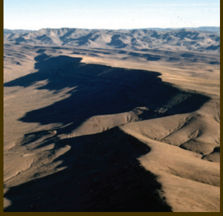
LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

DECEMBER 2008



1663

Playing in the X-Games

Window on the Extreme Universe

Yucca Mountain

The Unseen Scholars

Los Alamos
NATIONAL LABORATORY
EST. 1943

1663

About Our Name: During World War II, all that the outside world knew of Los Alamos and its top-secret laboratory was the mailing address—P. O. Box 1663, Santa Fe, New Mexico. That box number, still part of our address, symbolizes our historic role in the nation's service.

Located on the high mesas of northern New Mexico, Los Alamos National Laboratory was founded in 1943 to build the first atomic bomb. It remains a premier scientific laboratory, dedicated to national security in its broadest sense. The Laboratory is operated by Los Alamos National Security, LLC, for the Department of Energy's National Nuclear Security Administration.

About the Cover: David Montgomery, director of the Laboratory's high-power-laser facility, Trident, is reflected in one of the facility's high-tech mirrors. The facility's main experimental chamber is in the background.

LOS ALAMOS ARCHIVE

Ernest Titterton of the British Mission, a contingent of the Manhattan Project, plays the piano during a wartime party at Los Alamos' Fuller Lodge.

From Terry Wallace

Innovation in the Service of Mission

Los Alamos was formed in the crucible of national need during World War II, with a mission to produce the world's first fission weapon. Robert Oppenheimer, the Laboratory's first director, recognized that while the "mission" could define the product, the scientific path to producing the product was unpredictable. To succeed, the Laboratory would need a broad scientific base and the best and brightest people. Oppenheimer established and fostered those "capabilities," and Los Alamos built the first atomic bomb in just two and a half years.

In the succeeding decades, the challenges presented to Los Alamos changed, but the Laboratory's solid scientific and engineering capabilities allowed it to be responsive to national need. In 1962 President Kennedy visited Los Alamos and expressed the rationale for the Laboratory:

"It is not merely what was done during the days of the second war, but what has been done since then, not only in developing weapons of destruction which, by irony of fate, help maintain the peace and freedom, but also in medicine and space and all other related fields, which can mean so much to mankind."

Today, the Laboratory's mission is undergoing tremendous change because of major new challenges to national security. Access to energy resources is now of vital concern, and research is needed to develop and perfect alternative, renewable energy sources. Just as important is the exchange of information, which is one of the central pillars of the nation's economy and which relies on an infrastructure of databases, communication satellites, and the Internet, all built in the last 30 years. The need to protect that fragile infrastructure and maintain the command and control of our utilities poses a tremendous security challenge.

Los Alamos is being asked to provide powerful solutions to these new problems, and as in Oppenheimer's time, innovation will be central to our efforts. The Laboratory's innovative spirit is much in evidence at the Trident facility, in the Milagro project's detection of high-energy gamma rays, and in the development of web-based research tools, all addressed in this issue of 1663. Our response to the nation's call is still only as good as the capabilities we have built here. Creativity and innovation are our greatest capabilities.

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PRINCIPAL ASSOCIATE DIRECTOR FOR SCIENCE, TECHNOLOGY, AND ENGINEERING

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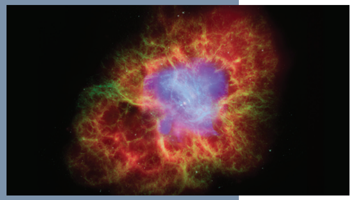

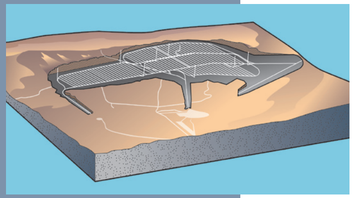

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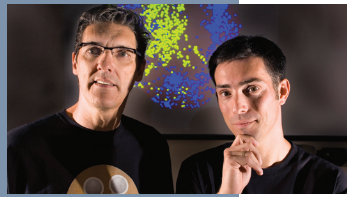

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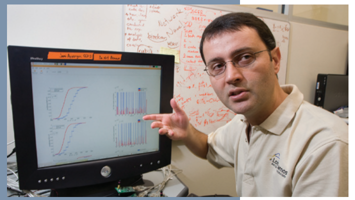
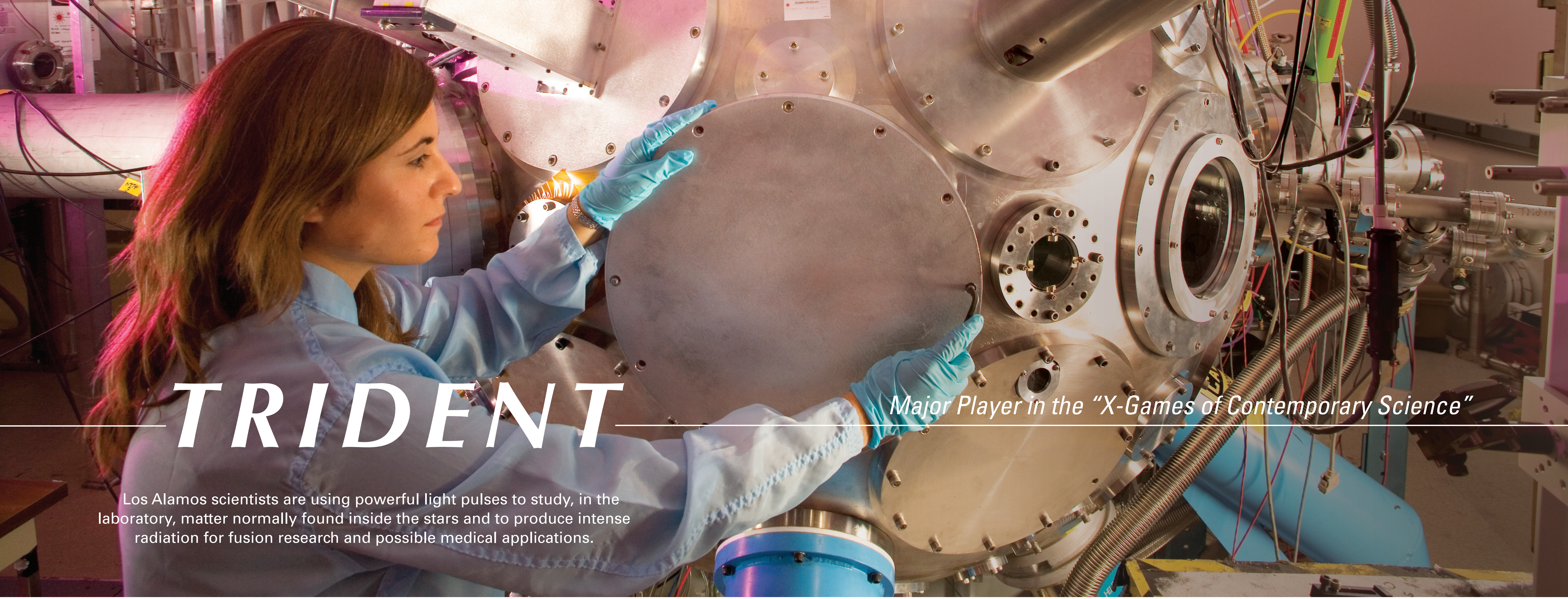




TRIDENT

Major Player in the "X-Games of Contemporary Science"

Los Alamos scientists are using powerful light pulses to study, in the laboratory, matter normally found inside the stars and to produce intense radiation for fusion research and possible medical applications.

If you're thinking of competing in the "X-Games of Contemporary Science," you might want to talk to David Montgomery, director of Los Alamos' Trident high-power-laser facility. He and other Trident scientists have cooked up some winning strategies for the events in the last 10 years or so.

In these X-Games, as the National Academy of Sciences calls them, scientists create and study, in the laboratory, the "extreme" matter usually found inside the sun, other stars, and gas giants such as Jupiter—or in even more exotic places such as near the edges of black holes and within gamma-ray bursts and the atmospheres of neutron stars. The conditions needed to sustain this matter are truly extreme; phrases like "millions of atmospheres," "millions of degrees," "many times the density of lead" are typically used to describe them.

More precisely, extreme matter is matter with an internal pressure of at least 1 million atmospheres, that is, 1 million times the pressure of Earth's atmosphere at sea level, and falls under the purview of "high-energy-density physics" (pressure can be expressed as an "energy density," or energy per unit volume).

Scientists can create extreme matter in the laboratory only briefly. But doing so lets them study it up close and personal, rather than through a telescope from millions or billions of light-years away. Such studies are already benefiting research on fusion energy and nuclear weapons, where these extremes also prevail.

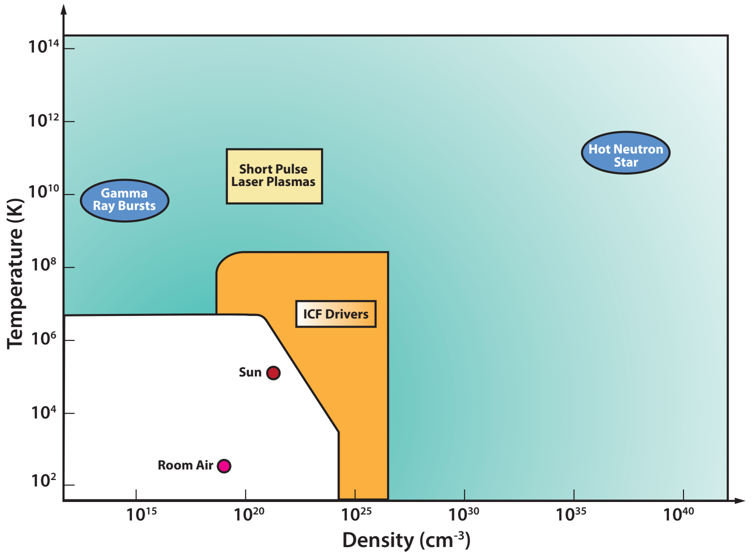
Cooking Up Extreme Matter

Extreme matter is usually a hot, dense plasma, ordinary matter broken down by extreme heat into a swirling soup of positively charged atomic nuclei (ions) and negatively charged electrons.

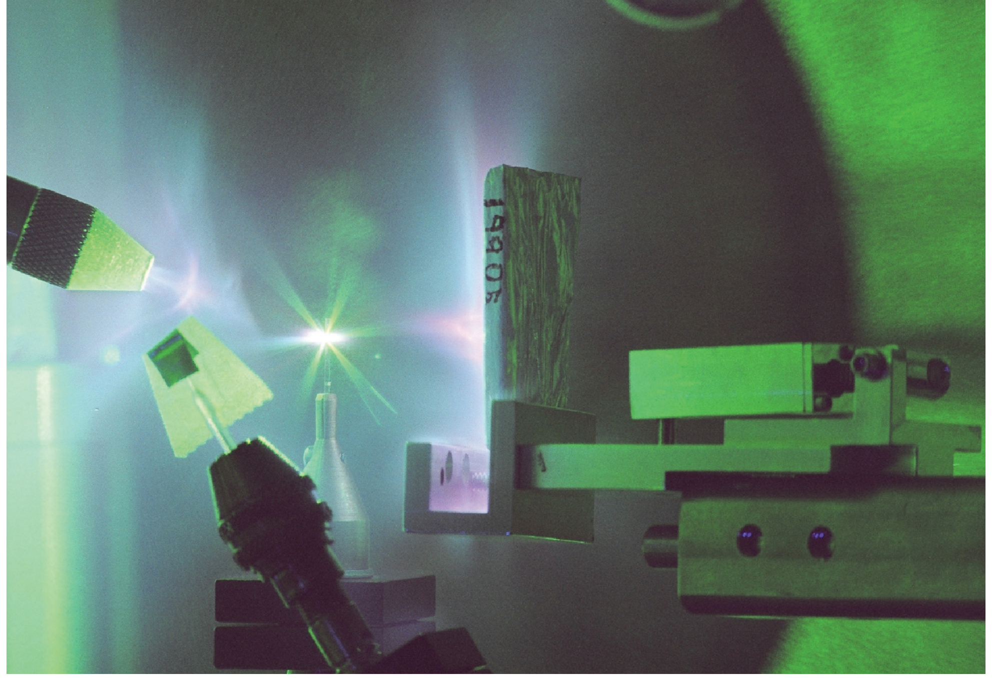
"One way to create extreme matter is to shine intense light—just a pulse of it—onto a solid target, usually a metal foil or wire, to quickly heat it up," says Montgomery. "Trident makes some of the most-intense light pulses on Earth."

In addition to being intense, the pulse must be extremely brief. Because hot plasmas disperse rapidly and lose energy quickly, mainly radiating it as ultraviolet light or even x-rays, the pulse must heat the matter much faster than the plasma disperses and cools through radiation. In a typical Trident experiment, a light pulse will turn a tiny bit of target material into a microplasma with a volume of 1 cubic millimeter (about the size of a large grain of salt) or less.

Above: Despina Milathianaki, a Ph.D. student from the University of Texas at Austin, installs a cover plate on Trident's main experimental chamber. Through the Trident User Program, she is studying the dynamic response of materials to laser-induced shock loading.



This "map" shows the temperatures and densities of extreme (green) and non-extreme (white) matter. The region of extreme matter is where X-Gamers compete. Extreme matter exists inside such things as gamma-ray bursts, hot neutron stars, and the plasmas produced by high-power lasers. Non-extreme matter includes sea-level air at room temperature and, surprisingly, the surface of the sun. The orange region comprises temperature-density combinations that might yield laser-induced fusion in the laboratory.



Inside an experimental chamber, a "short" Trident light pulse (source not seen here) strikes a molybdenum wire, quickly turning it into plasma (the bright "star"). The green cone at left is the tip of a pinhole camera that photographs x-rays emitted by the wire. Right of the plasma "star," a stack of film sheets wrapped in aluminum foil (marked "19905") measures high-energy protons, which are also produced. The structure in the foreground (bottom, left of center) is part of another camera setup. PHOTO COURTESY OF JOSEPH COWAN AND KIRK FLIPPO.

The light energy required to do that and the time in which the energy must be deposited in the target determine the light pulse's power, which is the energy of the pulse divided by its duration.

To produce 1 cubic millimeter of extreme matter requires about 1 trillion watts (a terawatt), equal to the combined power output of all the electrical plants in the United States. But don't worry about the lights dimming each time Trident spits out a light pulse. Trident packs the terawatts into the pulse by cramming a small amount of energy—about what's needed to light a 100-watt light bulb for a few seconds or so—into a very brief time. The longest pulse produced at the facility lasts for only a few tens of microseconds. Trident also produces pulses that pack 200 terawatts of power, more than enough to create some very extreme matter, but those pulses are even shorter—only half a trillionth of a second.

Moreover, Trident can provide its short pulses and long pulses simultaneously. "For example," Montgomery says, "a long pulse can be used to create extreme matter while a series of short pulses acts as a fast strobe light to photograph how the matter behaves. With two long-pulse beams and one short-pulse beam, as well as great versatility in being able to change the pulses' shapes in time, Trident is probably the most-flexible high-power-laser system in the world."

When focused onto a target, a Trident short pulse is also very small, with a diameter of 9.6 millionths of a meter (9.6 micrometers)—that's about the diameter of a red blood cell—and a length about equal to the thickness of a sheet of paper (about 150 micrometers). Squeezed into this tiny volume, the light can exert a pressure of billions of atmospheres. This "radiation pressure" can very effectively push a plasma's electrons around, a phenomenon scientists can exploit to spectacular effect.

The power, duration, and size of a Trident short pulse are typical of the short pulses produced at the handful of high-power-laser facilities that exist around the world. But Trident's short pulses contain more of the available light energy than other lasers in its class. The method used to generate powerful short pulses also produces a preceding jolt of light, a "prepulse," which hits a target before the short pulse does. However, because the short pulses at Trident and other high-power-laser facilities contain so much energy for their size, the premature arrival of even a tiny fraction of that energy can blast a target to smithereens before the short pulse arrives. For this reason, experiments with metal-foil targets thinner than 1 micrometer require as small a prepulse as possible.

At Trident, the prepulse value of the short pulses is less than one 10-billionth of the available light energy. That leaves nearly all of the energy—at least 99.99999999%—to be packed into the Trident short pulse. To put that in perspective, if the prepulse were a wave an eighth of an inch high, the short pulse would be at least 20,000 miles high. Trident's prepulse value is about 10,000 times smaller than those of the four other operational short-pulse lasers in Trident's energy class. No wonder Trident researchers can do experiments that cannot be done elsewhere!

Stunts with Short Pulses

In the mid-1960s, scientists realized that intense laser light could compress and heat matter enough to produce significant amounts of fusion energy, which powers the sun and other stars and could one day provide an inexhaustible source of terrestrial energy. The nuclei in a plasma are all positively charged, so they strongly repel each other when they're close together. But in a hot, dense plasma, they approach each other at such high speeds and so often that many pairs of them can overcome their repulsion and fuse—releasing enormous amounts of nuclear energy.

In the last decade or so, the pursuit of laser-induced fusion has spurred the development of several swimming-pool-size laser systems that produce short pulses with powers well over a trillion watts. In 1996, one beam line of the Nova laser—which was built for fusion research at Lawrence Livermore National Laboratory (LLNL) in 1984—was converted to short-pulse operation. The result was the first petawatt (1,000 trillion watts) laser. The appropriately named "Petawatt" was used to study laser-induced fusion, among other things, before being dismantled in 1999 to make way for LLNL's National Ignition Facility (NIF). The size of three football fields, NIF will house the world's largest laser, which many hope will sustain fusion reactions for a few billionths of a second—an event that could occur as soon as 2010.

With NIF fusion on the horizon, scientists at Trident and other high-power-laser facilities are gearing up to support NIF efforts by exploiting a key discovery made with the Petawatt—that ultraintense short pulses can produce intense beams of electrons, protons, and other ions, as well as intense bursts of high-energy x-rays. The proton beams could be used to ignite fusion plasmas, while the x-rays will be used to take pictures of them.

Plasma Portraiture

Capturing images of fusion plasmas is no easy task because such plasmas can be 100 times denser than lead. However, x-rays that are bright enough and energetic enough can shine through the densest plasma to produce a "shadowgraph," just like a medical x-ray. Trident researchers recently implemented the Petawatt's x-ray-production technique to do just that—in order to take pictures of fusion plasmas; fusion-fuel compression, leading to the fuel's "ignition"; and hot, dense plasmas in general.

The researchers aim a short pulse at a metal wire with a diameter of 12 micrometers. The intense light quickly frees some of the electrons in the wire and accelerates them to energies of 100,000 or so electron volts. These energetic electrons then strike other electrons in close orbit around the metal's nuclei, "exciting" the orbiting electrons to move in larger orbits. The excited electrons quickly drop back to their original orbits, but they emit high-energy x-rays as they do.

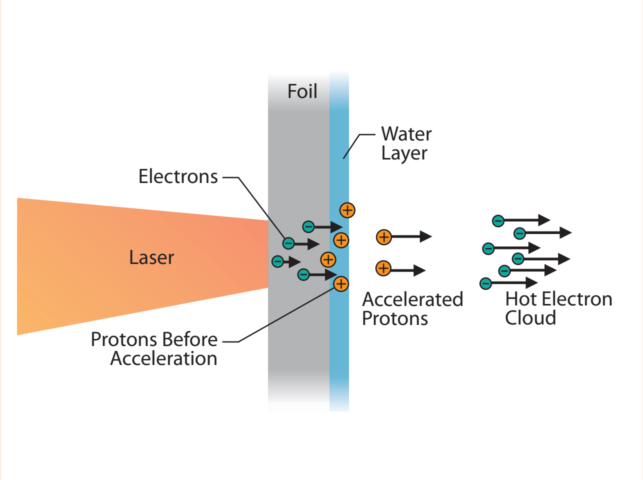
The resulting x-ray burst can produce good x-ray photos of hot, dense plasmas. The burst is also brief enough—about as short as the light pulse—to freeze a swirling plasma's motion. Moreover, the x-rays are emitted from the end of the wire, so the source of the x-rays is about the size of the wire's diameter. This source size can capture details as small as 10 micrometers in an x-ray shadowgraph.

Other facilities around the world, including the University of Rochester's Omega-EP and the Z-R, a "z-pinch" plasma facility at Albuquerque's Sandia National Laboratories, are also using this technique to take pictures of hot, dense plasmas. NIF will use this same type of source.

Potent Proton Acceleration

Trident was built in 1992, about 10 years before the National Academy of Sciences came up with the X-Games theme, but Trident's original mission—to support an earlier, never fully realized, national laser-induced-fusion program (ICF, for inertial confinement fusion)—was well aligned with the pursuits of many present-day X-Gamers. An upgrade completed in 2007 boosted Trident's maximum power from 30 terawatts to over 200 terawatts through the addition of the short-pulse capability. This was all Trident needed to seriously compete with other short-pulse, high-power-laser facilities.

Proton Acceleration



When a Trident "short" pulse strikes a metal foil, the pulse's light is so intense that it quickly accelerates some of the foil's electrons to nearly the speed of light. These electrons pass through the foil and a thin layer of residual water, to form a hot electron cloud near the back of the foil. The cloud's electric field ionizes the molecules in the water layer to form a plasma (not shown) of protons (hydrogen nuclei), oxygen ions, and electrons. The field also accelerates protons from the plasma, forming a beam. That proton beam, which can include some electrons from the cloud, can have energies of up to 58 million electron volts. Such proton beams can be used to ignite fusion plasmas or possibly to perform table-top nuclear physics and to treat cancerous tumors.

Going for the Gold

Lawrence Livermore's National Ignition Facility will be the site of renewed efforts to try for the first time to sustain fusion reactions in the laboratory. If all goes well, the facility's intense laser beams will compress and heat to fusion a mixture of two hydrogen isotopes—deuterium and tritium—contained in a hollow, BB-size sphere of beryllium or plastic.

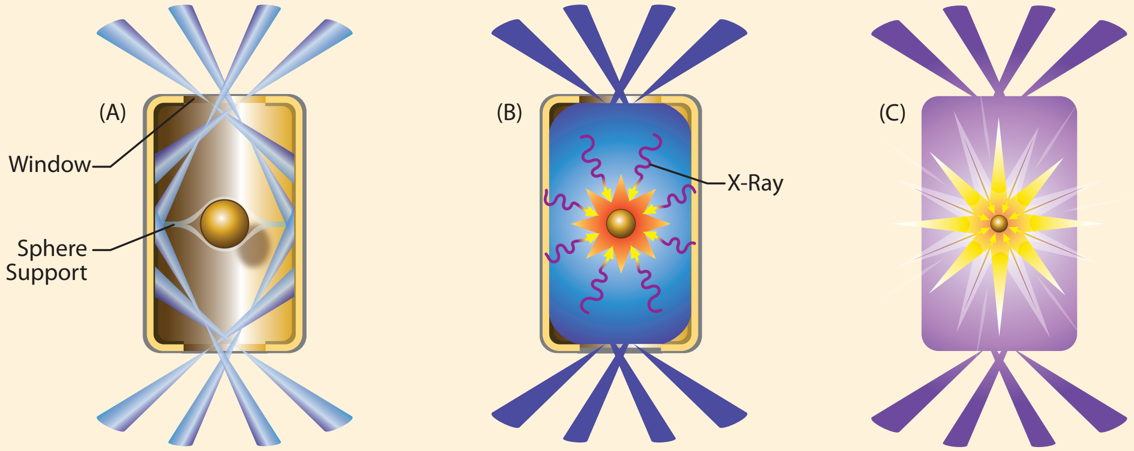
The beams will compress the fusion fuel indirectly, as shown in the figure below. (A) They will strike the inner walls of a hollow gold cylinder about the size of a pencil eraser, producing a hot gold plasma. (B) The gold plasma will then radiate x-rays that compress the sphere, which will be positioned at the cylinder's center. (C) The compressed and heated fuel will "ignite" to produce sustained fusion reactions. However, earlier experiments with the Nova laser showed the beams might fail to reach the gold walls because of another plasma that the beams will form first by ionizing the sphere supports, the helium gas that surrounds the sphere, and plastic windows at the ends of the cylinder.

The problem is that large periodic density variations, or waves, could develop in the first plasma. Such waves reflect light, and although small waves are always present in a plasma, laser light can pump energy into them so they grow large enough to reflect all the laser light away from its original path.

Normally, a laser beam contains hundreds of bright points called "speckles" caused by the beam's constituent light waves interfering with each other. (The overlapping of the crests of two waves produces a speckle.) The ideal way to study how a laser beam interacts with a plasma is to first study how one of those speckles interacts with a plasma. Montgomery headed a small team from 1999 to 2007 to do just that. The more-realistic situation was later addressed by applying what was learned for one speckle to the hundreds of speckles in an actual laser beam.

In Montgomery's experiments, one Trident beam produced a single speckle, and a second beam produced a well-characterized plasma.

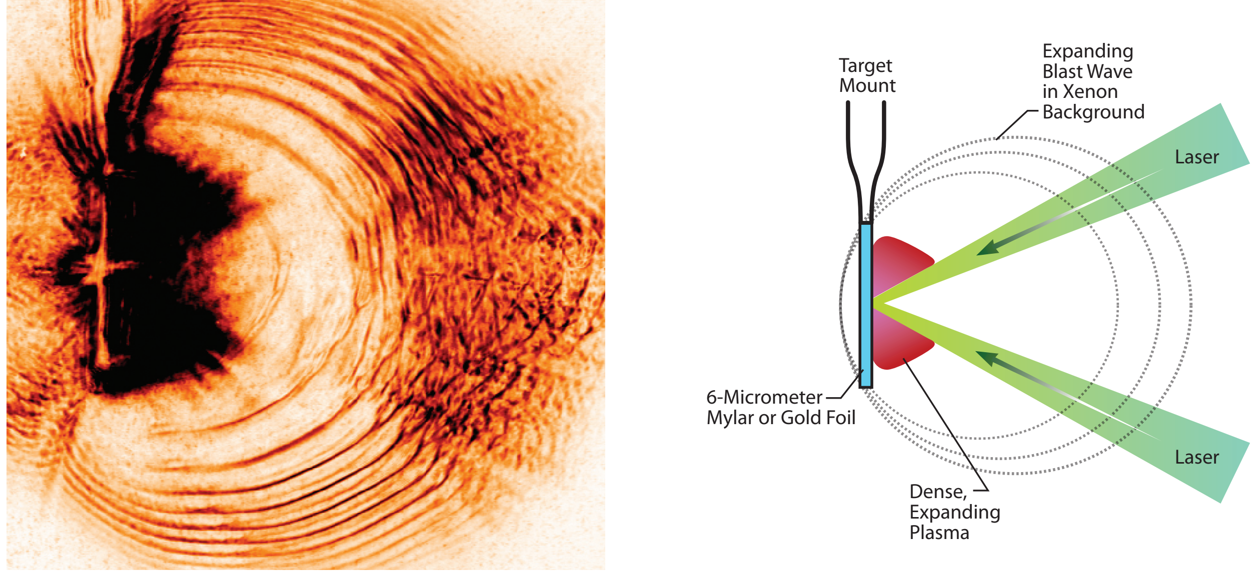
Before these studies, no one really knew, despite various theories, exactly how laser light can cause plasma waves to grow and how their growth can be stopped. These experiments have provided that understanding.



In addition to a super-low prepulse value, the intensity of a Trident short pulse can be higher than those of more-powerful short pulses produced at other facilities. This feature has contributed to a major improvement in the method of proton-beam generation discovered with the Petawatt.

The intensity of a pulse is its power divided by the area on the target illuminated by the pulse. Trident achieves high intensity by focusing a larger fraction of a short pulse's power into a small area than can some higher-power lasers. Since the radiation pressure of a pulse is proportional to its intensity, a Trident short pulse can more effectively push a target's electrons around—the first step in accelerating protons with a light pulse (see "Proton Acceleration" box).

In addition to igniting fusion plasmas, the proton beams could also be used to treat cancerous tumors. Many different types of cancer have been successfully treated by blasting tumors with protons accelerated to about 200 million electron volts (MeV) in a circular accelerator called a cyclotron. Cyclotrons typically 12 feet in diameter are now offered commercially for proton-radiation treatment. But they could be replaced one day with much smaller and cheaper systems based on laser acceleration—in part because ultraintense short laser pulses can accelerate protons in about 1 millionth the distance required by existing accelerators to reach the same energy.



Results of a Trident experiment, an example of "laboratory astrophysics," that confirmed a theory about how supernova remnants are produced. The photo at left consists of 10 superposed images of a nearly spherical blast wave expanding from left to right in low-pressure xenon gas. The blast wave was backlit by 10 "strobe" flashes—a series of Trident short pulses at 30-nanosecond intervals. The blast wave eventually became unstable near its leading edge, producing irregular structures like those of supernova remnants. The blast wave was launched (diagram at right) from a dense plasma created by vaporizing and ionizing a 6-micrometer-thick Mylar or gold foil with green light pulses from Trident's two long-pulse beam lines. PHOTO COURTESY OF GOTTFRIED SCHAPPERT.

A few months ago, Trident researchers led by Kirk Flippo produced protons with an energy of 58.5 MeV—surpassing by 0.5 MeV the record set by the Petawatt but using only about one-sixth the power that the Petawatt needed. This is a significant step toward developing compact proton accelerators.

When Trident protons reached 58.5 MeV, the energy of the Trident prepulse was less than one 10-millionth that of the short pulse. However, the best proton acceleration requires a foil target that is very thin but still intact and cold when the short pulse hits it. To permit ideal conditions for proton-acceleration experiments, the Trident researchers thought about how they could reduce the prepulse energy even further.

"Randy Johnson, another of our staff members, came up with a highly effective remedy," Flippo says. The Trident "crew" successfully implemented Johnson's idea this year in early September, reducing the prepulse energy to less than one 10-billionth that of the short pulse—a thousandfold improvement that has already permitted proton-acceleration experiments with metal-foil targets as thin as 5 billionths of a meter. Other high-power lasers can use targets no thinner than 10 to 20 micrometers without destroying them (prematurely). Trident's super-low prepulse value promises to be one more significant step toward developing compact proton accelerators.

Want to Play?

Trident is ideal for exploring—on a smaller but scientifically useful scale—proton acceleration; laser-plasma interactions (see "Going for the Gold"); small, intense pulsed x-ray sources; and other concepts useful to X-Gamers, says Montgomery. Although larger facilities have more than enough power to pursue such studies, they lack Trident's beam quality and flexibility, which allow Trident to perform some high-energy-density physics experiments not presently possible at larger facilities. Larger facilities are also much more expensive to use. So it's productive and cost effective to explore interesting possibilities at Trident, even if the work eventually moves to another facility.

Trident is no secret in the scientific community. Researchers from around the world bring their experiments to the Los Alamos facility to take advantage of its quality and versatility, the hands-on research that can done there, and the opportunity to interact with Trident's resident scientists. This past summer, 27 proposals were received for access to Trident beam time during the first half of 2009, and more proposals were submitted in October.

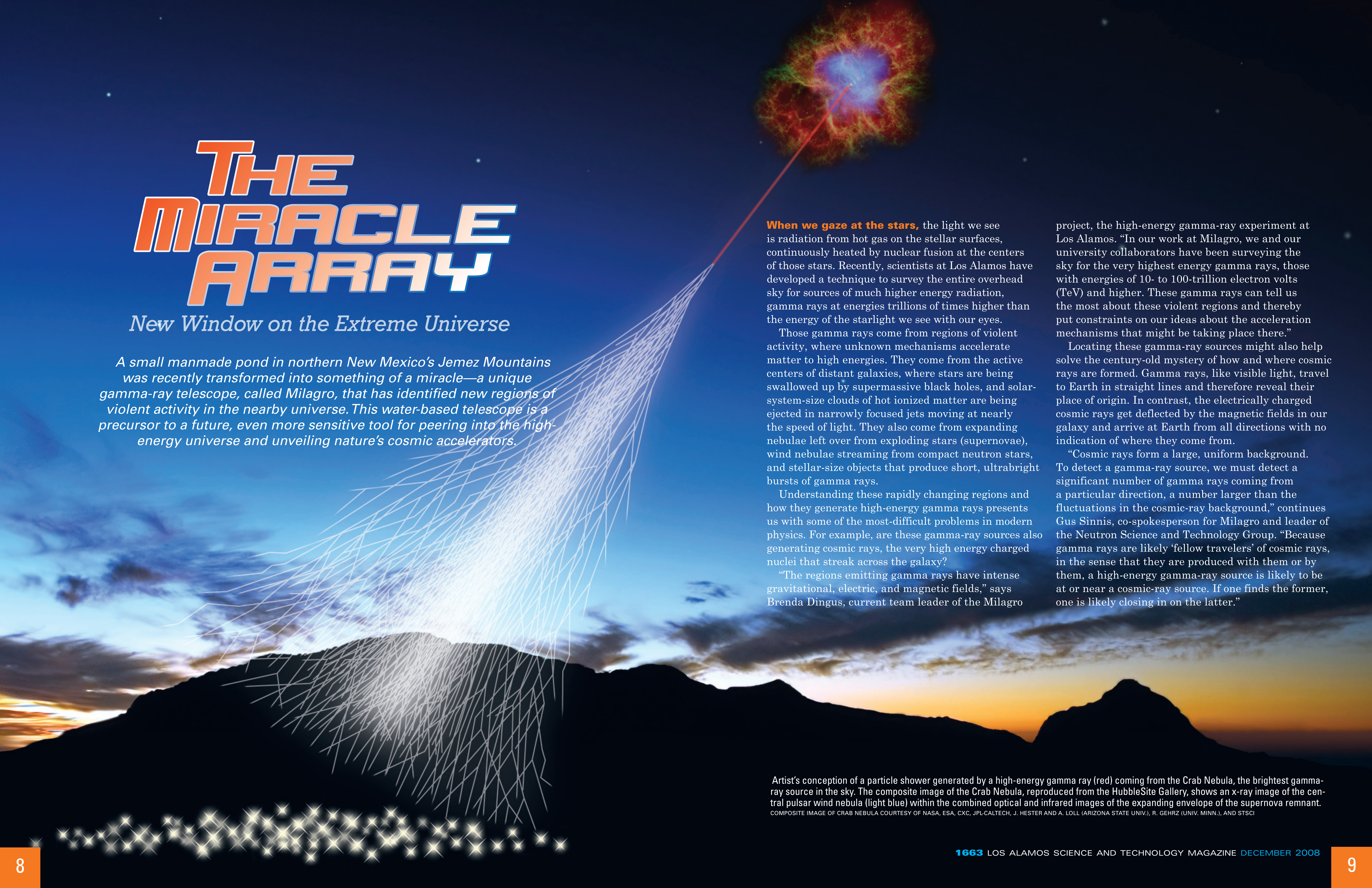
So, if you're thinking about the X-Games, David Montgomery could be the guy to call. ❖

—Brian Fishbine

THE MIRACLE ARRAY

New Window on the Extreme Universe

A small manmade pond in northern New Mexico's Jemez Mountains was recently transformed into something of a miracle—a unique gamma-ray telescope, called Milagro, that has identified new regions of violent activity in the nearby universe. This water-based telescope is a precursor to a future, even more sensitive tool for peering into the high-energy universe and unveiling nature's cosmic accelerators.



When we gaze at the stars, the light we see is radiation from hot gas on the stellar surfaces, continuously heated by nuclear fusion at the centers of those stars. Recently, scientists at Los Alamos have developed a technique to survey the entire overhead sky for sources of much higher energy radiation, gamma rays at energies trillions of times higher than the energy of the starlight we see with our eyes.

Those gamma rays come from regions of violent activity, where unknown mechanisms accelerate matter to high energies. They come from the active centers of distant galaxies, where stars are being swallowed up by supermassive black holes, and solar-system-size clouds of hot ionized matter are being ejected in narrowly focused jets moving at nearly the speed of light. They also come from expanding nebulae left over from exploding stars (supernovae), wind nebulae streaming from compact neutron stars, and stellar-size objects that produce short, ultrabright bursts of gamma rays.

Understanding these rapidly changing regions and how they generate high-energy gamma rays presents us with some of the most-difficult problems in modern physics. For example, are these gamma-ray sources also generating cosmic rays, the very high energy charged nuclei that streak across the galaxy?

"The regions emitting gamma rays have intense gravitational, electric, and magnetic fields," says Brenda Dingus, current team leader of the Milagro project, the high-energy gamma-ray experiment at Los Alamos. "In our work at Milagro, we and our university collaborators have been surveying the sky for the very highest energy gamma rays, those with energies of 10- to 100-trillion electron volts (TeV) and higher. These gamma rays can tell us the most about these violent regions and thereby put constraints on our ideas about the acceleration mechanisms that might be taking place there."

Locating these gamma-ray sources might also help solve the century-old mystery of how and where cosmic rays are formed. Gamma rays, like visible light, travel to Earth in straight lines and therefore reveal their place of origin. In contrast, the electrically charged cosmic rays get deflected by the magnetic fields in our galaxy and arrive at Earth from all directions with no indication of where they come from.

"Cosmic rays form a large, uniform background. To detect a gamma-ray source, we must detect a significant number of gamma rays coming from a particular direction, a number larger than the fluctuations in the cosmic-ray background," continues Gus Sinnis, co-spokesperson for Milagro and leader of the Neutron Science and Technology Group. "Because gamma rays are likely 'fellow travelers' of cosmic rays, in the sense that they are produced with them or by them, a high-energy gamma-ray source is likely to be at or near a cosmic-ray source. If one finds the former, one is likely closing in on the latter."

Artist's conception of a particle shower generated by a high-energy gamma ray (red) coming from the Crab Nebula, the brightest gamma-ray source in the sky. The composite image of the Crab Nebula, reproduced from the HubbleSite Gallery, shows an x-ray image of the central pulsar wind nebula (light blue) within the combined optical and infrared images of the expanding envelope of the supernova remnant.

COMPOSITE IMAGE OF CRAB NEBULA COURTESY OF NASA, ESA, CXC, JPL-CALTECH, J. HESTER AND A. LOLL (ARIZONA STATE UNIV.), R. GEHRZ (UNIV. MINN.), AND STSCI

Unfortunately, high-energy gamma rays are few and far between—there are thousands of cosmic rays for every gamma ray. Further, as the energy increases, the number of both cosmic rays and gamma rays drops. Ten times the energy means fewer than a hundreth the number of gamma rays. So the higher the energy, the greater the challenge of detection.

Showers, Showers Everywhere

Until the Milagro experiment, gamma-ray astronomers had great difficulty detecting sources of gamma rays with energies as high as 10 to 100 TeV.

To detect a source of gamma rays in that energy range, one must detect at least 10 to 20 such gamma rays per day coming from a particular direction.

That's an impossible task for satellite-borne detectors. Their area is so small that the number of very high-energy gamma rays intercepting the detector's small area per year goes down to almost zero.

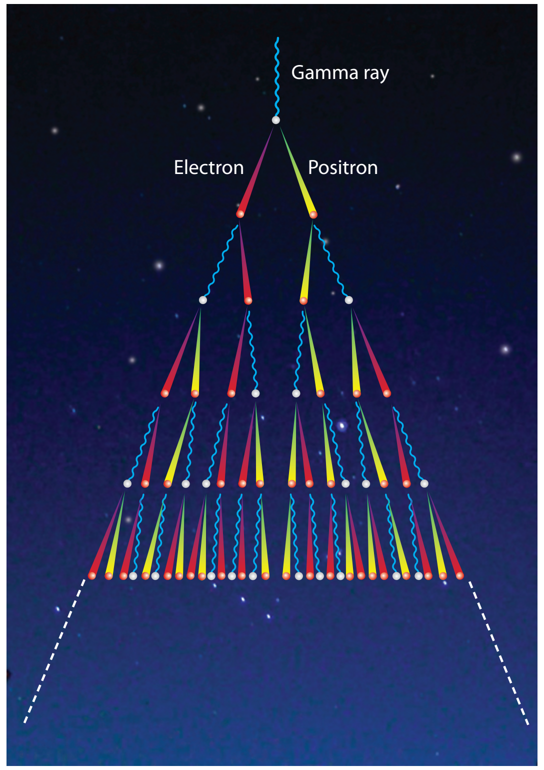
The ground-based gamma-ray telescopes known as atmospheric Cherenkov telescopes are much larger, but they cannot detect gamma rays directly because gamma rays never reach the ground. Instead, gamma rays produce a shower of secondary particles when they enter Earth's atmosphere (see figure below), and the atmospheric Cherenkov telescopes pick up the (Cherenkov) light radiated in the wake of those secondary particles.

Those telescopes have been very successful and were the first to discover a cosmic source of TeV gamma rays (the Crab Nebula, shown in the opening illustration). However, their narrow field of view, combined with the requirement for moonless, cloudless nights, restricts their viewing to a discrete number of directions and a limited viewing time (50 hours per year) in each direction. They therefore have difficulty detecting sources that emit gamma rays above 10 TeV or that are spread over a wide area in the celestial sky.

These limitations on field of view and observation time can be overcome by a ground-based *array* of particle detectors spread over a large area. This large-area array can operate around the clock and simultaneously view the entire overhead sky. However, it will detect only the shower particles that survive to ground level, and of those, only the small fraction, typically less than 1 percent, that intercept the sparsely distributed detectors. The rest fall, you might say, between the cracks. Large-area arrays are therefore sensitive to the showers from gamma rays that are 100 TeV and above because those showers cover the largest areas and generate the largest numbers of particles: millions of particles and more.

Unfortunately, the number of 100-TeV gamma rays entering Earth's atmosphere is so low that the enormous Cygnus array at Los Alamos and the Chicago Air Shower Array, covering over 200,000 square meters in Dugway, Utah, failed to detect a significant number of 100-TeV showers coming from any particular direction. Thus, no sources were found.

The Los Alamos team concluded that a successful ground-based array would have to be sensitive to showers from much lower-energy gamma rays—down to 0.1 TeV. At that energy, the showers are millions of times more numerous, but each shower contains only thousands as opposed to millions of particles, and many particles would be absorbed before reaching the ground. The array would therefore have to detect almost all the particles that reach the ground, which meant creating an array with end-to-end detectors. That approach would be way too expensive.

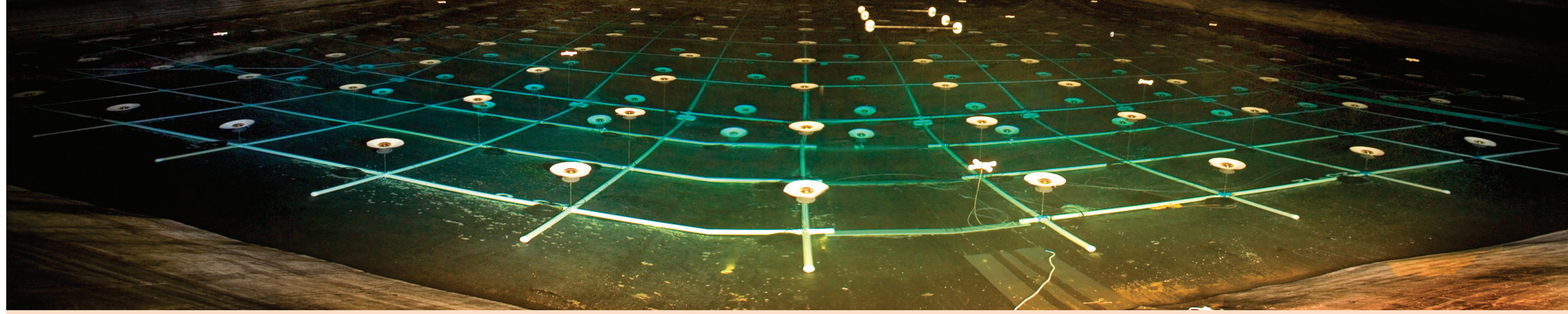


A TeV gamma ray entering the atmosphere will transform into an electron and a positron (the antimatter version of the electron). Each of those then radiates a lower-energy gamma ray, which creates an electron-positron pair, which creates more gamma rays and so on until the energy of the TeV gamma ray is spread over thousands of particles, each with an average energy of about 80 million electron volts (MeV).

The Miracle Array

The impasse provided an important moment for Los Alamos' Todd Haines. When still a graduate student at the University of California, Irvine, Haines had begun working on a new approach to detecting gamma-ray showers—an approach involving water.

Shower particles that intercepted a huge tank of water would streak through the water at nearly the speed of light, setting electrons in the water in motion. Those electrons would radiate light, and because light has only two-thirds its normal speed when going through water, the light would trail behind the speeding particle and form a wide-angle (41-degree) wake, like the bow wave formed by a boat traveling faster than the speed of water waves or like a supersonic plane's shock wave, which creates the sonic boom. Any light detector within the wake would detect the shower particle.

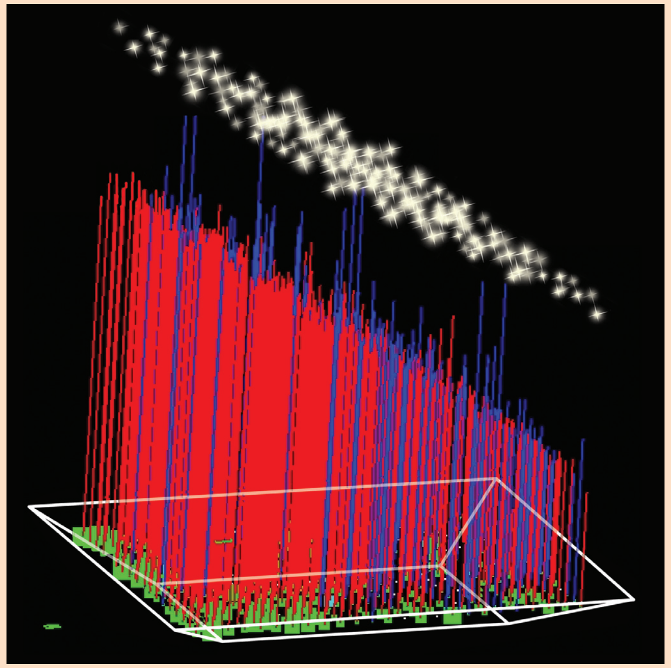


The Milagro pond with its array of PMT light detectors hooked together by fast electronics.

How Milagro Worked

At an instant in time, an air shower looks like a pancake of high-energy particles descending toward Earth along the direction of the initiating gamma ray or cosmic ray. The particle density is highest at the center of the pancake (the shower's core) and decreases with distance from the core.

Milagro determined the direction of the shower by recording the time of arrival of the different particles in the shower. In the figure at right, the tops of the red lines represent those arrival times. Those tops define a plane parallel to the plane of the shower (white dots), and the shower direction is perpendicular to that plane.



The greater the energy of a shower, the larger its area. Therefore, the energy of the shower can be estimated by counting the number of light detectors (PMTs) that give a signal. It's a rough measure but capable of distinguishing showers within Milagro's broad range of sensitivity, from 0.1 to 100 TeV.

HAWC, the planned successor to Milagro, will have a much-larger area and higher altitude and therefore get a much more accurate measure of the energy.

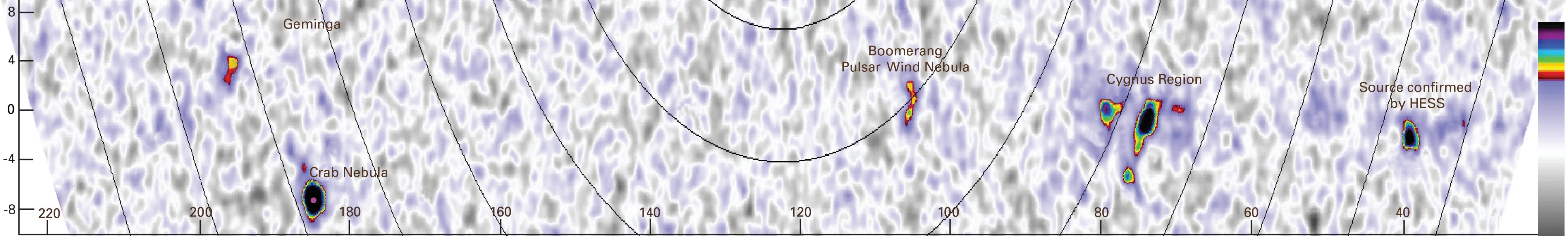
Now, if an array of hundreds of light detectors (photomultiplier tubes, or PMTs) were immersed in a mammoth tank, an arrangement could be found that guaranteed that light from every particle entering the pond would be detected. In addition, the array could operate during the day if covered with a light-tight tent that kept out every ray of sunshine.

The idea was very promising, but with no funds to construct the water tank, it was just another new idea. Then one day Darragh Nagle, a Los Alamos nuclear physicist, burst into Haines' office and announced, "I know where we can build your project."

Nagle took Haines to Fenton Hill in the Jemez mountains west of Los Alamos. There an abandoned manmade pond, once used as a holding tank for an experimental geothermal well, now stood ready for another purpose.

Thus began Milagro (Spanish for "miracle"), in which a small pond was transformed into a new window on the universe, one that would view the most-extreme phenomena in our galaxy and regions nearby.

The Fenton Hill pond was 195 feet by 260 feet and 26 feet deep. It was smaller than desired but could be supplemented by small water tanks outside the pond—outriggers—each containing a PMT. The outriggers would be spaced over an area 10 times the size of the pond. For showers that intercepted the pond only partially, those outriggers would detect the central core of a shower, thereby enabling accurate reconstruction of the shower direction.



Above: Milagro data for the part of the Milky Way disc that's visible in the Northern Hemisphere (from longitude 20 to 220 degrees, where 0 degree is in the direction of the galactic center). The gamma-ray data are shown in a color scale that indicates the excess events (measured in standard deviations) above the uniform background.

"The outriggers increased Milagro's sensitivity by a factor of two, and that made all the difference. We went from barely seeing the Crab Nebula, the brightest gamma-ray source in the northern sky, to discovering new sources of TeV gamma rays in our galaxy and finding a path towards proving that certain sources are cosmic-ray sources," says Sinnis.

Milagro Yields the Unexpected

From 2000 to 2008, Milagro detected over 200 billion showers from both gamma rays and cosmic rays, collected at the rate of 1,700 showers per second. Each was recorded electronically, analyzed on the spot, and characterized by statistical features that were saved for further analysis.

The analysis produced the most-sensitive survey of the TeV sky to date and led to several surprises. First were the five bright sources of TeV gamma rays (in the figure above, the sources with dark centers), with average gamma-ray energies of 12 TeV, standing out loud and clear above the uniform background of cosmic rays, and four less-prominent candidates.

Several of these sources overlapped the much lower energy gamma-ray sources that were discovered 5 to 10 years earlier by satellite-borne gamma-ray detectors. Ground-based atmospheric Cherenkov telescopes had not seen them, despite having searched for TeV gamma rays in the directions of these known sources.

One explanation was that some Milagro sources are spatially extended, up to a few degrees in diameter, making them difficult to detect with narrow-view telescopes. Of these, some turned out to be nearby pulsar wind nebulae, exotic nebulae left over from supernovae that have at their center a neutron star pulsar creating a wind of high-energy particles (see opening illustration showing the Crab Nebula).

A follow-up search with longer observation times by the HESS atmospheric Cherenkov telescope array in Namibia resulted in detection of one of Milagro's sources. The HESS result not only confirmed Milagro's measurement of the total flux of TeV gamma rays but also determined that this source was unusually bright at the very highest energies at which Milagro has its greatest sensitivity.


Gus Sinnis and Brenda Dingus, leaders of both Milagro and HAWC.

Another major Milagro discovery was a surprisingly large number of TeV gamma rays coming from an extended region of the Milky Way known as Cygnus. The expected number is calculated by assuming the gamma rays are produced by the uniform background of cosmic rays impinging on the interstellar matter and radiation in the Cygnus region. However, Cygnus contains an unusually high number of objects (supernova remnants, young stellar clusters, and stars called Wolf-Rayet stars that emit large winds) that could be cosmic-ray sources. "The excess of gamma rays detected by Milagro could be the smoking gun for a recent cosmic-ray source, an explosion of a star within the region in the past 10,000 years," explains Sinnis.

Milagro has taught us to "expect the unexpected" says Dingus. "When we open a new window on the universe, the biggest discoveries are not the ones predicted."

HAWC and the Future

"With all its success, Milagro provided only a proof-of-principle for the basic technique of using Cerenkov radiation in water to detect shower particles," says Dingus. "Our experience over the last decade and our computer simulations of Milagro's performance convinced us that we could build a much more sensitive detector, and with support from the Laboratory-Directed Research and Development program, we've designed it."

Funding is being sought from the National Science Foundation and Mexican institutions for the new array: HAWC, for High Altitude Water Cerenkov array. It will be built on the shoulder of Sierra Negra, Mexico's highest peak. At 13,500 feet, HAWC will be 4,000 feet higher than Milagro was.

At the higher altitude, the number of particles reaching the ground from a shower of a given energy is 5 times higher than that at the Milagro altitude. The HAWC PMTs will be distributed one per tank in 900 water-filled tanks placed place side-by-side over an area about 10 times that of the Milagro pond. Because each PMT will be in its own large tank, the light from each shower particle will be seen by only one PMT, which will allow more-accurate determination of the shower energy.

The increase in altitude, the larger area, and the optical isolation of the PMTs will increase the overall sensitivity 10 to 15 times—high enough to detect many new gamma-ray sources and to monitor the variability of these sources.

Atmospheric Cherenkov telescopes have detected, at distances of billions of light-years, extragalactic sources that flare in only a few minutes, but they have been able to monitor only a few sources for a small amount of time. HAWC will observe the TeV sky every day, and its higher sensitivity will increase the energy range over which these sources can be detected. Milagro found a few sources, but HAWC will add important details for understanding the physical mechanisms in nature's high-energy particle accelerators.

The enormous progress in gamma-ray astronomy over the past decade has fueled intense interest in future instruments. Large investments are planned for the next generation of atmospheric Cherenkov telescopes. Meanwhile, Los Alamos has blazed a new path that will culminate in HAWC, a highly sensitive all-sky survey instrument able to reveal the transient high-energy universe. Sinnis summarizes its promise this way: "With HAWC, we will be in a unique position to close in on the century-old question of the origin of cosmic rays." ❖

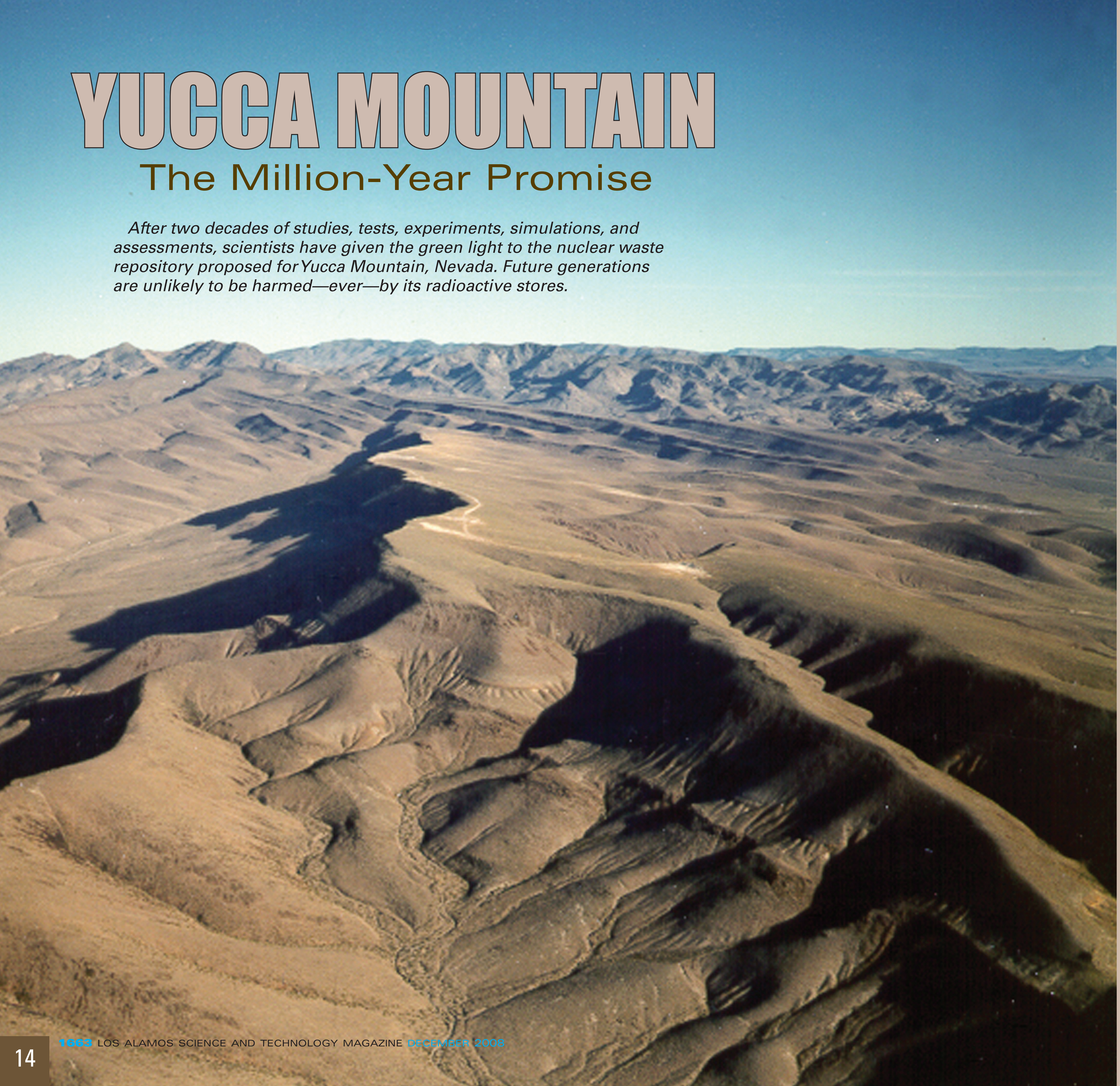
—Necia Grant Cooper

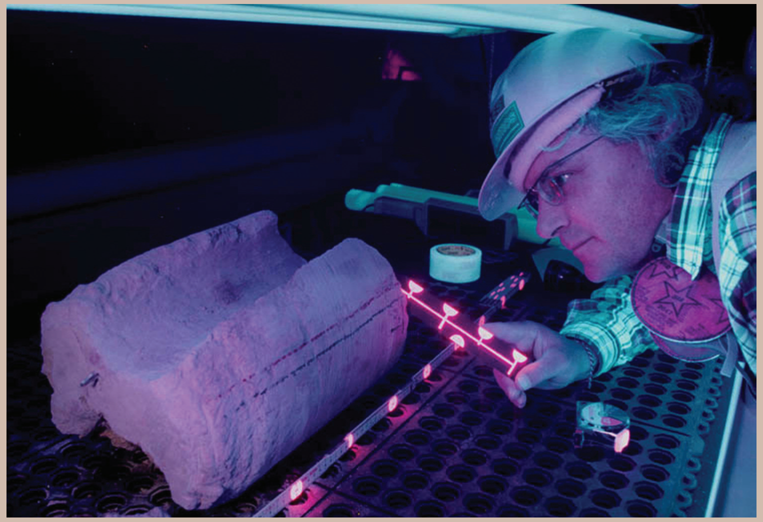

Sierra Negra in Mexico, shown here with a graphic depiction of the proposed HAWC array of water-filled tanks in place. (Inset) One of the tanks that will compose HAWC.

YUCCA MOUNTAIN

The Million-Year Promise

After two decades of studies, tests, experiments, simulations, and assessments, scientists have given the green light to the nuclear waste repository proposed for Yucca Mountain, Nevada. Future generations are unlikely to be harmed—ever—by its radioactive stores.





In the grand scheme of the American west, Yucca Mountain appears to be little more than a geologic afterthought. Not even a unified "mountain," but an amalgamation of long, low, and bone-dry ridges, it lies unsung within a desolate region of southern Nye County, Nevada, sandwiched between Death Valley National Monument some 30 miles to the west and the Nevada Test Site a stone's throw to the east.

The mountain is far from an afterthought for the Department of Energy (DOE). In 1982, Congress, by way of the Nuclear Waste Policy Act, made DOE responsible for licensing, building, and operating an underground repository where the nation could bury its radioactive debris. Five years later, Congress charged DOE with assessing whether the repository could be built inside one of Yucca Mountain's parched ridges.

DOE's assessment had to describe how the repository would be built and operated but also address the issue of long-term risk. The waste—spent fuel from commercial and military nuclear reactors and the "hot" leftovers from decades of nuclear weapons work—would remain highly radioactive for more than a million years. Could DOE demonstrate a "reasonable expectation" that a person living near the mountain would receive only a negligible dose if the waste were to leak from the repository 100 or 100,000 years from now?

To answer that question meant gaining a fundamental understanding of how some radioactive atoms—radionuclides—might become mobile and enter the local environment. Yucca Mountain therefore became one of the most scientifically scrutinized pieces of real estate in the world, with DOE employing approximately 2,000 scientists over the years to map, measure, and model its every essence.

Los Alamos scientists were key players in the massive research effort and made major contributions toward understanding the mountain's geology, hydrology, and

Left: Yucca Mountain as seen from the south. The ridge in the center is the site of the proposed nuclear waste repository. Above: Former Los Alamos scientist Gilles Bussod uses ultraviolet light to study how fluids move through rock. Such studies informed decisions about the Nevada site.

PHOTOS COURTESY OF U. S. DEPARTMENT OF ENERGY.

geochemistry and the region's volcanism. The Laboratory also led the Test Coordination Office (TCO), which coordinated all tests conducted at the site. Currently headed by Los Alamos' Doug Weaver, the TCO was crucial to ensuring that every experiment was vetted properly and that the data and their analysis met all criteria for scientific integrity.

After two decades and millions of hours of investigations, DOE was able to assess the viability of Yucca Mountain. The conclusion: Yes! The repository can be built and operated safely and will pose little risk to future generations.

Meeting Regulations

Before reaching that determination, DOE had to show that the repository would comply with federal Environmental Protection Agency (EPA) regulations, which are meant to ensure the lowest reasonable risk to members of the Nevada public.

If radionuclides were to become mobile because, for example, water had infiltrated the repository and gained access to and dissolved some of the waste, some radionuclides might be transported through the mountain's rock layers and down to the water table, where they could flow underground into the bordering Amargosa Desert. Future residents might then pump the tainted water to the surface.

Given that possibility, the EPA considered a person living a certain distance from the repository, eating some locally grown food, and drinking the local water. The repository could not be built if that person might potentially receive more than a small dose of radiation in addition to doses normally received from naturally occurring "background" sources. Radiation is everywhere, and across the nation, Americans receive an average dose of 360 millirem per year because of background, evidently with no harm.

In 2008, the EPA stipulated that for the first 10,000 years following the repository's closure, a potential leak must not cause an additional dose greater than 15 millirem per year, a small fraction of the background value. Furthermore, the EPA specified that the additional dose could be no more than 100 millirem per year over a million years.

Regulations Plus Margin

"How can you guarantee anything a million years from now? I hear that a lot," says Bruce Robinson, program manager for the Yucca Mountain project at Los Alamos. Having dedicated 20 years of his life to studying and modeling Yucca Mountain, he finds it easy to spend a few minutes clarifying misconceptions.

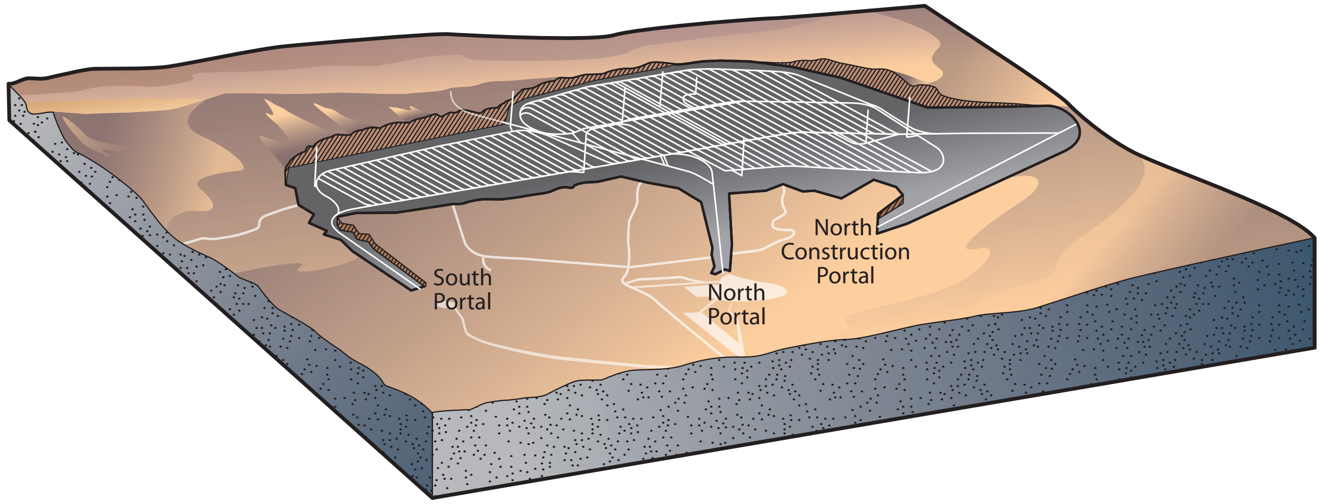
"I explain that we don't make guarantees. We run lots of computer simulations and draw conclusions about what's likely to occur. I tell people that the decision to build or not build the repository needs to be made by comparing our scientific results with the EPA's requirements, which factor in human health risks and a myriad of other considerations. That's the way we move forward."

These days, Robinson manages the Los Alamos effort to assess the long-term performance of the repository. The results are reassuring.

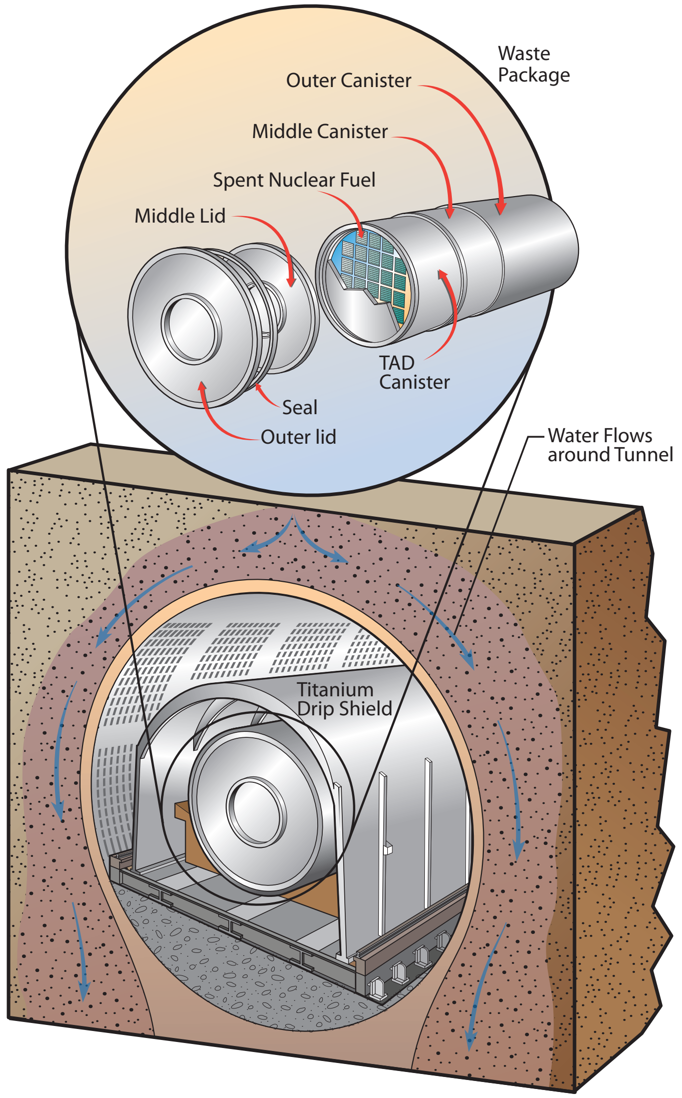
"We can say with very high confidence that the dose will be well below the EPA's maximum limits," he says. "We run our simulations hundreds of times, varying the model parameters and calculating the dose each time. For the first 10,000 years, we calculate an average dose of 0.24 millirem per year, a small fraction of the allowable limit, and 95 out of 100 times, our calculations yield 0.67 millirem per year or less. The corresponding 95th percentile value for maximum dose over the entire million years is 9.1 millirem per year, which is also very small."

Informed by those results, DOE in June 2008 filed a license application with the Nuclear Regulatory Commission, asking for permission to build the repository. The document stating the department's case is over 8,600 pages long.

The application represents a major milestone in the project's 20-some years. The repository has faced strong opposition that has effectively halted its construction. (It was supposed to have begun accepting waste in 1998.) By filing for the license, DOE makes a de facto statement: We've done our job, we've done it well, and it's time to move forward.



The nuclear waste repository at Yucca Mountain will sit inside a long ridge, approximately 1,000 feet beneath the surface and 1,000 feet above the water table. Consisting of 40 miles of tunnels, the repository will accommodate an estimated 77,000 tons of nuclear waste.



Several engineered barriers will prevent water from reaching the waste. The first barrier is the tunnel itself. Water will be redirected around it through capillary action, but if a crack or fissure allowed some in, it wouldl still have to work its way through a titanium drip shield to get to the giant 20-foot-long, 6.5-foot-wide waste packages. Each package will be a set of three nested canisters, the outer one made of a super-corrosion-resistant nickel alloy and the middle one of 2-inch-thick stainless steel. The innermost container will vary, depending on the type of waste contained. Shown is a stainless steel transportation, aging, and disposal (TAD) canister, which is used to contain and transport spent nuclear fuel and which will be used for final storage of some waste. Calculations show that water could breach these barriers only if they are defective or become damaged.

Safety Assessment

Two aspects of Yucca Mountain position it well as the site of a nuclear waste repository. The first is that no one lives within 14 miles of the sprawling mountain, although roughly 1,300 people have made the Amargosa Desert their home, preferring the desert's stillness to the kinetics of Las Vegas just 90 miles away.

The second is that the mountain sits in one of the driest locales in the United States. Water is the bane of the repository, because given near-eternity, the mighty water droplet can corrode and/or dissolve nearly anything.

The repository, a series of steel-lined tunnels dug within the middle of the ridge and roughly 1,000 feet beneath the surface, will have several barriers that prevent water from reaching the radioactive material. The waste will be sealed inside enormous stainless steel canisters, each of which will itself be sealed inside a canister of 2-inch-thick stainless steel, which will be sealed within a third canister made from a super-corrosion-resistant nickel alloy. The massive "waste packages" will be loaded end-to-end into the tunnels and covered with a titanium "drip" shield. When all tunnels are filled, the repository will be closed for all time.

Scientists assessed what was likely to happen to the waste during the millennia by using what's called a total system performance assessment (TSPA). They first attempted to identify all events that might befall the repository. Then they estimated the likelihood of each of those things occurring and assessed the consequences of their happening. Likelihood combined with consequences equals risk.

"Events that represent a great-enough risk are investigated further, and a separate analysis is done for each one," says Paul Dixon, deputy postclosure science integration manager. "We develop models of the individual processes that allow us to estimate the dose associated with each event. Then for TSPA, you evaluate all of these 'process models' together and come up with a prediction of the total dose to a person living in the region at any time in the future."

Bruce Robinson, project manager for the Yucca Mountain project at Los Alamos.

In the baseline scenario, very little happens inside the repository over the million-year regulatory period. There are no disruptive events such as earthquakes or volcanic eruptions. The engineered barriers remain intact, water reaches only a few waste packages, few waste packages ever corrode, and the waste stays within the repository.

In TSPA simulations, that scenario almost never plays out. That's because as time goes by, disruptive events, even improbable ones, become increasingly likely to occur. Earthquakes could knock the waste packages off their stands, rocks could fall from the ceiling and crack the drip shield, tunnels could collapse, or, in a very unlikely event, a volcano could rip through the repository.

Disruptive events, along with undetected faulty welds or material defects, are the repository's Achilles' heel. They could crack the waste packages, or at a minimum, allow water to contact the waste packages and begin a millennia-long corrosion process.

In the TSPA, these low-probability events eventually breach the waste packages, and water dissolves the waste material from the damaged waste packages. Once they are in solution, radionuclides can start to migrate through the 800–1,000-foot-thick layers of porous volcanic rock.

The rock's pores are only partially filled with water (it is "unsaturated"), but under the pull of gravity, the contaminated water percolates downward, and the radionuclides perform a random dance in which they bind to then break free of the rock surface. There are several such dances—sorption is one, mineralization is another—and which one occurs depends on the composition and chemical structure of the radionuclides and the rock surface, the pH of the water, and other parameters.

After several hundreds to many thousands of years, the particles reach the water table, where pressure differences cause the water to flow through "saturated" rock. The radionuclides again bind and breakdance their way through the rock for about 11 miles, at which point they might be pumped to the surface. If not brought up, the radioactive material would remain trapped below in the nearby desert, which is a closed water basin.

Map, Measure, and Model

All of the processes alluded to here (water infiltration, corrosion, transport through unsaturated and saturated rock, etc.) were investigated in great detail. As a small example, of the 7 inches of rain that falls annually on Yucca Mountain, scientists learned that only about 5 percent is absorbed by the thirsty mountain. The rainwater then takes thousands of years to percolate through the mountain, but small amounts (less than 0.1 percent) could reach the repository in only decades by flowing along cracks or fault lines.

Los Alamos scientists contributed heavily to much of the research and were instrumental in evaluating how the waste particles move through unsaturated and saturated rock. Los Alamos staff also wrote or co-wrote five sections of the license application, those pertaining to climate and infiltration (Dan Levitt), waste package and drip-shield corrosion (Neil Brown), radionuclide transport in the unsaturated zone (Bruce Robinson), flow and transport in the saturated zone (Ken Rehfeldt), and igneous activity (Frank Perry).

Along with scientists and engineers from the Sandia, Lawrence Berkeley, and Lawrence Livermore national laboratories and other institutions, Los Alamos scientists constructed numerical models of water flow and radionuclide transport through the mountain and conducted many of the basic field investigations and laboratory experiments needed to measure the parameters that go into those models.

But regardless of the skill of the experimenter, the parameters were not and could not be measured with complete certainty.

"It's the uncertainties in the parameters that raised lots of eyebrows," says Dixon. "People asked how we could know if the models are correct, and hence extendable to a million years, if the parameters aren't understood fully.'"

FEHM: One Code, Many Uses

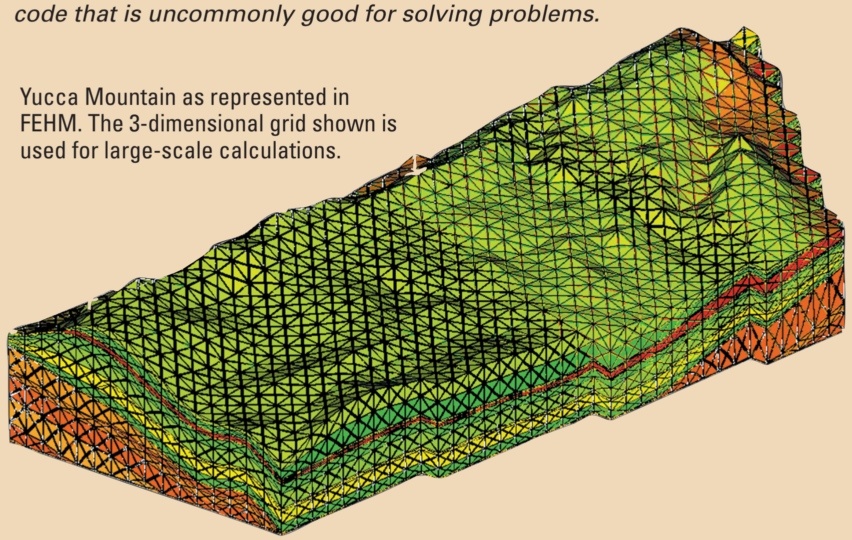
During the late 1970s, when the Laboratory's Hot Dry Rock geothermal energy project at Fenton Hill was trying to heat water by drilling deep into the earth and tapping its high temperatures (250°C–300°C), George Zyvoloski was trying to figure out just how hot the water would get as it circulated through an underground heat exchanger. Zyvoloski had a pioneering idea: find the answer by using Los Alamos' world-class supercomputers and computational facilities to solve the equations that govern how heat and mass are transported through porous media. The computer code that he began using was called Finite Element Heat and Mass, or FEHM.

"I remember submitting jobs on the Lab's Cray-1 supercomputer," says Zyvoloski, "and competing with others who were queuing up to access the Cray's awesome 133 megaflops of processing power and 8 megabytes of main memory. I was trying to understand the rate at which heat would be extracted from the rocks. The simulations proved to be essential."

Zyvoloski and others realized the inherent power of using numerical models to simulate the transport of heat, mass, and chemical constituents in porous media. They further realized that by focusing on the general set of transport equations, rather than on equations geared toward a particular application, major advances could be made in many different research areas.

The Yucca Mountain project made extensive use of FEHM to simulate how radionuclides might migrate through the mountain's porous rock. Broad new capabilities had been added to the initial code, including ways to simulate multiple fluid phases and ways to account for chemical processes that arose from interactions between fluids and minerals. So-called inverse modeling methods, in which the computer model is automatically adjusted until its output matches the available data (instead of simply running the model to see what one gets) became part of the code's repertoire. These methods were especially advantageous to project scientists in that they would help quantify the uncertainty in the model's predictions.

Today FEHM helps researchers model and understand many phenomena, including the movement of actinides in the groundwater beneath Los Alamos, the sequestration of carbon dioxide in deep saline aquifers, the extraction of organic compounds from oil shale, and the potential use of methane hydrates to meet our future energy needs. It's a commonly used code that is uncommonly good for solving problems.



Yucca Mountain as represented in FEHM. The 3-dimensional grid shown is used for large-scale calculations.

He responds that because of the uncertainties, every model gets developed for a range of parameter values. And while the exact value of a parameter is uncertain, the range of values (the parameter "space") is known quite well. Plugging a range of values into the process models can demonstrate that the conclusions drawn from the TSPA model don't change, regardless of the uncertainty of its parameters. "Within the ranges that are applicable to the repository, the mountain, and the region, we know the models are reliable," says Dixon.

Even so, once the repository is built, DOE will continue to conduct performance-confirmation tests that ensure the models are sufficiently accurate. The repository won't be sealed off for its first 100 years or so. While no one expects a startling "oops" that requires a rethinking of the repository's design, assessing *real* repository performance is the prudent thing to do.

Will the repository at Yucca Mountain be built? For Robinson, that's a societal and political decision that doesn't affect his going to work each morning.

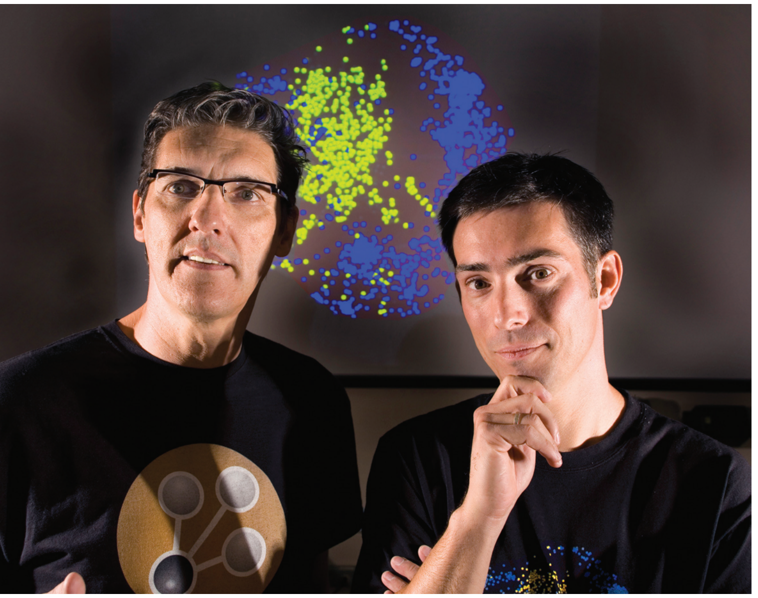
"Our job is to make sure that whatever the decision is, it's informed by science," says Robinson. "It's the complete scientific case, not simply the numbers that come out of a computer model, that provides the evidence needed for the decision. Even though natural systems are messy, complex, and uncertain, we've conducted our repository science within the structure of total system performance assessments, which show that the repository will comfortably meet the full set of regulatory requirements. That's why I believe it's safe." ❖

—Jay Schecker

The Unseen Scholars

Researching Information in the Digital Age

Computers and the World Wide Web have radically changed the way scientists and scholars do their research, including how they gather and exchange information. The Los Alamos Research Library has helped bring about those changes by conceptualizing and developing innovative, web-based research tools. Herbert Van de Sompel, head of the Research Library's Digital Research and Prototyping Team, and Johan Bollen, also of the Prototyping Team, sat down with 1663 to discuss this evolution and to touch upon ways of adapting scientific communication to the digital age.



Herbert Van de Sompel (left) and Johan Bollen

1663: Many people are surprised to learn that the Research Library employs several Ph.D. researchers, including the two of you. Why does the library need such high-powered talent?

Herbert: The library recognizes that our research, which has a significant international impact on technologies and policies for scientific communication, helps to create services that benefit researchers here at Los Alamos.

These days, scientists rarely go to the library to browse the journals for papers; they log onto the library from their computers and use a search engine to discover papers in a collection of thousands of electronic journals. The search engine is a library-provided "service." Other library services let the scientists download papers, extract citations, get alerted to new articles, get recommendations about what they should read next, etc. These services don't emerge out of thin air, and some of the more-advanced ones are built around my team's concepts and tools.

Johan: OPPIE, the Research Library's new search engine, is an example. It's very fast, much faster than the previous search engine. OPPIE searches a large archive of over 90 million records, most of them the bibliographic metadata—the title, author(s), abstract, etc.—of published articles. After finding the relevant metadata, OPPIE leads the user to the article itself.

1663: And you created OPPIE?

Herbert: The Library's Application Development Team created OPPIE. My team's focus was the archive where OPPIE's content is stored. The archive's design is very scalable, meaning we'll be able to store hundreds of millions of digital records without the system crashing or slowing down. The architecture is really novel and was designed and developed by my team. It's very modular, and all components are based on standards, some that I helped develop.

1663: What do you mean by standards?

Herbert: Standard specifications. Most of my work applies to a level that's way below the computer interface that users see. Basically, I find ways for information systems to work with each other better, and I create specifications that describe how they can do that. For example, a specification might be a set of instructions that tells two servers how to exchange information. Once a specification is released as a standard, it can be adopted by information systems on the Web. There's nothing fancy about it. It's plumbing, like the pipes running beneath the house. People are never aware of the plumbing, but because it's there, they can build fancy bathrooms and kitchens.

Johan: Plumbing is Herbert's private joke. Many people are acutely aware of his work because it's had such an influence on the way the academic and research communities access and exchange information.

1663: Joke or not, plumbing's a great analogy. Can you give us a concrete example?

Herbert: There's the Protocol for Metadata Harvesting (PMH). Soon after the Web emerged, hundreds of scientific publishers around the world started making their journals and associated article metadata available online. That was a good thing. The bad thing was that one had to search each publisher's metadata separately. In order to overcome this problem, you wanted to collect the metadata into one large pool and search it there. But there was no uniform way to collect metadata from the publishers' information systems, and they used different metadata conventions.

Johan: It was crazy. You couldn't just tell a search engine to look for an author; you had to do multiple searches in several systems. But there were hundreds of publishers, and you couldn't cover all the bases.

Herbert: In 1999, Paul Ginsparg, who created the Los Alamos preprint archive, Rick Luce, then the director of the Research Library, and I founded Open Archives Initiative (OAI). Its goal was (and still is) improving the dissemination of scholarly information through technical means. Under the OAI umbrella, several colleagues and I began to develop a protocol, a set of commands that would tell one computer system how to present metadata in a standard way, no matter how it was stored internally, so another computer system could grab it. The protocol created an interface for metadata exchange between the two systems, and it became a standard.

Systems around the world now use PMH in a variety of ways. Our own OPPIE uses it to obtain its metadata from its underlying content archive. Via PMH, OPPIE checks whether new content is available and if so, grabs it (also via PMH) and adds it to the search engine. OPPIE harvests about 90,000 new records a week in this way.

Johan: But once a scientist searches for and finds a paper, he or she wants to read it. Just a few years ago, there were some more problems involved in doing that, but another of Herbert's ideas, SFX, fixed it.

Herbert: The situation was this: a scientist logged onto the library to read a research paper and found in it a link to another paper. The first paper was in a journal published by Elsevier, a large publishing firm, while the second was in a journal published by Wiley. Because the library has a subscription to access content from both publishers, the scientist should have been able to click on the link and read the second paper, but when he clicked on the link, he was told, "Sorry, you don't have a license to access this article."

The problem was that many institutions would subscribe to a publisher indirectly through a content aggregator like

OPPIE: Bringing the World to the Laboratory

The Research Library's new, remarkably fast search and discovery engine, OPPIE, was born this year in May. "We worked on bringing this cutting-edge technology into production for about 4 years," says Miriam Blake, director of the Laboratory's Research Library. "The result is a search tool so well designed that it will be able to service the Laboratory's special needs long into the future."

The Research Library needs to provide Los Alamos employees with access to the world's scientific information, while preventing the world from knowing what information those employees are seeking. So in 1994, the library began to purchase content—articles and metadata—from publishers and store it in the library's own digital archive. Instead of searching the Web for research papers, Los Alamos scientists search this local archive, and their activities remain confidential and secure.

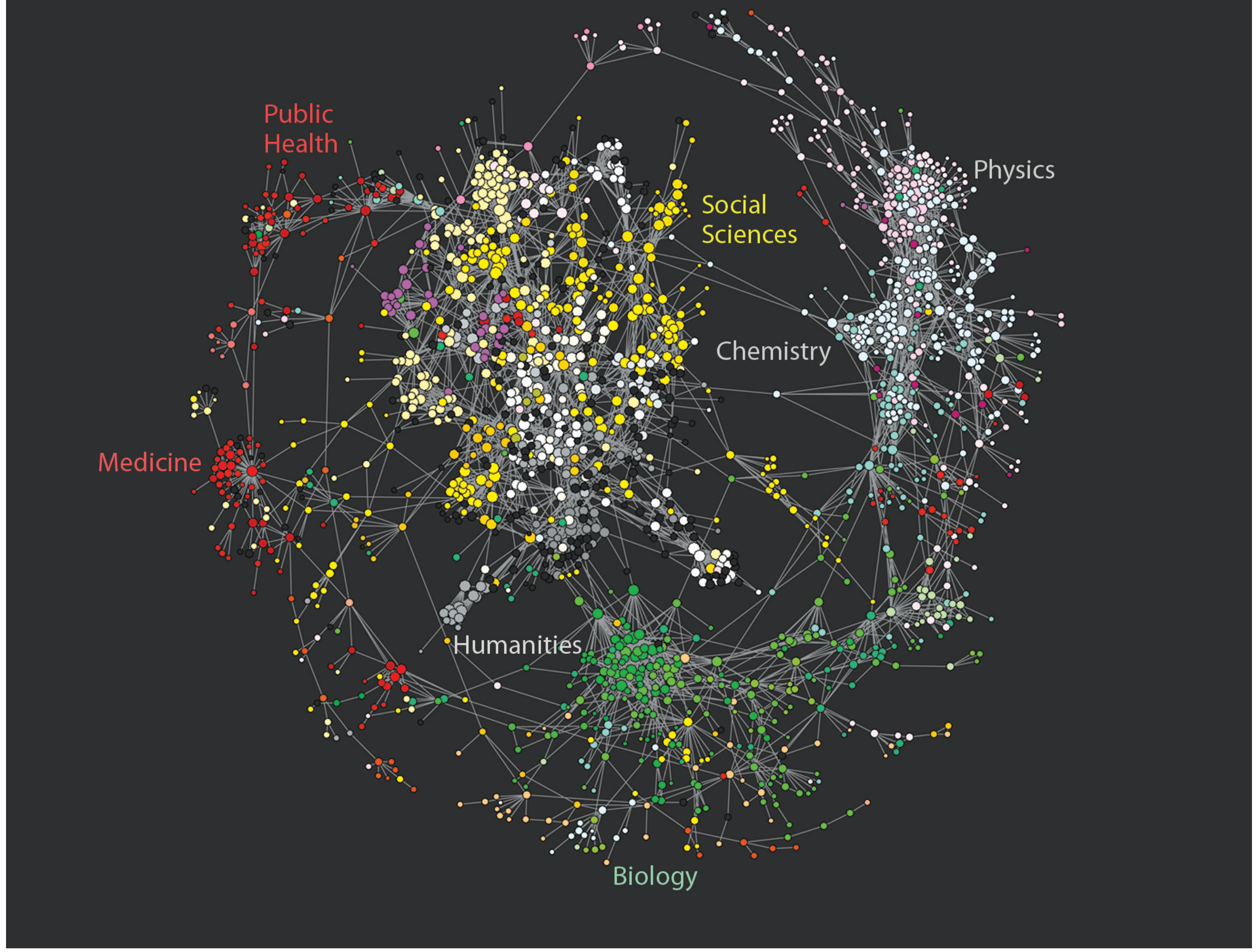
By 2000 the archive had swollen to over 70 million records and was having growing pains. Because of the way data were stored, the archive did not scale, and as the number of records increased, the archive got more difficult to search. Users began to notice that SearchPlus, the search engine that interfaced with the archive, was running more and more slowly.

A completely new type of archive, known as aDORe (pronounced "adore") was designed and developed by the library's Prototyping Team. This new archive has a unique architecture that incorporates many of Herbert Van de Sompel's standard technologies (OAI-PMH, OpenURL, OAI-ORE, info URI) and is highly scalable.

The library's Application Development Team then built OPPIE on top of aDORe, converting the millions of records into a standardized format and loading them into the distributed aDORe archive. The team built the OPPIE interface that researchers use to search the archive and continues to add other tools, many of which are implemented using freely available open-source software. OPPIE can run without expensive commercial products and should be well supported by the open-source community.

"We used widely accepted standards and open-source tools to make OPPIE sustainable and compatible with other systems. There is immense flexibility," says Blake. "We can plug in new tools and features very easily, so as the Laboratory moves into the future, we can be very responsive to evolving customer needs."

OPPIE
science starts here



Ebsco, which provides access to lots of electronic journals. Elsevier, however, would send everybody to Wiley indiscriminately, even though the scientist should go to Ebsco, because that is where their institutional subscription existed. It was a huge problem.

1663: And the fix?

Herbert: The fix was SFX, a link server, or a computer that acts as a sort of concierge. Once installed at an institution, it knows all about the institution's subscriptions and services. Now when a scientist clicks, Elsevier's link goes to SFX at the scientist's institution because that link server knows which publisher or provider the scientist should get the Wiley content from. SFX sends the scientist a pop-up message that says, "Click here to access this paper."

Johan: But Herbert didn't tell every institution around the world to buy an SFX link server. Instead he created a standard—OpenURL—that specifies how an information system such as Elsevier should link to a link server such as SFX. As a result, many commercial link servers were developed, and most academic institutions worldwide now use one. OpenURL is even supported by Google Scholar.

1663: That's very clever.

Johan: It gets better. The network of link servers opened up a whole new area of research. Every user who clicks on a link is announcing to his institution's link server, "I want to access this now." So the link server can maintain a log file of what's being accessed and when. The log is called usage data.

Herbert and I realized that if we could access the usage data of researchers worldwide, we could build an incredible picture of what is going on in science. The Andrew W. Mellon Foundation, a philanthropic foundation interested in scholarship and new tools for scholarship, came to the same conclusion and funded the MESUR project, which I've been working on for the past few years. One goal is to see if usage data will give us a way to assess scholarly impact, that is, to see who are the most-influential people, which are the most-important journals, what are the critical institutions, etc.

The value of a research paper is currently assessed using citation data. People literally count how many times the paper is cited. It's assumed that good papers get cited more often. But citation data provide a view of how science existed several years ago. It may take a year before a scientist's idea is written up, peer reviewed, and published, and then an equally long time before another scientist reads the paper and writes a new paper that cites it. It often takes several years for citations to mature in a particular discipline. If the number of citations is the only metric used to assess scholarly worth, young researchers who have been publishing for only a few years may be undervalued.

Above: In this "map" of real usage data, each dot is an electronic journal; a line between dots indicates that people accessing one journal went on to access the other. Shorter lines mean a stronger correlation. The map shows an interconnected cluster of journals from the social sciences and humanities surrounded by a network of journals from the natural sciences. The flow of information between the two domains is largely through interdisciplinary fields.

Herbert: And there is more that citation data do not reveal. Say a journal doesn't get cited much but is read by both physicists and archeologists. The journal fosters the flow of ideas between the two fields. Citation data do not reveal this because a physicist will typically not cite the archeology paper, but usage data show the connection.

Johan: We've collected perhaps the largest existing set of usage data in the world—over a billion "clicks" gathered over the years from some of the world's most-significant publishers and aggregators and a set of institutional consortia that includes the University of California, California State University, the University of Texas, and lots of others. It's an enormous dataset that we believe covers a good chunk of the online activity pertaining to research in science and the humanities, including medicine.

1663: Did you have to twist arms to get institutions to part with their usage data?

Johan: I often joke that all of my gray hair has been acquired in the past year from begging these people for their usage data. Really, most were eager to collaborate with us, in part because of the reputation that our team and the Research Library have in the community. They also know the data have value; they just don't know how to exploit the data yet. I tell them right off that usage data can be used to assess value because they reveal immediately how many people are reading which papers. That information could be used, for example, to price the journals or to reward the authors. And the value assessment would be statistically more accurate than a citation-based value because a poorly cited paper may nonetheless be read thousands of times.

But as Herbert said, we can also look at relationships between papers, or between journals, and define, say, a "bridge value" metric that quantifies to what extent a paper connects normally disparate groups. We've come up with dozens of metrics that can be used to measure value and to improve our understanding of science.

1663: Wow! You may change the entire notion of what constitutes a good research institution or who should get tenure.

Herbert: That's a general theme of the Prototyping Team's work: use the new capabilities of the digital era to improve scientific communication. Another example is the Object Reuse and Exchange project (ORE), which we worked on for the past two years. Its starting point was the consideration that in so-called eScience, a publication is not just a paper, but rather the aggregation of a paper, a dataset, maybe a video recording of a computer simulation, some software, etc. All these resources sit on different Web servers, but they form a logical whole—a digital-era scientific publication. So, somehow we must be able to express that these distributed resources belong together. We need to glue them together.

The Web gives us a fantastic mechanism, the URI, to talk about each of those resources individually by means of its Web address. It does not give us a way to talk about an aggregation of resources. I have worked with my team and with colleagues around the world to give the Web the ability to handle such aggregations. The resulting solution is based on the principles of the Semantic Web—the Web for machines—and the specifications were recently published. The Mellon Foundation, the National Science Foundation, and Microsoft funded this project. There are already groups in the United States, Europe, and Australia implementing these new specifications, and also the library is developing compliant tools. Pretty cool.

1663: Scientific communication will never be the same.

Herbert: Not if we have it our way. ✣

—Jay Schecker

Above: The open-source djatoka (with silent "d") image server, designed and developed by Ryan Chute, is another of the Prototyping Team's realizations. It facilitates delivering high-resolution images, such as the ribosome simulation shown here, to a Web browser. Just two months after djatoka's release, both scientific and cultural heritage institutions have already expressed a strong interest in the software.

SPOTLIGHT

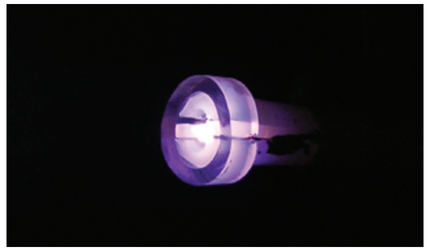
Goodbye to Pinpricks

For millions of patients with diabetes, pain inevitably accompanies blood-sugar monitoring. Pricking a finger to extract a drop of blood onto a testing strip for a glucose reading—repeated maybe four to seven times a day—is necessary to control glucose levels and to prevent serious complications such as kidney failure, blindness, nerve damage, and poor blood circulation.

Los Alamos scientist Yixiang Duan and his colleagues are developing a new noninvasive breath test to replace the painful prick.

In diabetics, low insulin levels allow sugar to accumulate in the blood instead of being metabolized and made available to cells. The body compensates by digesting fatty acids and producing chemical byproducts called ketones. Acetone, one of those ketones, builds up in the blood and gets transferred preferentially to the breath, where a high concentration is a sure sign of increased blood sugar. In healthy people that concentration is about several hundred parts per billion, but it can be 10 to several hundred times greater in diabetics, depending on the level of insulin in the body.

Duan and his colleagues have designed and developed a very-sensitive compact device for testing the breath acetone level. First, a small precision device ionizes a stream of inert gas (helium or argon) to form a stable micro-size volume of plasma the size of the tip of a ballpoint pen.


Microplasma for monitoring glucose levels.

A sample of breath is allowed to mix with the microplasma, breaking the acetone molecules and creating a special set of excited or ionized fragments that emit optical light. A palm-size spectrometer analyzes that light and displays the results on a screen. For a certain range of acetone concentrations, the amplitude of the light signal is proportional to, and therefore a quantitative measure of, the breath acetone level.

This method has been patented, and both the device that generates the microplasma and the palm-size spectrometer have been developed and implemented. Duan and his colleagues expect to integrate their apparatus into a compact hand-held device for on-site breath-gas monitoring and analysis in hospitals and private homes.

A Boost for Wireless Monitoring

The Internet and cell phones have revolutionized telecommunications. The next revolution could be in wireless sensor networks, which are webs of distributed battery-powered sensors that monitor such things as temperature, vibration, or nearby movement—movement on a battlefield or border, for example.

In Los Alamos, computer scientist Sami Ayyorgun helps these networks reach their potential with his new operational scheme: BSTeR (pronounced “booster”), for Boost by Smart Transmit-power Random-variables. The BSTeR scheme adjusts the sensors’ transmission powers intelligently, while dynamically adapting to changes in the network’s condition (sensor locations, for example), resulting in a “self-organizing” network.

Unlike cell phones, which use an array of towers to pass messages between phones, wireless sensor networks deal directly with their fellows. One sensor “hops” a message to another, which relays it forward until, sensor by sensor (multihopping), the information reaches its destination.

In a standard, fixed-power scheme, each sensor always transmits each hop at the same power level, over the same distance, and through the same forwarding sensors. Since the same sensors are always being activated, their batteries run down more quickly.

“Energy efficiency is a first-class design criterion,” says Ayyorgun, so he has designed the BSTeR scheme to *not* always send messages down the same path.

With BSTeR, each sensor chooses one of many possible power levels for each hop it transmits, basing that choice on a random number generated by an internal processor. A higher power level turns a hop into a leap, sending a message to a more-distant sensor, which then generates its own randomly powered hop.

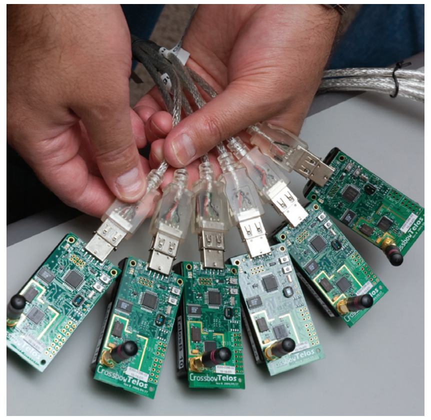
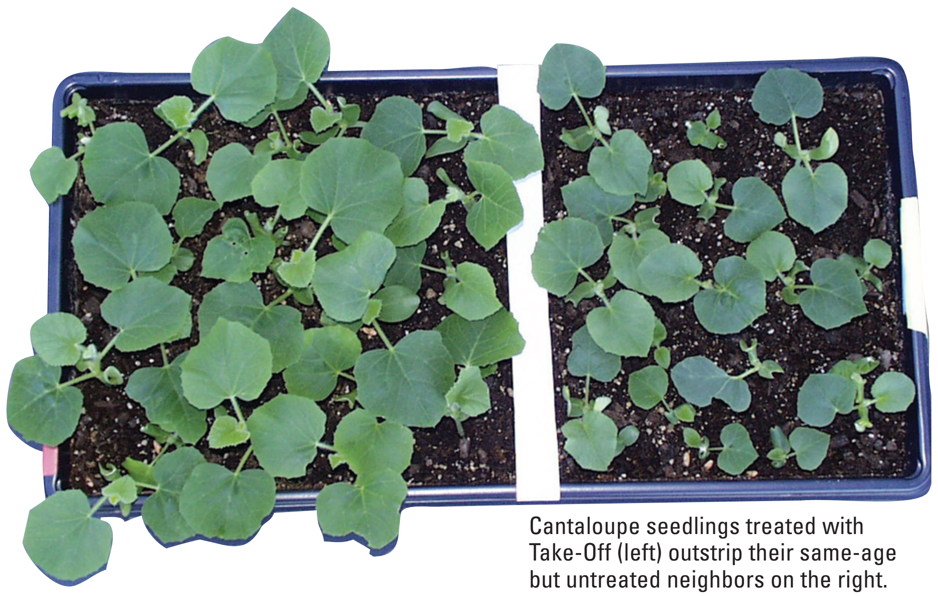


PHOTO BY DIXON WOLF

The international research community has given high recognition to Ayyorgun’s communication scheme for wireless sensors (shown here).

The diversity of transmission powers for each sensor exponentially yields many different pathways, activating different sensors and spreading power usage across the network. Over many messages, the improvements on speed and other performance metrics add up significantly, resulting in concurrent performance gains over many metrics—the first such concurrent gains reported in the literataure.

Ayyorgun presented the BSTeR scheme in the Plenary Session of the Institute of Electrical and Electronics Engineers’ (IEEE) International Conference on Mobile Ad Hoc and Sensor Systems (a premier publication venue of the IEEE) in Atlanta on September 30.


Cantaloupe seedlings treated with Take-Off (left) outstrip their same-age but untreated neighbors on the right.

Building a Better Plant

Growing more and better food crops has traditionally meant pouring on the nitrogen fertilizer, which is expensive to use and pollutes waterways through runoff. This is not a good situation, especially now when the world needs to add biofuel production to a global agricultural system that is struggling to feed rapidly growing populations. Can we cost effectively produce more food and biofuel and do so without further degrading the environment?

Pat Unkefer and her team in Bioscience Division say yes, and they’ve got a product that proves it.

Take-Off, licensed by Biagro Western, is a metabolite, an amino acid that coordinates aspects of a plant’s metabolism. It increases both the amount of carbon dioxide that the plant converts to carbohydrates and the amount of nitrogen it draws from the soil. When Take-Off is sprayed on crops, they grow faster, mature earlier, and leave less nitrogen fertilizer in the ground to contaminate water supplies. Plants treated with Take-Off also use more of their nitrogen for growth instead of storing it in their tissues.

Unkefer and her team discovered the metabolite—2-oxoglutaramate—while studying plant metabolism. They learned they could stimulate growth, without the use of hormones, by increasing a plant’s supply of this naturally occurring substance.

Synthesizing 2-oxoglutaramate proved prohibitively expensive, however, so the team identified a cheaper compound of similar structure (an analog) that replicates the metabolite’s function. It is that analog that is now on the market as Take-Off. The analog is biosynthesized and biodegradable and is thus a very eco-friendly technology, certifiable even for organic farming.

Take-Off is now being used commercially on wheat, barley, and grapes and on the biodiesel crop canola. It is significantly increasing overall yields, and is being developed for additional crops as well. The farmers are also realizing greater profitability, thus increasing their own sustainability.

In July the Federal Laboratory Consortium, a nationwide network of federal laboratories, honored Take-Off with a Notable Technology Development Award during a Denver meeting of regional members of the organization.

A Sweet Reaction

Recent studies done at Los Alamos on an enzyme that turns one type of sugar into another have yielded some unexpected insights into the reaction.

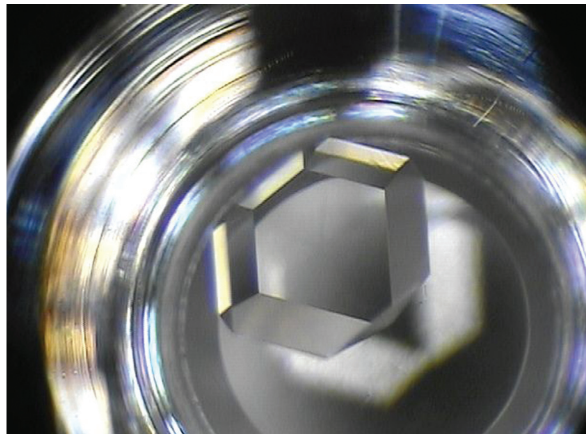
The enzyme xylose isomerase (XI) can convert the sugar glucose into fructose and is used in manufacturing high-fructose corn syrup for food products. Similarly, XI can convert the sugar xylose into xylulose, which can be used in producing different kinds of biofuels. Understanding those conversion reactions in detail may aid efforts to make the enzyme work better and hence contribute to more-efficient production of fuel and food products.

Xylose has five carbon atoms and one oxygen atom bonded into a hexameric ring, with several hydrogens and hydrogen-oxygen pairs dressing the carbons. To convert from xylose to xylulose, the enzyme helps the ring to open and then helps move two hydrogen atoms from the second to the first carbon in the now-linear molecule.

Researchers from Fox Chase Center, the University of Toledo, the University of Tennessee, and Los Alamos used the Bioscience Division’s Protein Crystallography Station (PCS) for their studies. They collected neutrons diffracted from a crystal of XI that had been soaked in a solution of xylose and that the enzyme had converted to xylulose. The neutron crystallographic data revealed the location and charge states (positive or negative charges) of atoms in the XI-xylulose complex. When the results were compared with the team’s studies of XI alone, it became possible to see how the atoms had been rearranged during the reaction.

In particular, the researchers discovered that a water molecule held in the active site of XI loses a hydrogen, whereas the enzyme itself acquires one during the shuffling of atoms. The finding, which suggests the water may play some role in the conversion reaction, may help researchers differentiate among several possible reaction mechanisms.

Paul Langan, who built the PCS with Benno Schoenborn, led the Los Alamos team, which also included Andrey Kovalevsky, Marat Mustyakimov, and S. Zoe Fisher. The work was published as a Rapid Report in the journal *Biochemistry* (Vol. 47, p. 7595, 2008) and listed as a “Hot” article.


This crystal may help scientists produce more biofuel.

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