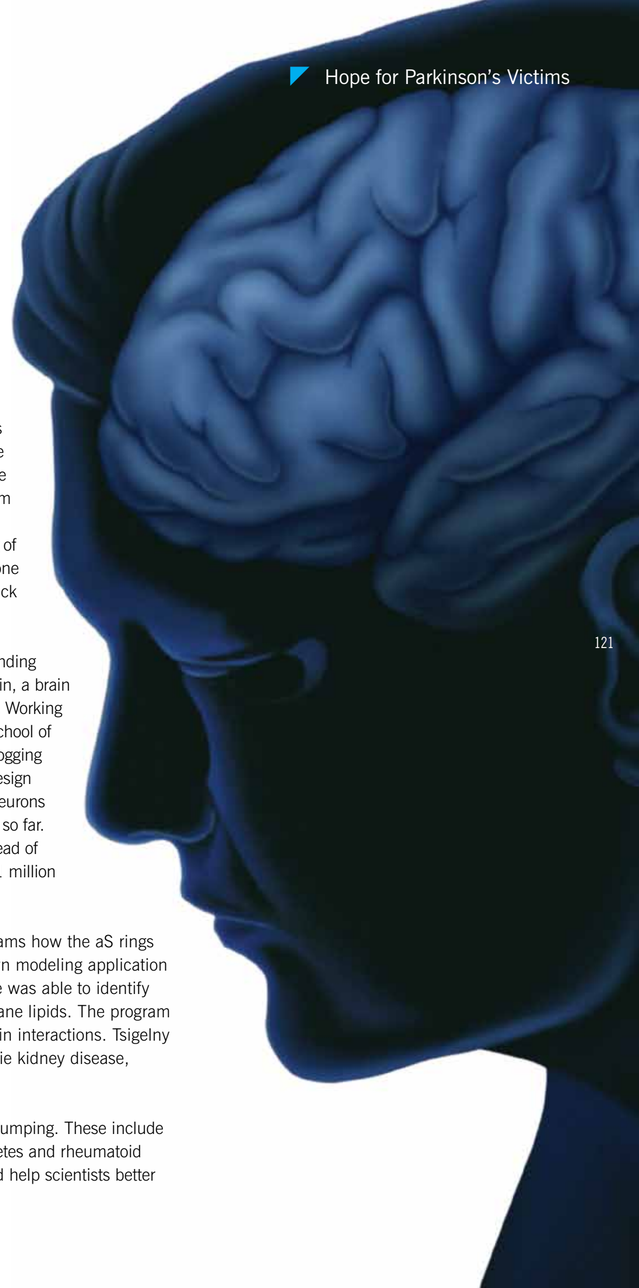
Tsigelny developed a simulation involving some 800,000 atoms. After using 16,000 processor hours in 2006 and 75,000 hours in 2007, Tsigelny observed aS forming ringlike pentamers and identified the protein conformation involved in oligomer formation. His finding bolstered a previous hypothesis suggesting that aS proteins aggregate to form pores that pierce the membranes of otherwise healthy nerve cells. The pores allow a flood of calcium ions to enter the neuron, triggering a cascade that leads to further clumping of aS and other proteins and ultimately results in cell death. "We couldn't have done this without the supercomputers," said Tsigelny. "They gave us the power to track enough molecules over time to see the interactions we were looking for."

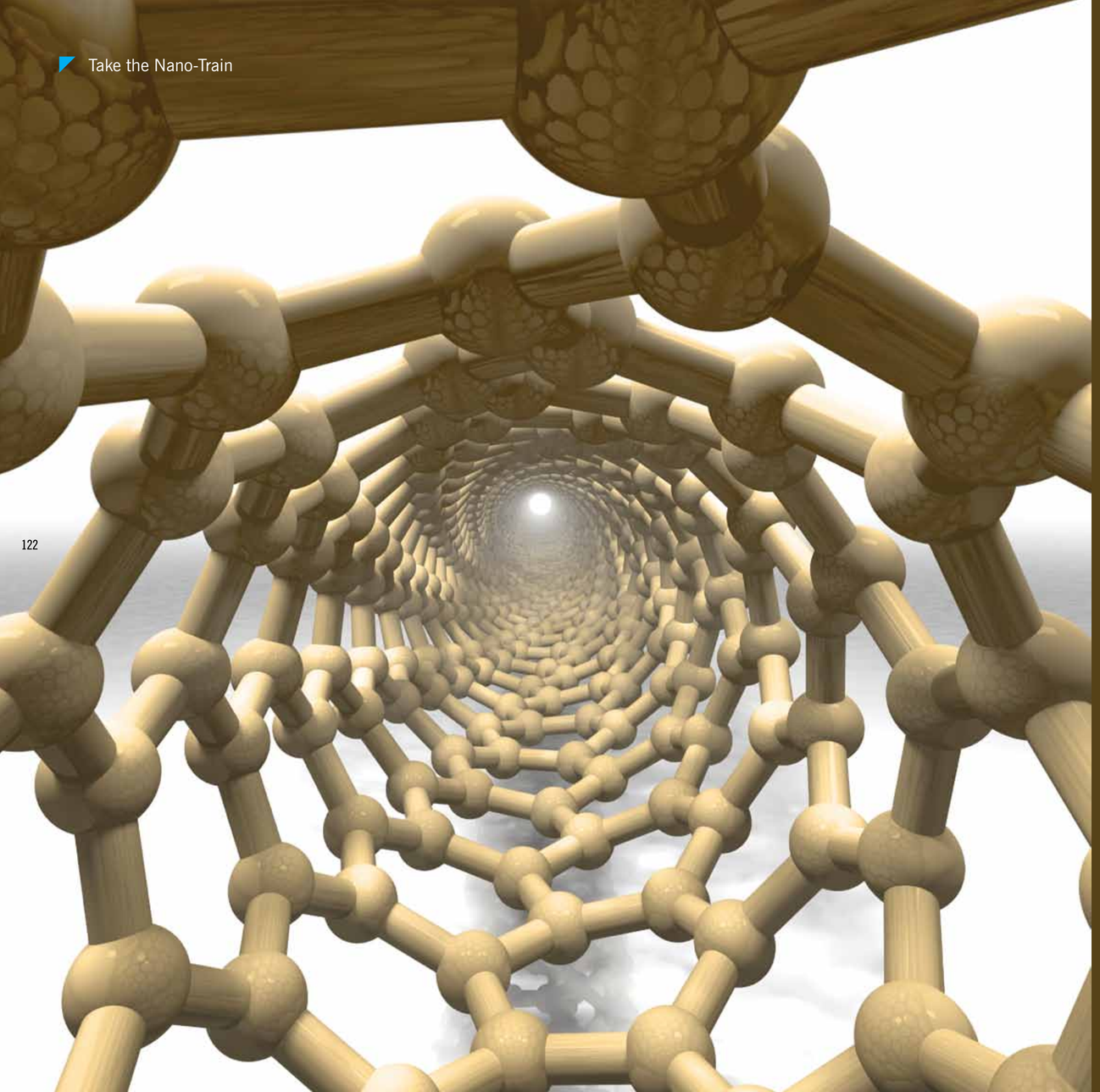
The treatment would offer hope to the more than 1 million people estimated to be living with Parkinson's disease today.

Tsigelny's virtual view of pore formation enabled him to identify the protein-binding sites on aS proteins in exquisite detail. Further studies revealed that beta synuclein, a brain protein very similar to aS, appeared to inhibit aS molecules from linking together. Working with Eliezer Masliah, a professor of Neurosciences and Pathology at the UCSD School of Medicine, Tsigelny has used these findings to develop a compound capable of clogging aS binding sites, halting pore formation. Tsigelny used his computer models to design and test the compound first. Masliah's later laboratory tests on cultured mouse neurons show the compound has a protective effect, and the drug appears to be nontoxic so far. If approved, "it will be the first drug to treat the cause of Parkinson's disease instead of the symptoms," Tsigelny said. The treatment would offer hope to the more than 1 million people estimated to be living with Parkinson's disease today.

But Tsigelny couldn't demonstrate with existing molecular dynamics programs how the aS rings insinuated themselves into nerve cell membranes. Instead, he created his own modeling application called MAPAS (Membrane-Associated Protein Assessments). With MAPAS, he was able to identify which regions of the aS proteins were most likely to interact with cell membrane lipids. The program is now in high demand among other scientists studying membrane and protein interactions. Tsigelny himself is now applying MAPAS in his studies of the mechanisms that underlie kidney disease, cancer and other disorders.

Parkinson's is one of about 16 diseases associated with abnormal protein clumping. These include Alzheimer's, prion diseases (such as spongiform encephalopathy), type 2 diabetes and rheumatoid arthritis. Tsigelny's molecular modeling findings and analysis techniques should help scientists better understand how proteins form plaques and how to block their formation.





TAKE THE NANO-TRAIN

Brookhaven National Laboratory's Center for Functional Nanomaterials is attracting researchers from around the world who like to think small…very small.

A short train ride from downtown New York City can take a researcher to a state-of-the-art facility to examine nanomaterials from beginning to end. Located in the heart of Long Island, the Center for Functional Nanomaterials (CFN) at Brookhaven National Laboratory (Brookhaven) is a user-focused facility, one of five Nanoscale Science Research Centers (NSRCs) in the United States, which provide world-leading expertise and infrastructure for nanotechnology researchers from across the nation and around the globe.

"We are at the interface between basic and applied research," said Emilio Mendez, director of CFN. A researcher can apply to use the centers' facilities for federally funded lab time as long as the results end up in the public domain. Companies that want to conduct proprietary research must pay for access.

Products that contain nanomaterials will grow to a market value of $3.1 trillion by 2015.

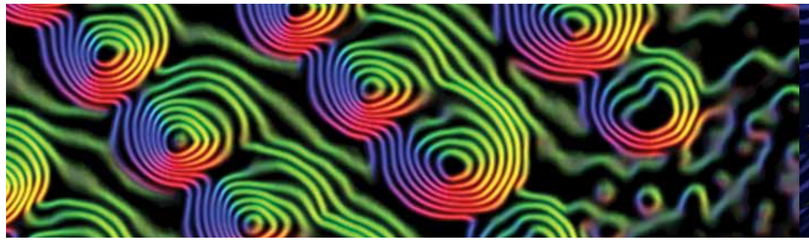
"Anyone with a good idea is welcome to submit a proposal, and we welcome users from industry as well as from academia, government labs and other institutions," said Altaf Carim, NSRCs program manager. "The NSRCs do fundamental research, focusing not on manufacturing per se. Each center has different strengths; each can draw heavily on the strengths of the lab they are located in."

At Brookhaven, CFN researchers conduct their own internal research projects, and spend half their research time in assisting outside users. As with its sister centers across the country, CFN scientists are not just lab technicians there to help outside users' research. They share their expertise with the variety of users who visit the facilities. Conducting experiments at any NSRC is both "a learning experience and a working experience," said Mendez.

"I collaborate as much as I can" with Brookhaven's CFN researchers, said Richard Osgood, a Columbia University professor. He regularly sends his students by train to conduct experiments at CFN. They may stay for a day or more to complete projects with the assistance and tutelage of CFN researchers at Brookhaven.

Osgood's group uses electron beams generated in the CFN clean rooms to "write" on the surface of silicon-based nanomaterials. The beams erase photoresist on silicon wafers, which are then exposed to solvent that etches tiny tracks to serve as nanowire templates. The final products—nanometer-thin, several centimeter–long nanowires—conduct compressed light to carry information. The team's fundamental nonlinear optics research could eventually lead to advanced ideas for solar cells, one of CFN's focus areas.

Take the Nano-Train

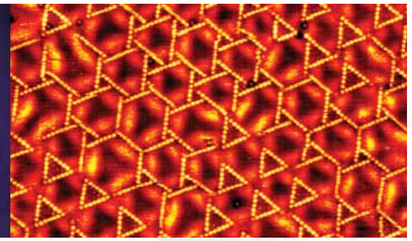


NICKEL NANOPARTICLE FLUX LINES Map showing magnetic flux lines for nickel nanoparticles.

NANOSCIENCE HIGH-PERFORMANCE COMPUTING FACILITY.

X-RAY NANOPROBE BEAMLINE.

NANOCHAIN as seen under an electron microscope.



NANOSCALE ARRANGEMENTS of sulfur atoms on copper.

Columbia University may have its own clean room, but it's not big enough to create the 3- to 4-centimeter–long wires Osgood needs. CFN has high-quality tools that can make centimeter-long segments. These sections still require "stitching" with a 100-keV electron-beam tool, housed at nearby Alcatel-Lucent, to join them together. That joining process creates fault lines in the final material that interfere with the high-intensity light beams the team uses. But CFN is about to buy its own lithography tool that will enable Osgood and his students to create seamless wires in the near future, all in one place.

Each center serves its region well and helps researchers get into nano in a big way.

Each of the five centers has that same "high density" of specialized equipment, Mendez said, which allows researchers to delve into all aspects of nanomaterials, from synthesis to processing to analysis and data crunching. "We have no single piece of equipment that is unique," Mendez explained. "The difference is that the equipment comes with institutional knowledge. For example, CFN is one of the world's leaders in working on analytical transmission electron microscopes," Mendez said.

U.S. Department of Energy (DOE) labs have pursued nanomaterials research for a decade or more, but the focused user facilities for nanoscience are relatively young. CFN, the newest of DOE's nanocenters, opened its doors in March, 2008. The oldest, the Center for Nanophase Materials Sciences at Oak Ridge National Lab (ORNL) in Oak Ridge, Tennessee, was fully operational by the end of 2006. Other centers include those located at Argonne National Laboratory (Argonne) in DuPage County, Illinois, and Lawrence Berkeley National Laboratory (Berkeley Lab) in Berkeley, California, as well as the jointly-operated Center for Integrated Nanotechnologies, with components at Sandia National Laboratories and Los Alamos National Laboratory in Los Alamos, New Mexico. Each DOE nanocenter has its own specialties and technical expertise, and leverages other nearby assets. Such is the case at Argonne's Center for Nanoscale Materials, which makes use of the unique capabilities of the hard X-rays from the Advanced Photon Source to characterize extremely small structures.

It's too soon to say exactly how much these federal user facilities have contributed to research and to the market for nanomaterials, said Michael Holman, a research director at Lux Research. Facilities like those of the NSRCs remain unaffordable for most universities, colleges or small businesses, but accessible through these centers. Holman notes that even larger companies such as IBM are willing to purchase time in the centers' labs, instead of buying and maintaining on their own campuses expensive equipment that might be rarely used.

The benefits will come, though it will take several years to see the impact of the partnerships forged at the five centers, Holman said. One challenge that DOE faces at these nanoscience user centers is how to take basic research and incorporate it into applications. Private companies seemed initially worried about divulging their proprietary work in a publicly funded space, Holman said. They voiced concerns over compromising their legal patents and possibly alerting competitors to their research directions. But DOE has adapted to a dual model, allowing companies to pay to access the facilities without "showing their hands" to the market. Products that contain nanomaterials, such as protective paint coatings or active pharmaceuticals, will grow to a market value of $3.1 trillion by 2015, according to Lux Research. Holman added that DOE user centers enable small startups to stay in the game, while also encouraging basic research that could lead to new discoveries.

One current example of fundamental research with a potential payoff is CFN's inquiry into plastic materials for photovoltaics (PV). CFN researchers are trying to figure out what limits plastic PV's efficiency. Though much cheaper than silicon PV, polymer PV is only 5 percent efficient at converting sunlight to energy, compared to silicon's 15 to 20 percent efficiency, Mendez said. At Berkeley Lab's Molecular Foundry, the center's researchers build new nanomolecules as part of basic research. The center shares its new molecules with outside users for further research and, perhaps, for product development.

The lure of specialized infrastructure and knowledge housed at the sister centers is "worth going cross-country" to use, said Osgood, from the computing expertise at Berkeley Lab's Molecular Foundry to experience with ferroelectric nanomaterials at ORNL's Center for Nanophase Materials Sciences.

Still, Osgood emphasizes, "Having the access to advanced fabrication tools in the New York metropolitan area is extremely important" to fostering materials research in the region, whether academic or industrial. Each center serves its own region well and helps researchers "get into nano in a big way."

ZOOMING IN ON ATOMIC STRUCTURE WITH NEUTRONS

Neutrons not only reveal the nanostructure of ordinary materials, they can also reveal secrets about the early universe.

Neutrons make up matter. They also make excellent detectives. The uncharged subatomic particle is an ideal probe for spying on the inner workings of materials at the most minute level, allowing scientists a window into the atomic structure and composition of matter. Essentially, neutrons reveal the nanostructure of biomolecules for the discovery of new drugs, magnetic materials for better computer memories, credit cards—even clothing. They can even reveal secrets about the origin of the universe.

In 1946, physicist Clifford Shull pioneered a technique called neutron scattering. A beam of neutrons fired at a target material scatters as the neutrons bounce off atoms in that material. Based on the change in their direction, Shull discovered he could model the positions of atoms in the target material in a very similar fashion as William Henry Bragg and William Lawrence Bragg did earlier for X-ray scattering. Knowing where atoms are and how they interact with one another is critical to understanding the properties of electronics, molecules used in drugs and even window glass. It's also critical to making materials more efficient.

Ever-more powerful neutron sources give researchers detailed snapshots of the inner workings of physical and biological materials.

Shull, a 1994 Nobel Prize winner in physics for this work, recognized early on that neutron scattering would be invaluable to researchers in a variety of scientific disciplines. It provides information not easily discovered using other techniques such as electron microscopy or X-ray diffraction.

Once Shull announced this work, performed at Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tennessee, the United States immediately built more neutron sources to study materials. But time passed, and the facilities were not updated. Meanwhile, the Europeans and the Japanese began to construct and maintain newer neutron scattering facilities. In the past 15 to 20 years, these facilities surpassed those built at U.S. National Laboratories ORNL, Brookhaven National Laboratory in Upton, New York and Argonne National Laboratory in DuPage County, Illinois.

Meanwhile, a growing world neutron science community began to recognize the need for both continuous reactor-based neutron sources and pulsed accelerator-based sources. Pulsed neutron sources produce short, intense-pulse neutron beams that enable scientists to study a wide range of scientific problems and perform real-time analysis of the scattered neutrons. The use of accelerator based pulsed neutron sources was pioneered at Argonne and the first of such sources was built using an old accelerator (Intense Neutron Pulse Source).

In the late 1980s, U.K. neutron scientists made significant advances in accelerator-based technology, and by the 1990s, the U.S. Department of Energy (DOE) was itching to reclaim the United States' prowess as a leader in the field. Consequently, DOE committed to building its own Spallation Neutron Source (SNS) in partnership with six National Laboratories. Ground was broken in 1999 for a

that was to produce neutron beams in very intense pulses, with a performance 50 to 100 times better than the best sources. By 2006, the $1.4 billion complex opened at ORNL and quickly became the world's most powerful accelerator-based, pulsed neutron source.

SNS, still ramping up to full capacity, already attracts researchers from a variety of scientific disciplines and countries. SNS aims to "provide research opportunities unavailable anywhere else in the world," said Ian Anderson, SNS director. If funding holds, the facility should host at least 25 instruments.

Although the spallation process involves smashing protons, or positively charged subatomic particles, into a neutron-rich target to deliver neutrons, the process at SNS begins with negatively charged hydrogen ions consisting of a proton orbited by two electrons. Scientists send the ions into a linear accelerator, pulling them along so that they reach very high energies up to 90 percent of the speed of light. The ions then pass through a foil that strips off each ion's two electrons, turning the particle into a proton. The protons pass into a ring where they accumulate in bunches. Each bunch is then released from the ring as a pulse.

SNS currently operates at 670 kilowatts, which is the power of the proton beam that pulses and then slams into a container of liquid mercury, splaying trillions of neutrons at each go. Then the neutrons are slowed to different energies and sent down different beam lines to instruments that house materials scientists want to study on an atomic scale, just as Shull did with his early nuclear reactor neutron source.

People often think that neutron scattering is complex and leads to basic science irrelevant to their lives. "But that's not true," Anderson responded. Neutrons contribute fundamentally to improving medicines and drug delivery and to understanding defects in aircraft wings, engines, turbine blades and even electronics' efficiency. Neutron scattering plays a role in meeting today's high demand for less expensive, stronger and lighter new materials that perform well under severe conditions, as well as designer drugs and genetic engineering, which are revolutionizing medicine and health care. SNS probes biomolecules to design drugs to more accurately target the specific cells they aim to kill or switch off. Commercial and military aircraft and space probes demand lighter metal structures and stronger welds for increased speed and fuel efficiency. Automobiles require more plastics, materials that can withstand higher temperatures and lightweight components to be more fuel efficient and emit less pollution. Electronic devices like cell phones and computers require smaller and faster components and ever-increasing storage capacity through development of advanced magnetic materials.

Even more powerful neutron sources give researchers more detailed snapshots of the inner-workings of physical and biological materials so they can begin to restructure materials at the atomic level to meet societal needs. At SNS, the first instrument to receive neutrons was BASIS, a backscattering spectrometer that shines neutrons onto a material. From the way the neutrons are scattered, scientists can learn about a material's composition and the distance between atoms. This is a "great clue" as to

OAK RIDGE NATIONAL LABORATORY SNS ring

what is going on at the subatomic level in materials, said Ken Herwig, an instrument specialist working with BASIS. Neutrons sent down the 84-meter beam line to the instrument also can probe how subatomic structures are moving inside a material. BASIS, for example, can measure the tiniest energy changes in a neutron—a change as small as 1/100 degree Fahrenheit.

One way to think about it is to picture the atoms and neutrons as billiard balls. "The atoms are moving on one end of the billiard table and the neutrons are directed toward them along a defined direction and at a determined speed," Herwig said. "When the neutron billiard ball collides with the atomic billiard balls, it may change direction and speed. If I can measure the change of this direction and speed, I learn something about how the atom billiard balls are moving."

By knowing how atoms move, scientists can determine a lot about the invisible interactions between the particles, which they then can use to make predictions about how the macromaterial with which they are working will respond to certain stresses or how it will react in the human body. "The science that BASIS addresses is wide ranging, with the basic information researchers gather about the materials' atomic world leading to more efficient energy usage, stronger materials and improved medications," Herwig said.

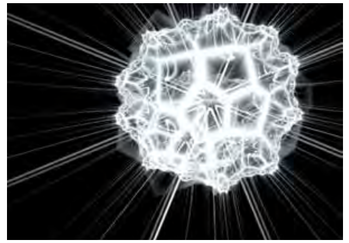
At SNS, one instrument does not look at materials, but studies neutrons themselves, reported Geoffrey Greene, University of Tennessee physicist who heads the Fundamental Neutron Physics Beam Line (FNPB) team. This instrument is the only of its kind at the neutron source. "[With it,] we'll look at the internal structure of the neutron and how ones not paired to protons—free ones—decay," he said.

Neutrons are stable in most nuclei, he explained, but when knocked from a nucleus in an SNS neutron beam, the subatomic particles live for only about 15 minutes. Neutrons have no electric charge but may still show a balance between internal positive and negative charges, deemed a "neutron electric dipole moment," Greene said.

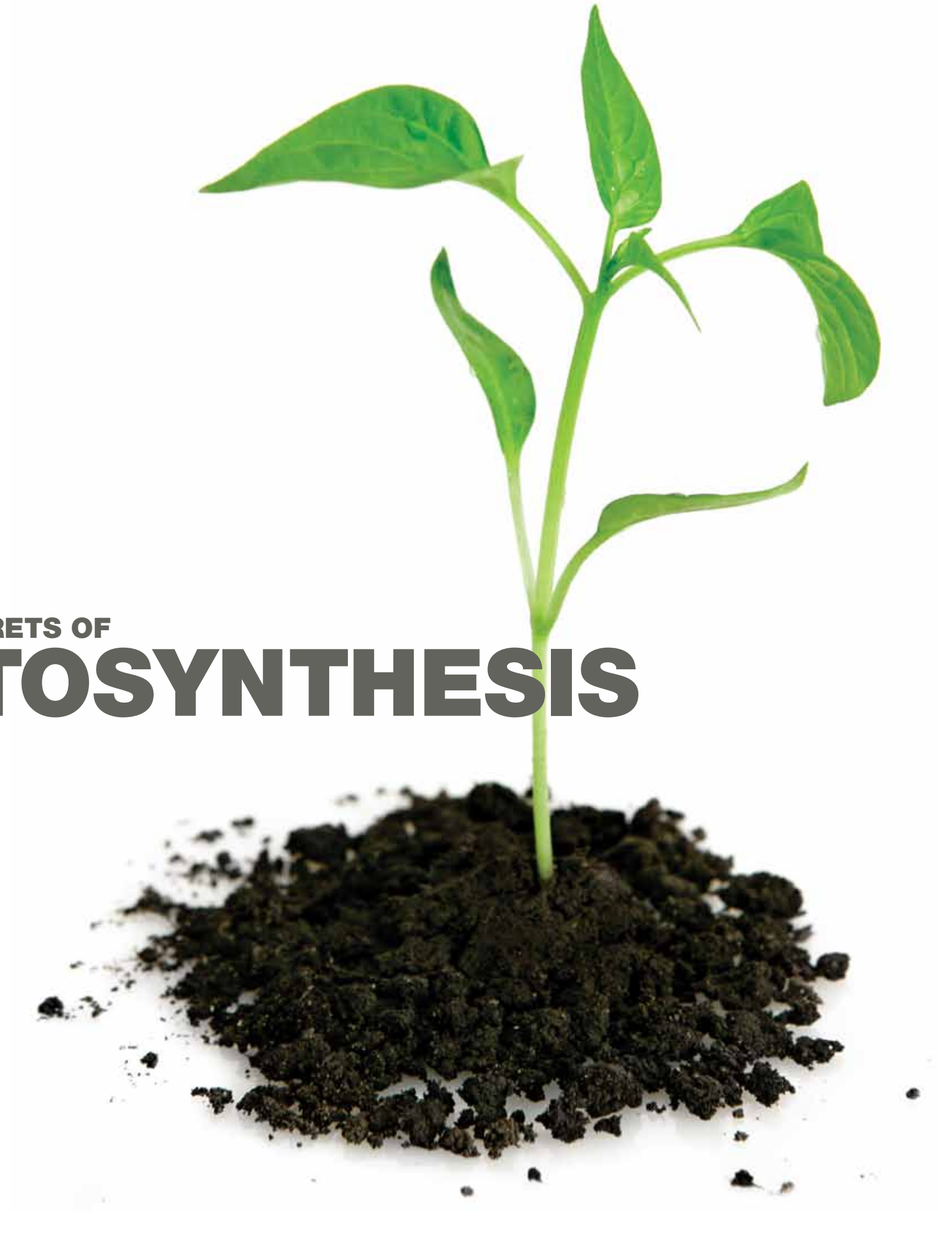
By knowing how atoms move, scientists can determine a lot about the invisible interactions between the particles.

Studying unbound neutrons and precisely measuring their lifetime will give physicists and astronomers clues about the beginnings of the universe. The research specifically hints at the abundance of each of the early chemical elements generated in the first few minutes of the big bang and sheds light on the amount of normal matter—as opposed to antimatter, dark matter and dark energy—in the cosmos, Greene said.

BASIS and the FNPB are among 10 instruments that are already running at SNS. The SNS instrument scientists are "working every day to bring more online soon," Anderson said. Ideally the facility could host 25 instruments and shoot protons at the mercury target with a beam power of 3 to 4 million watts, which, he noted, would match any up-and-coming neutron facility for decades to come.



ARTIST'S RENDITION of subatomic structure



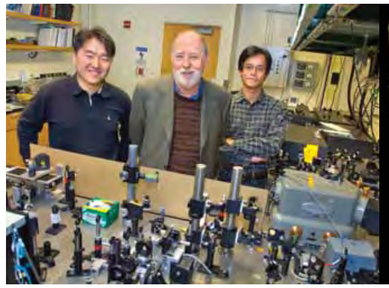
QUANTUM SECRETS OF PHOTOSYNTHESIS REVEALED

At the quantum level, plants are no longer plants. They are physics laboratories.

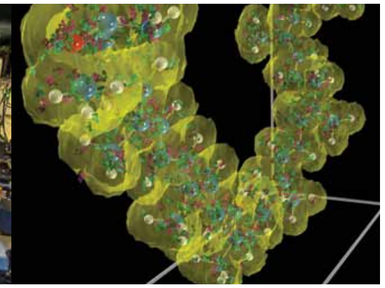
An artificial version of photosynthesis, the process by which green plants convert solar energy into electrochemical energy, would provide humanity with a clean and renewable source of electrical power. An artificial version of photosynthesis also would help scrub the atmosphere of excessive carbon dioxide that results from the burning of fossil fuels.

The key to photosynthesis efficiency is speed—energy transfer takes place almost instantaneously, so little energy is lost as heat.

To reach this promised land, however, scientists need a far better understanding of how nature is able to transfer nearly 100 percent of the photons absorbed by the leaves of green plants to reaction centers for conversion into electrochemical energy. It has long been recognized that the key to this remarkable efficiency is speed—the transfer of the solar energy takes place almost instantaneously, so little energy is wasted as heat. But how this near-instantaneous energy transfer is accomplished had been a long-standing mystery, before a research effort led by Graham Fleming, a physical chemist with the Lawrence Berkeley National Laboratory (Berkeley Lab), in Berkeley, California.



GRAHAM FLEMING (center) is Deputy Director of Berkeley Lab, the Melvin Calvin Distinguished Professor of Chemistry at UC Berkeley, and a co-director of the California Institute for Quantitative Biomedical Research (QB3). He is also a leading authority on spectroscopic studies of photosynthesis. (Photo by Roy Kaltschmidt, Berkeley Lab Creative Services Office.)



SUNLIGHT absorbed by bacteriochlorophyll (green) within the FMO protein (gray) generates a wavelike motion of excitation energy whose quantum mechanical properties can be mapped through the use of two-dimensional electronic spectroscopy. (Image courtesy of Greg Engel, Berkeley, Physical Biosciences Division).

With the development of a laser-based technique the team developed, called two-dimensional electronic spectroscopy, Fleming and his group have been able to track the flow of light-induced excitation energy through photosynthetic molecular complexes with femtosecond resolution. In the time it takes to pronounce the word femtosecond, a quadrillion femtoseconds have passed. They discovered that the secret behind the efficiency of photosynthetic energy transfer is quantum mechanics.

Prior to the discovery by Fleming and his group, photosynthetic energy transfer was described as a classical physical chemistry process in which light-induced excitation energy hops from light-capturing pigment molecules to reaction center molecules step-by-step down the molecular energy ladder. Fleming characterized this classical hopping description as both inadequate and inaccurate.

"We obtained the first direct evidence that remarkably long-lived wavelike electronic quantum coherence plays an important part in energy transfer processes during photosynthesis," he said. "This wavelike characteristic explains the extreme efficiency of the energy transfer because it enables the system to simultaneously sample all the potential energy pathways and choose the most efficient one."

The team reported that instead of excitation occupying one energy state at a time, the photosynthetic system performs a single quantum computation, sensing multiple different states all at once, selecting the correct answer and sending excitation energy back and forth throughout the system without penalty for reversing direction.

In 1932, French physicist Francis Perrin first proposed the possibility that quantum oscillations played a part in the transfer of energy. But as Gregory Engel, a former member of Fleming's group and lead author on a paper published in the journal *Nature* that first reported this work in 2007, explained, "The wavelike motion of excitation energy had never been observed until our study."

Light excites electrons in pigment molecules called chromophores—for plants, the main chromophore is chlorophyll. After moving through the chromophores the energy is trapped in a reaction center where it is used to produce carbohydrates.

"In natural light–harvesting systems, chlorophyll pigments are arranged together in an 'antenna,' sometimes with elegant symmetry and sometimes with apparent randomness, but always with a precise structure that is supplied by a protein scaffold," wrote chemist Roseanne J. Sension of the University of Michigan in a commentary for *Nature* about the paper by Fleming and his group.

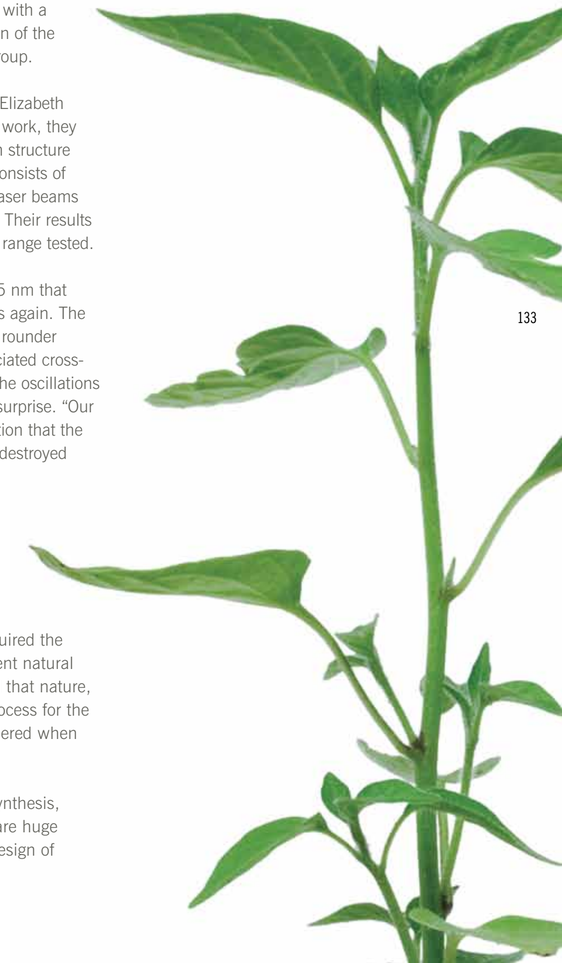
In addition to Fleming and Engel, the original discovery team included Tessa Calhoun, Elizabeth Read, Tae-Kyu Ahn, Tomáš Mančal, Yuan-Chung Cheng and Robert Blankenship. For this work, they targeted the Fenna-Matthews-Olson (FMO) antenna complex, a bacteriochlorophyll protein structure that is considered a model system for studying photosynthetic energy transfer because it consists of only seven pigment molecules and its chemistry has been well characterized. They used laser beams to flash on the antenna and record the effect in 2-D spectra at a temperature of 77 kelvin. Their results showed quantum beating signals that lasted as long as 660 femtoseconds, the maximum range tested.

This "long-lived" electronic quantum coherence came with a peak in the spectra at 825 nm that "clearly oscillates," the team reported. "Its amplitude grows, fades and subsequently grows again. The peak's shape evolves with these oscillations, becoming more elongated when weaker and rounder when the signal amplitude intensifies. The associated cross-peak amplitude also appears to oscillate." That the oscillations lasted as long as 660 femtoseconds came as a surprise. "Our observation contrasted with the general assumption that the coherences responsible for such oscillations are destroyed very rapidly," Engel explained.

We may find that nature has settled on an inherently quantum-mechanical process for the critical mechanism of efficient light harvesting.

In her commentary, Sension said, "The data also suggest that the protein scaffold might itself be structured to dampen fluctuations that would induce decoherence of the electronic excitation." She called the observation of electronic coherences in such a complex system "remarkable," despite the low temperature conditions under which the team acquired the data. "Assuming that the effect is general—that similar coherences occur in many different natural light–harvesting systems, and are observed at noncryogenic temperatures—we may find that nature, through its evolutionary algorithm, has settled on an inherently quantum-mechanical process for the critical mechanism of efficient light harvesting. This is an interesting lesson to be considered when designing artificial systems for this purpose."

In commenting about the impact of this work on the development of artificial photosynthesis, Engel said, "Nature has had about 2.7 billion years to perfect photosynthesis, so there are huge lessons that remain for us to learn. Our results provided a new way to think about the design of future artificial photosynthesis systems."



FERMILAB EXPERIMENTS DECODE MYSTERIES OF THE UNIVERSE

Redefining our knowledge of the nature of the universe is job one at Fermilab.

Much of what we know about the physical laws that govern the universe we owe to the past four decades of discoveries at Fermilab, the U.S. Department of Energy's (DOE) Fermi National Accelerator Laboratory, located near Chicago, Illinois. Established in 1967, the facility quickly assumed prominence in the field of high-energy particle physics. The discovery of both the bottom quark (1977) and its counterpart, the top quark (1995), were made here. Today, Fermilab is best known for science at the Tevatron, the world's highest-energy particle collider.

Some 1,900 Fermilab employees, including about 900 physicists, engineers and computer professionals, and another 2,300 scientists and students from across the country and around the world conduct research at Fermilab's Tevatron Collider. Much of their work centers on the DZero and Collider Detector at Fermilab (CDF) experiments.

To chronicle their progress, the lab's daily e-mail newsletter, *Fermilab Today*, publishes each Thursday a new "Result of the Week" from the collider detectors. That weekly report, which has been published since September 18, 2003, links the record-breaking performance of the Tevatron particle accelerator to the extraordinary results of the DZero and CDF experiments. Among the topics covered are leptoquarks, pomerons, tau leptons, top quarks, single top quarks, mesons by the dozens, matter-matter asymmetry, W bosons, Z bosons, charm quarks, strange quarks, bottom quarks, electrons, the strong force, the weak force and multiple searches (including those for supersymmetry), dark matter, extra dimensions and the Higgs boson. Taken together, these precision results redefine our knowledge of nature.

The Fermilab collider program is running at full speed.

"The Fermilab collider program is running at full speed," said Dennis Kovar, associate director of the DOE's Office of Science for High-Energy Physics. "In the past year alone, the two experiments have produced 77 Ph.D.s and 100 publications that advance the state of our knowledge across the span of particle physics at the energy frontier."

The DZero experiment is an international collaboration of about 600 physicists from 90 institutions in 18 countries. DZero scientists conduct research on the fundamental nature of matter as revealed by the high-energy interactions of protons and antiprotons—an intense search for subatomic clues that reveal the character of the building blocks of the universe.

One discovery announced in September, 2008, is a new particle comprising three quarks, the Omega-sub-b (Ωb). The discovery of this doubly strange particle brings scientists a step closer to understanding exactly how quarks form matter and to completing the "periodic table of baryons." Baryons are particles that contain three quarks, the basic building blocks of matter. "The observation of the doubly strange b baryon is yet another triumph of the quark model," said Dmitri Denisov, DZero cospokesperson at Fermilab. "Our measurement of its mass, production and decay properties will help to better understand the strong force that binds quarks together."

The CDF experimental collaboration, which involves 700 physicists from 61 institutions and 13 countries, is also committed to studying particle collisions at the world's highest-energy particle accelerator. Their goal is to discover the identity and properties of the particles that make up the universe and to understand the forces and interactions among those particles.

You have to sweat every detail of the analysis.

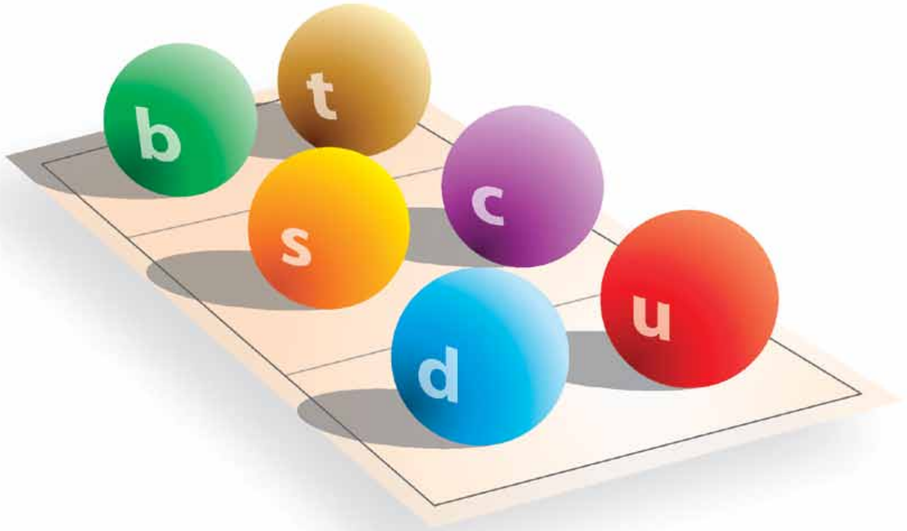
In August, both collaborations reported that for the first time ever, they were able to exclude, with 95 percent probability, a mass for the long-sought Higgs boson of 170 GeV. Their results came from combining Tevatron data from the two experiments to advance the quest for the Higgs boson. This result not only restricts the possible masses where the Higgs boson might lie, but also demonstrates that the Tevatron experiments are sensitive to potential Higgs boson signals.

In April, 2007, the scientists presented results from rare particle processes never observed before and new constraints on the mass of the Higgs boson, which in principle make the observation of this elusive particle at the Fermilab Tevatron collider more likely. And earlier that year, CDF collaboration scientists announced results of the world's most precise measurement made up until then by a single experiment of the mass of the W boson, the carrier of the weak nuclear force and a key parameter of the Standard Model of particles and forces. Prior to this, ALEPH, an experiment at CERN (the European Center for Nuclear Research), held the record for the most precise W mass measurement.

Having gained a much better understanding of their detector and the processes it records, CDF scientists are optimistic that they can soon further improve the precision of their W-mass result. "You have to sweat every detail of the analysis," said Fermilab physicist and cospokesperson Robert Roser. "Our scientists cannot take anything for granted in an environment in which composite particles such as protons and antiprotons collide. We need to understand the many different subatomic processes and take into account the capabilities of our detector for identifying the various particles."

THE COCKCROFT-WALTON preaccelerator, where protons begin their journey to the world's highest energies in the Tevatron.

TEVATRON OPERATING CENTER where the world's highest-energy particle collider is monitored and operated.



STRANGE QUARKS

COULD REVEAL MYSTERIES OF THE UNIVERSE

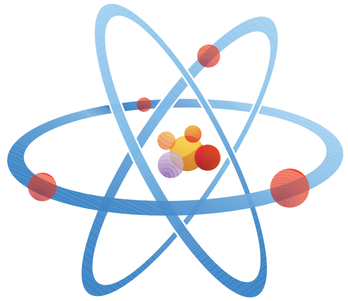
To understand the nature of stars and galaxies, scientists must delve into the subparticle universe in search of strange quarks.

Ever since the Greek philosopher Democritus proposed that matter could be cut into smaller and smaller pieces until a piece was so tiny it could no longer be split, scientists have been exploring the nature of matter. For years, scientists believed the atom was the smallest form of matter, until 1897 when J.J. Thompson discovered the electron, one of the building blocks of the atom.

It's been an open question over the last 20 years whether or not these sea quarks have a significant effect on the nucleon's properties.

Since then, scientists have learned that most matter on Earth is built of protons, neutrons and electrons, and that protons and neutrons (known collectively as nucleons) account for more than 98 percent of the visible universe. Scientists also have learned that protons and neutrons are made up of even smaller particles, called quarks and gluons. Through experimentation, scientists have determined that six "flavors" of quarks (up, down, strange, charm, top and bottom) exist. They also have determined that quarks are bound together by a fundamental force of nature known as the strong force.

Today, nuclear physicists at Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Virginia, are studying the structure of protons and neutrons to learn how the universe is made. The research, which uses the lab's unique electron accelerator to probe inside protons and neutrons, is important because it can lead to an understanding of how protons and neutrons merge to form the nucleus of the atom and what forces bind protons and neutrons together. Such research can lead to new fundamental discoveries and the development of technologies useful to other fields such as biology and material science.



One method researchers are using to study ordinary matter is by studying the building blocks of protons and neutrons. Protons and neutrons are both made of up- and down-flavored quarks held together by gluons. They also contain a seething "quark-gluon sea" of particles that are constantly popping into and out of existence. Scientists wondered how much, if any, these very-short-lived particles in the quark-gluon sea contribute to the properties of protons and neutrons. The easiest of the quarks to study is the strange quark.

So far, two different approaches to studying the strange quark conducted by two separate collaborative groups have resulted in groundbreaking discoveries. A multiyear, multimillion-dollar experiment at Jefferson Lab conducted by nuclear physicists in the G-Zero collaboration reported in 2005 that strange quarks do indeed contribute to the proton's properties. Specifically, this group of 108 international physicists from 19 institutions found that strange quarks help determine a proton's charge distribution and its magnetization.

HALL A PROTON PARITY EXPERIMENT and HAPPEx

MAGNET

HALL A BEAM DUMP

To make this discovery, the scientists probed the proton with spinning electrons from Jefferson Lab's accelerator. They flipped the electrons' spin from one direction to another and measured the minute differences in the proton's response. "Normally, you'd think those measurements would be exactly the same, but there's a small contribution that violates that mirror image principle called the weak interaction," explained Doug Beck, G-Zero collaboration spokesman and professor of physics, University of Illinois, Urbana-Champaign.

It turns out that electrons can interact with strange quarks inside the proton via the electromagnetic force or the weak force. Alternating the spin of the electrons from the accelerator during the experiment allowed the scientists to separate electromagnetic force interactions from weak force interactions. "If we look via the electromagnetic interaction, we see quarks inside the proton," said Beck. "If we do it with the weak interaction, we see a very similar, yet distinctly different view of the quarks." By comparing these views, the researchers were able to measure the strange quark contribution. "One of the unique things this experiment gives us is a measurement over a broad range," Beck explained.

Research by the Hall A Proton Parity Experiment (HAPPEx) collaboration also studied strange quarks in the proton. But rather than measuring a range of distance scales, or resolutions, at which the strange quarks may contribute to the proton's properties, the group looked at one distance scale very precisely. Consequently, the HAPPEx collaboration reported in 2006 that strange quark contributions to the proton's charge distribution and magnetic field at this one scale are so small that it may be zero.

"It's been an open question over the last 20 years whether or not these sea quarks have a significant effect on the nucleon's properties, such as the mass, the spin and the charge and

HALL A ACCELERATOR

APPLIED RESEARCH CENTER

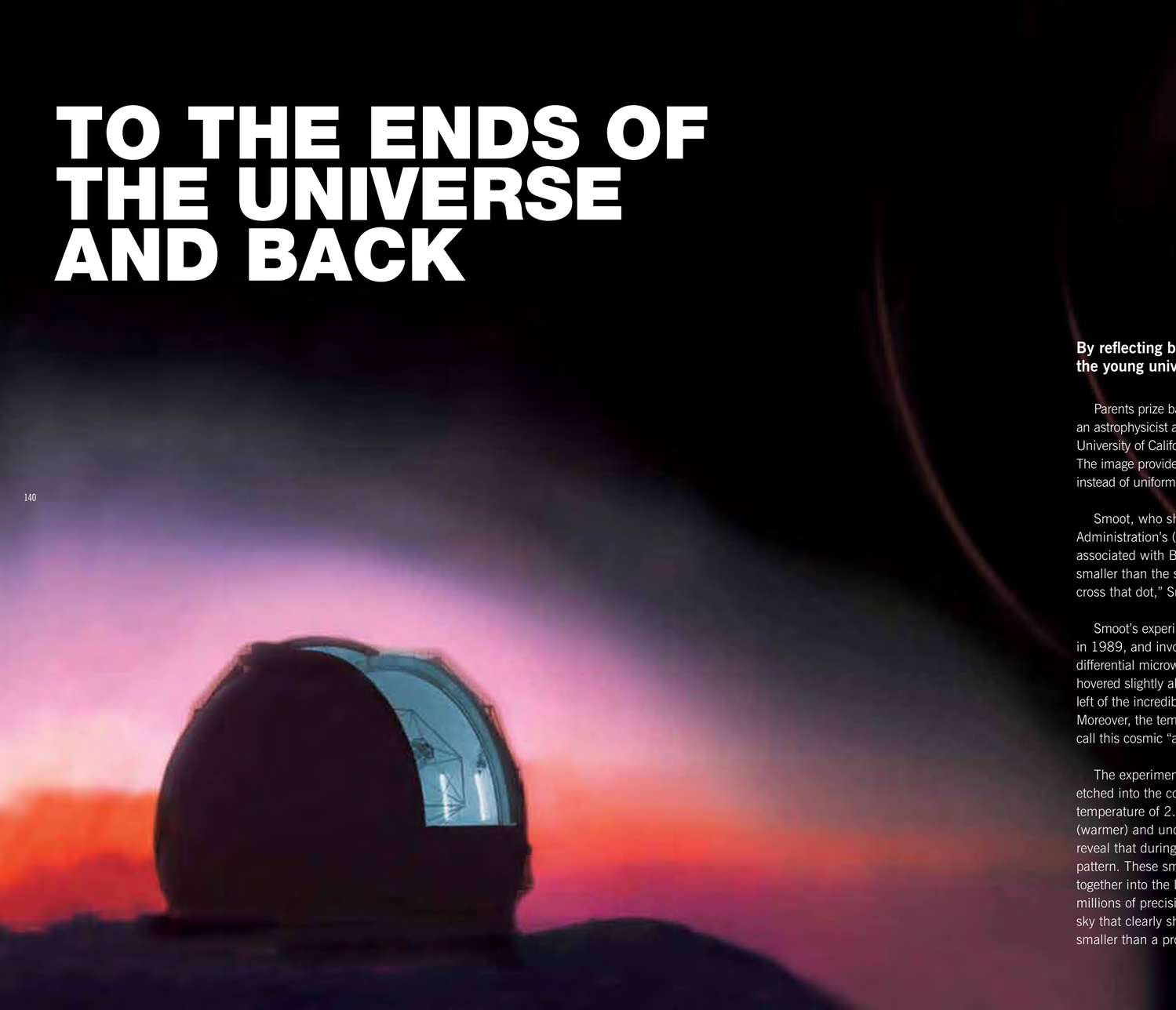
Nuclear physicists are studying the structure of protons and neutrons in an effort to learn how the universe is made.

magnetic moment distribution," said Krishna Kumar, HAPPEx collaboration spokesman and professor at the Department of Physics at the University of Massachusetts, Amherst. "The result will have a profound impact on our qualitative picture of the nucleon." Kumar said the results from both experiments are giving theorists better information to build and improve theoretical models of the unseen, though ubiquitous interactions at the heart of matter. "It would also provide a way to distinguish between theoretical models of the nucleon such as the Constituent Quark Model and the fundamental quantum theory of the strong force: Quantum Chromodynamics (QCD)."

Strange quarks present a uniquely identifiable contribution to the properties of the nucleon. Both experiments agree with recent results from lattice QCD calculations, supercomputer simulations of the theory of Quantum Chromodynamics. This and other research concerning quarks, gluons, protons and neutrons will help scientists gain a better understanding of the building blocks and forces that shape our visible universe.

These experiments were primarily financed by the U.S. Department of Energy's Office of Science, with assistance from the National Science Foundation. Other organizations contributing to this international effort include the Centre National de la Recherche Scientifique (CNRS) and the Commissariat à l'Énergie Atomique (CEA) in France, the Natural Sciences and Engineering Research Council (NSERC) in Canada and the Istituto Nazionale di Fisica Nucleare (INFN) in Italy.

TO THE ENDS OF THE UNIVERSE AND BACK



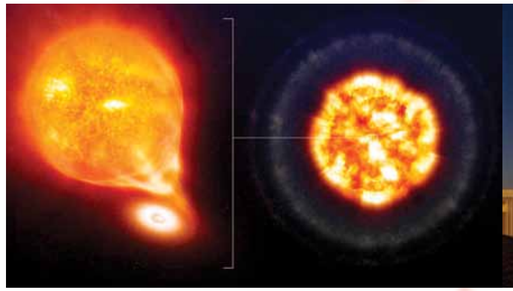
By reflecting back to the Big Bang, astronomers have a better understanding how the young universe evolved to the one we see today.

Parents prize baby photos, but only one baby photo has won a Nobel Prize. In 2006 George F. Smoot, an astrophysicist at Lawrence Berkeley National Laboratory (Berkeley Lab) in Berkeley, California and the University of California-Berkeley, won the Nobel Prize in Physics for capturing the infant universe on film. The image provided bulletproof evidence of the "Big Bang" theory and explained why the cosmos is lumpy instead of uniform, with matter clumping into stars, galaxies and galaxy clusters.

Smoot, who shared the prize with John C. Mather of the U.S. National Aeronautics and Space Administration's (NASA) Goddard Space Flight Center, became the 11th Nobel Prize winner associated with Berkeley. "At the time captured in our images, the current observable universe was smaller than the smallest dot on your TV screen, and less time had passed than it takes for light to cross that dot," Smoot said in a 2006 Berkeley press release.

Smoot's experiment flew on the Cosmic Background Explorer (COBE), a NASA probe launched in 1989, and involved an instrument called the Microwave Anisotropy Experiment, composed of differential microwave radiometers. The instrument essentially took the universe's temperature, which hovered slightly above absolute zero—2.72 kelvin, to be more precise. This remnant heat is all that is left of the incredible temperatures generated at the moment of the Big Bang some 14 billion years ago. Moreover, the temperature is uniform across the sky to better than one part in 100,000. Astronomers call this cosmic "afterglow," the cosmic microwave background (CMB).

The experiment also found that the CMB's temperature distribution isn't quite perfect. Regions etched into the cosmic microwave background fluctuate slightly above and below the median temperature of 2.72 kelvin. These hill-and-valley temperature ranges represent a "froth" of overdense (warmer) and underdense (cooler) regions of matter. As Smoot showed, these density fluctuations reveal that during the Big Bang, quantum forces flung particles outward in a not-quite-uniform pattern. These small irregularities provided the seeds for gravity to do its work and draw matter together into the large-scale structures of the universe seen today. After analyzing hundreds of millions of precision measurements from COBE, Smoot and his team produced maps of the entire sky that clearly showed the distribution of "hot" and "cold" spots, produced when the universe was smaller than a proton.

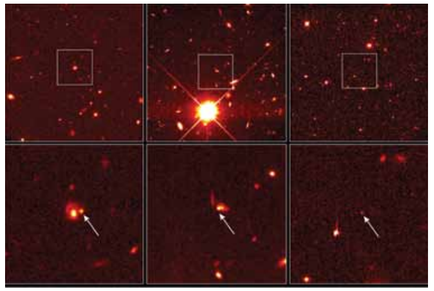


A TYPE 1A SUPERNOVAE before and after the explosion.

THE DOMES of the two telescopes of the W.M. Keck Observatory in Hawaii.

SUPERNOVA COSMOLOGY TEAM Members of the Supernova Cosmology project in 2007. From left, front: David Rubin, Saul Perlmutter, Josh Meyers, Hannah Swift; standing: Tony Spadafora, Kyle Dawson, Rahman Amanullah, Nao Suzuki and Kyle Barbary.

DARK ENERGY Saul Perlmutter of Berkeley Lab led the team examining Type 1a supernova as standard candles—objects whose distance can be inferred from their apparent brightness—to investigate the history and fate of the universe.



REDSHIFT Supernovae research has been used to measure the expansion rate of the universe.

Theorists had been predicting the existence of the cosmic microwave background since the Big Bang theory was first proposed in the 1940s. It was finally detected, accidentally, in 1965. Not until Smoot and his team announced their discovery in 1992, however, could the temperature variations of the CMB be precisely pinned down. Cosmologists hailed the finding as the strongest evidence yet that the Big Bang theory is correct.

"The tiny temperature variations we discovered are the imprints of tiny ripples in the fabric of space-time put there by the primeval explosion process," Smoot explained. "Over billions of years, the smaller of these ripples have grown into galaxies, clusters of galaxies and the great voids in space."

Smoot was one of the first astrophysicists to devise methods for conducting experiments that produce data and information about the early universe. As such, he helped move cosmology from a purely theoretical science into the realm of hard data.

The universe was not decelerating—as it should if gravity was doing its job of preventing the cosmos from flying apart—rather, it was *accelerating.*

Adding a twist to the CMB story, in 1998 astronomers with the Supernova Cosmology Project (SCP), also led by a physicist at Berkeley, Saul Perlmutter, announced that, contrary to what had been assumed for years, the universe is not decelerating as would be expected if gravity was doing its job of preventing the cosmos from flying apart. Rather, it was *accelerating*.

Perlmutter, who still heads the SCP, and his colleagues used brightness measurements of dozens of exploding stars (called Type 1a supernovae) to determine their distances. This indicated how rapidly the universe is slowing down. The idea was that in a decelerating universe, observers would see the cosmos expanding at an increasingly slower rate over time. Hence, in a flagging universe, the peak

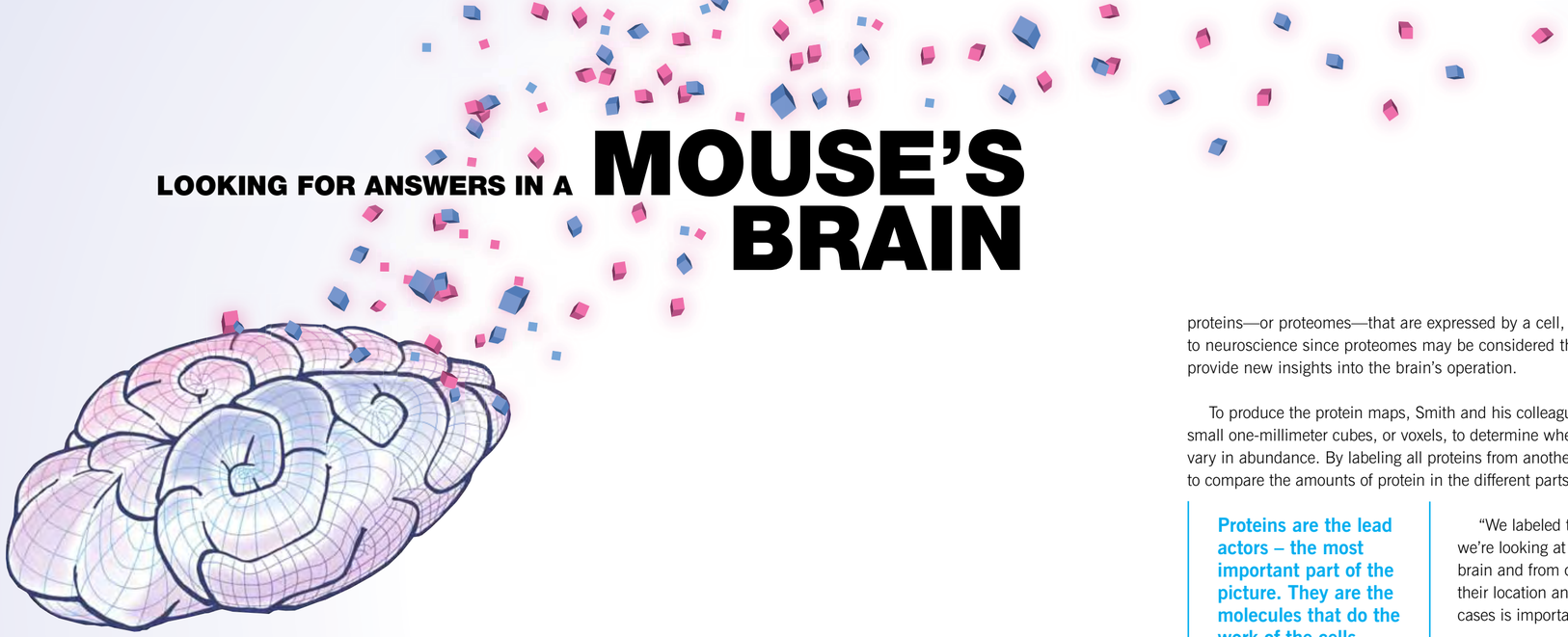
brightness of ever more-distant supernovae would decline predictably with distance, just as the taillights of a receding automobile moving at progressively slower speeds (but never stopping) would fade predictably with increasing distance. Instead they found just the opposite: Although remote supernovae did in fact decline in brightness with distance, the decline was much greater than predicted. The universe wasn't putting on the brakes—it was flooring it. The only conclusion to be drawn is that we are being carried away from these far flung supernovae (and they from us) at an ever-increasing rate. The team's findings were soon confirmed by a competing group of astronomers, and both groups earned *Science* magazine's "Breakthrough of the Year for 1998."

Cosmologists hailed the finding as the strongest evidence yet that the Big Bang theory is correct.

Now astronomers are beginning to view the CMB findings in light of an accelerating universe. Measurements of the CMB irregularities indicate that the universe is close to being flat, that is, the universe is not curved, and that it will expand forever at a continually decelerating rate. But the supernovae findings clearly contradict this. Moreover, the total amount of matter (visible and dark), as measured in the CMB results, accounts for only 30 percent of the matter needed to slow and reverse universal expansion. Therefore, in an accelerating universe, some form of additional energy is required to account for the 70 percent deficit. Astronomers refer to this unaccounted-for-energy as "dark energy." It is one of the biggest challenges in cosmology today.

"People have contemplated the origin and evolution of the universe since before the time of Aristotle," said Smoot. "Although cosmology has been around since the time of the ancients, historically it has been dominated by theory and speculation. Very recently, the era of speculation has given way to a time of science. The advance of knowledge and of scientific ingenuity means that at long last, we can actually test our theories."

LOOKING FOR ANSWERS IN A MOUSE'S BRAIN



Hope for future cures of several debilitating diseases may be found in the brain of an ordinary mouse.

Every year incurable degenerative diseases like Alzheimer's, Parkinson's and multiple sclerosis threaten the lives of millions of Americans, particularly the elderly. Now research being conducted at the Environmental Molecular Sciences Laboratory, a U.S. Department of Energy (DOE) national scientific user facility located at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, is giving reason for hope. Their research, aimed at accelerating the development of cures for these frightening disorders, is being conducted through—as incredible as it sounds—advanced 3-D mapping of a mouse's brain.

Richard D. Smith, a Battelle Fellow at PNNL, is spearheading the effort. His proteome mapping, a breakthrough developed in collaboration with Desmond Smith of the University of California-Los Angeles' (UCLA) David Geffen School of Medicine, is the first to apply quantitative proteomics, the study of protein structures and functions, with three-dimensional imaging. Prior to this, proteomics, which uses a specially modified instrument called a mass spectrometer to identify and match proteins, was akin to flying blind over a lake of proteins.

"Proteins are the lead actors—the most important part of the picture," said Smith. "They are the molecules that do the work of the cells."

Smith, who holds 31 patents and has been the recipient of seven R & D 100 awards, has devoted the last decade to developing and applying new methods for probing the entire array of proteins—or proteomes—that are expressed by a cell, tissue or organism. His research is significant to neuroscience since proteomes may be considered the protein counterpart to a genome, and can provide new insights into the brain's operation.

To produce the protein maps, Smith and his colleagues characterized brain pieces in hundreds of small one-millimeter cubes, or voxels, to determine where proteins appear in the brain and where they vary in abundance. By labeling all proteins from another mouse brain, they developed reference points to compare the amounts of protein in the different parts of the brain from one mouse to another.

Proteins are the lead actors – the most important part of the picture. They are the molecules that do the work of the cells.

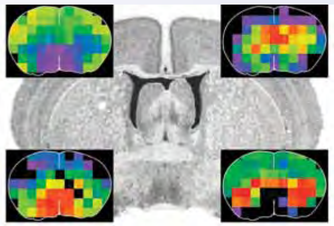
"We labeled them to have reference points so that we know we're looking at the same protein between different parts of the brain and from one mouse to another," said Smith. "Knowing their location and how their abundance changes in different cases is important for understanding their functions."

The next step for Smith and his researchers is to develop 3-D visualization of an entire mouse brain, then compare proteome maps for healthy brains with others who have diseases with strong similarities to humans.

The brain's molecular complexity has challenged neuroscience. Research found that roughly one-third of the mammalian genome, or the complete set of genetic material, appears to be dedicated exclusively to brain function. But with information such as the types and locations of a living organism's organic molecules, or biomolecules, within the mammalian brain, scientists are beginning to understand the origin and progression of brain diseases. Holding them back, however, have been current imaging techniques that, in spite of good spatial resolution technology, can identify one or only a few proteins (generally the most abundant) at a time. But by using a mouse's brain, now scientists are able to detect more than a thousand different proteins in a single experiment and map them to the brain structures.

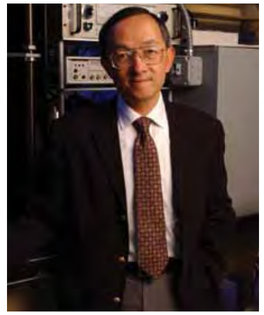
By using a mouse's brain, now scientists are able to detect more than a thousand different proteins...and map them to the brain structures.

The research represents a major step forward for completely characterizing detailed spatial abundance patterns of the brain proteome and provides a methodological basis for future studies. Contrasts in location and abundance of proteins might signal the earliest detectable stages of Alzheimer's disease, Parkinson's disease and other neurological diseases. This research could reveal possible blood biomarkers that would enable better diagnosis or identify new protein targets for the treatment of neurological diseases, raising the hope that such diseases might be curbed if caught and treated early.



BRAIN PROTEOMICS IN 3D: Abundance profiles of four different proteins compiled from 1 millimeter cubes (voxels) in a mouse brain. The boxes correspond to the locations of the voxels in the brain, and the colors represent their relative abundance in each region (from high, red, to low, violet).

MOLECULAR ANALYSIS IN THE FAST LANE



ED YEUNG Senior Chemist, Ames Laboratory and Distinguished Professor in Liberal Arts and Sciences, Iowa State University

"Multiplexed capillary electrophoresis" may sound like a mouthful, but it is rapidly revolutionizing the field of chemical analysis.

Among those who track DNA sequences or develop new medicines, "high throughput"—science-speak for "more"—is a favorite term. Scientists want to test more chemicals faster to decode what makes a human a human or to identify the drugs that will improve or even save human lives.

Scientists at Ames National Laboratory in Ames, Iowa, developed technology to enable this express-lane molecule analysis. Led by senior chemist Ed Yeung, researchers bundled 96 separate experiments into one machine, complete with automation, so that the experiments can run at night and software can analyze the barrage of data when lab workers are sleeping. The technology netted Yeung an R & D 100 Award from *R & D* magazine as one of the top inventions of 2001.

Scientists often want to sort molecules, such as DNA, by size or electrical charge. In gel electrophoresis, an electrical current propels the molecules through a gelatin-like material. The smaller molecules zip through the gel, while larger chemicals take more time to navigate the matrix.

Couple the technology with robotics...and the experiment practically runs itself.

A standard gel ranges from dessert size to the size of a piece of paper, and holds a dozen or so samples. When scientists tackled the Human Genome Project, reading each of the three billion letters in a human DNA, they knew running every strand through the ordinary gels would take far too long. In 1990, Yeung developed a way to turn those gels into skinny capillary tubes—two feet long and the width of a human hair—and run 96 capillaries at the same time. Called multiplexed capillary electrophoresis, the technique is now standard for DNA sequencing. Couple the technology with robotics to control it, and the experiment practically runs itself."The key point is to do it at high speed and high throughput," Yeung said. "By doing it 96 at a time instead of one at a time, you immediately get that roughly hundredfold advantage."

Capillary electrophoresis runs faster not only because many samples race through the strands at one time, but also because scientists can use much higher voltages to power the molecules' travel. Standard gels run at around 100 volts, but capillaries can take as much as 20,000 volts. At that voltage, a regular gel "will basically start to boil," Yeung said. Capillaries, in contrast, are exposed to cooling air on all sides, so the experiments are complete in minutes, instead of hours, without becoming overheated.

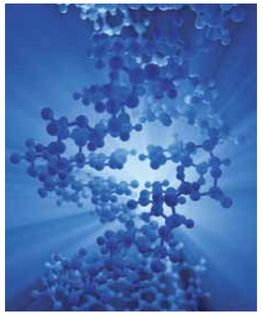
The key point is to do it at high speed and high throughput.

"One of the hallmarks of capillary electrophoresis is the exquisite level of separation that you can get," said Steve Siembieda, chief operating officer at Advanced Analytical Technologies, Inc. in Ames, Iowa, which produces multiplexed capillary electrophoresis equipment. The technique can separate DNA strands that differ in length by a single base—that is, one of the three billion letters in the human genome. No other electrophoresis technique can match it, so it's ideal for purifying compounds.

DNA sequencing depends on fluorescent tags glued to each molecule. A scanner reads the color to record when the molecules reach the end of their ride. But many molecules don't fluoresce, and the colored tags can be expensive and toxic. In the late 1990s, Yeung realized that the technology could have more widespread application if it relied on ultraviolet (UV) light, instead of fluorescence, to detect the molecules whizzing through the tubes. Nearly all molecules absorb UV light.

In multiplexed capillary electrophoresis with UV absorption, the machine shines UV light on the samples as they reach the end of their journey. A scanner can detect the molecules based on how much light is absorbed. This kind of electrophoresis is "universal," Yeung said. DNA, proteins and small molecules all show up.

The technology is now common lab equipment. Commercial machines run as many as 384 samples at a time. Researchers use it to sort proteins and carbohydrates and test how potential drugs interact with other compounds. Because the equipment processes multiple experiments simultaneously, costs are the same as or less than other techniques. For high-throughput work, the better, faster, cheaper capillaries have replaced the old-fashioned gel slabs for good.



DNA SEQUENCING relies on absorption of ultraviolet light, instead of fluorescence, to detect molecular movement.

ELECTRONEEDLE TO THE RESCUE!

Is it Sci-Fi? New diagnostic tool may soon eliminate guesswork and save lives.

When the ambulance screeches to a halt and emergency medical technicians rush to aid an unresponsive patient, there can be a lot of guesswork. Heart failure? Drug overdose? Diabetic shock? The appropriate treatment may not come for hours, until after the ambulance returns to the hospital and doctors receive the blood test results that determine the diagnosis.

But emergency medical technicians may soon have a new tool that could provide a diagnosis while en route to the emergency room. Scientists at Sandia National Laboratories (Sandia) in Albuquerque, New Mexico, are collaborating with companies on a fingernail-sized patch that could perform those blood tests immediately, when the ambulance reaches the scene. The patch bristles with tiny needles that feed test results into a handheld device, enabling emergency room doctors to have the treatment ready and waiting when the patient arrives.

The patch would enable ER doctors to have the treatment ready and waiting when the patient arrives.

Called Electroneedles, the painless jabs could be a boon for diabetics, who must prick their fingers for blood samples at least three times a day. Testing cholesterol could become a matter of minutes. Doctors in developing countries could diagnose patients even when they lack access to a medical lab.

The tiny needles, about the width of a human hair, reach only half a millimeter into the skin. They do not need to reach a vein. They analyze the fluid that bathes cells. Since nerve endings are deeper than half a millimeter, the prick doesn't even hurt. “They go into the skin very easily,” said Jeb Flemming, chief engineering officer at Albuquerque-based Life BioScience, Inc., one of two companies that are commercializing the technology. Multiple needles in an array form a single Velcro-like patch that could perform dozens of tests in minutes. No comparable technology can do so many tests at once.

Electroneedles grew out of a Sandia Grand Challenge—a collaborative project to develop fuel cells that harvest energy from living organisms. The ultimate goal was a matchbox-sized fuel cell that soldiers could use in the field to collect energy from plant sugar (or glucose) to power equipment.

The ability to monitor patients without waiting for lab results will not only save time, but lives.

Flemming, a design engineer on the project, wondered if the same needles that collect the glucose energy could reach fluids in patients and allow medical diagnostics. A glucose meter was an obvious possibility.

“If you’re a diabetic, your glucose level is a topic of enduring importance to you,” said Steve Casalnuovo, manager of the Biosensor and Nanomaterials Department at Sandia. Diabetics routinely check their blood sugar levels to make sure it’s not too high or too low.

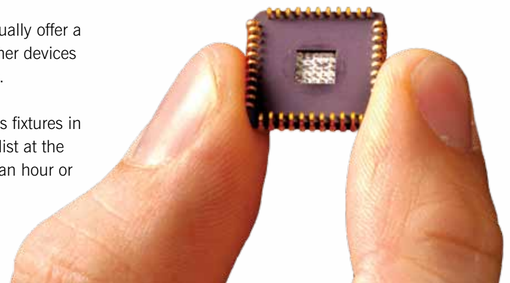
The scientists tested their idea using skin from pigs’ ears and a glucose solution as a stand-in for human tissue. The order for pigs’ ears from the local butcher shop “was one of the strangest purchase requests I’ve ever signed,” Casalnuovo said.

Since glucose can swap electrons with another molecule, glucose oxidase, it didn’t need to be sucked through the needle. Instead, the scientists filled the needle with metal and affixed glucose oxidase to the tip. When the oxidase encountered the glucose, the electrons changed hands and sent an electrical signal through the metal that the scientists picked up on the other end.

In addition to glucose meters, scientists at Sandia, Life BioScience, and New Mexico Biotech, Inc., are expanding the technology to detect proteins, carbohydrates, toxins and pathogens—all without a single blood draw. Since only a subset of molecules is electrically active, researchers are developing compounds that will emit light when they meet their target. The light signal will be transmitted to the detector through a transparent needle. “It allows a little tiny window into the human body,” Flemming said. These light-based devices are called microposts, or μposts.

The first commercial units will likely cost thousands of dollars, but the hope is to eventually offer a ballpoint pen–sized glucose meter that will cost $1 per test, making it competitive with other devices already on the market. Commercial products could be on the market in three or four years.

Electroneedles and μposts could someday join stethoscopes and blood pressure cuffs as fixtures in physicians’ offices. “I think it has a lot of potential,” said Dr. Dominic Raj, a kidney specialist at the University of New Mexico in Albuquerque. The ability to monitor patients without waiting an hour or more for lab results will “not only save time, but save lives.”



TINY NEEDLES about the width of a human hair analyze the fluid that bathes cells.

CONTRIBUTORS

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