LOS ALAMOS SCIENCE AND TECHNOLOGY MAGAZINE

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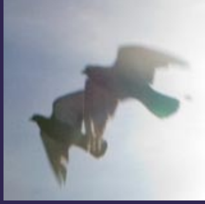


1663

DARHT Delivers

Cibola Takes Flight

Plutonium Superconductivity

Not for the Birds

LOS ALAMOS NATIONAL LABORATORY

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:
Joe Sandoval (left) and Gabriel Olivas (right) seal up one of DARHT's giant induction cells, 74 of which will be used to accelerate electrons to within a hair's-breadth of the speed of light. The electrons will produce x-rays that capture images of the inside of an imploding nuclear-weapon mockup.

LOS ALAMOS ARCHIVE

From Terry Wallace

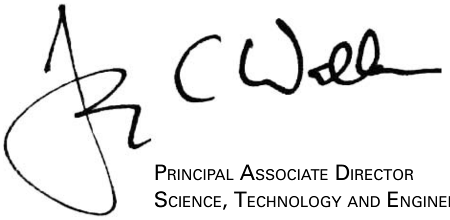
Exceptional Facilities for Exceptional Science

The rich history of Los Alamos National Laboratory is founded on science serving the nation. During World War II, the Laboratory had but a single mission—to perfect an atomic fission bomb. Immediately after the war, Director Norris Bradbury pushed Los Alamos to become a national security laboratory and had the mission diversified to include nuclear rocket propulsion, both fission and fusion nuclear energy, and the very first computational biology. Meeting those challenges required assembling a scientific work force second to none.

However, the scientists were not enough—the mission also required exceptional facilities. One of the first was MANIAC I, Mathematical Analyzer, Numerical Integrator and Computer. It was an extraordinary, programmable calculation machine that could execute 10,000 instructions per second. Today's science challenges demand significantly more computational power, and Los Alamos has teamed with IBM to build Roadrunner, a computer that will have sustained speeds of more than a petaflop—1,000 trillion calculations per second.

The most famous, widely used facility at the Laboratory is the Los Alamos Neutron Science Center, or LANSCE, which began in the 1960s as the Los Alamos Meson Physics Facility. The science pursued at LANSCE has resulted in thousands of advances in topics ranging from nuclear physics to the behavior of matter at the Earth's core.

This issue of 1663 *presents articles on two of the newest Los Alamos facilities: the Dual Axis Radiographic Hydrodynamic Test facility, often simply called DARHT, and the Center for Integrated Nanotechnologies, or CINT. Both are state-of-the-art, and both are just beginning their journey of discovery. I expect them to be keys to ensuring that the Laboratory's scientific endeavors will have significant positive impacts on our national security.*



Principal Associate Director
Science, Technology and Engineering

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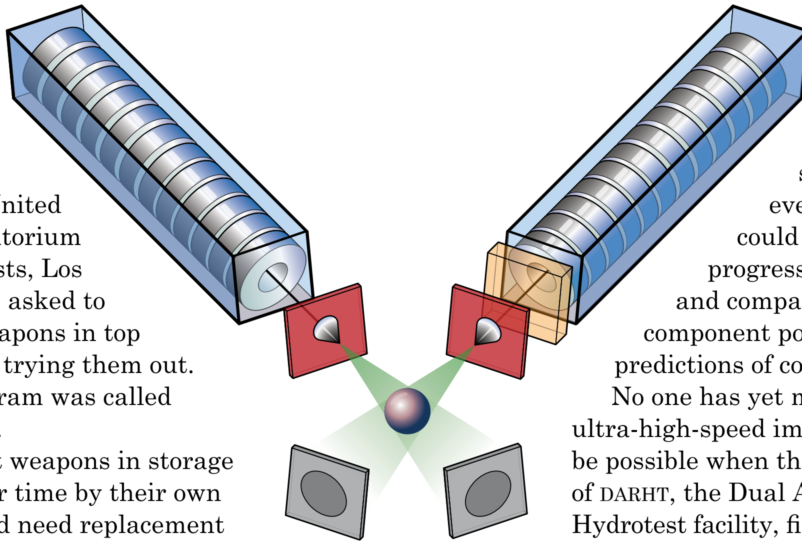
The skeptics kept saying it could never be done, but never say never…

DARHT Delivers

Through a heroic effort, Los Alamos scientists are building the world's most powerful x-ray machine for analyzing nuclear weapons. It will be the first to generate a sequence of pictures showing the dynamic events that trigger a nuclear detonation.

David Honaberger examining one of the refurbished accelerator cells for DARHT's second-axis accelerator.



The Idea behind DARHT

In 1992, when the United States declared a moratorium on nuclear weapons tests, Los Alamos scientists were asked to keep the stockpiled weapons in top condition without ever trying them out. The maintenance program was called Stockpile Stewardship.

Scientists knew that weapons in storage would be damaged over time by their own radioactivity and would need replacement components. But would the replacements function as required? And how could that be checked under the testing moratorium?

The answer was to perform the next best thing to a real nuclear test—a full-scale mockup of the events that trigger the nuclear detonation.

During a weapon's crucial triggering phase, explosive charges that surround the nuclear fuel are detonated at multiple points. The result is a shock wave that moves inward (implosion) at supersonic speeds, compressing the fuel to higher and higher density. Implosion ends when the fuel reaches a supercritical density, the density at which nuclear reactions in the fuel build up an uncontainable amount of energy, which is then released in a massive explosion.

To make the mockup non-nuclear, a heavy metal surrogate (such as depleted uranium or lead) stands in for the nuclear fuel, but all other components can be exact replicas of the real thing and their behavior tested under implosive conditions.

During the test the surrogate fuel and other components become hot enough to melt and flow like water, so this mock implosion is called a *hydro*dynamic test, or hydrotest.

Standard practice is to take a single stop-action snapshot of the weapon mockup's interior as the molten components rush inward at thousands of meters per second.

A *series* of snapshots would be even better. Scientists could follow the implosion's progress for as long as possible and compare the pictured component positions with the predictions of computer simulations. No one has yet made such a set of ultra-high-speed images. But it will finally be possible when the second arm (axis) of DARHT, the Dual Axis Radiographic Hydrotest facility, finally comes online.

The Beginning at Los Alamos

Planning for DARHT began in the early 1980s. The idea was to have a pair of separately housed giant x-ray machines pointing at right angles toward a test object between them. During a hydrotest, a single short pulse of x-rays from each machine would simultaneously penetrate the imploding test object, affording scientists instantaneous front and side views of the implosion. From those would come the first accurate three-dimensional picture of implosion dynamics.

At the onset of the test moratorium in the early 1990s, DARHT's planned capability was seen as the perfect match for the new challenges of Stockpile Stewardship. Hydrotests at DARHT, in combination with accurate computer simulations, would let scientists guarantee, without testing, that stockpiled nuclear weapons would perform as specified if they were ever needed.

Approval for the two DARHT axes came in stages, with the first axis approved for construction in 1992 and the second axis (initially to be a twin of the first) in 1997. But by then, the U.S. Department of Energy (DOE) had made a different decision. It wanted the second axis to deliver not one view of the implosion, but the never-before-captured *series* of views.

The change in scope was to have unexpected consequences.

Construction of the twin accelerator buildings for DARHT's two axes began in 1994.

(top of page) DARHT was originally designed to produce two simultaneous x-ray images taken in perpendicular directions. The facility's intense x-ray flashes (the green rays shown here) will be generated when high-energy electron pulses from each accelerator axis slam into tungsten targets (red).

DARHT's First Axis—Sharpening the X-Ray Image

The challenge for the first stage, the first axis, was to design a much more powerful and precise x-ray source that would yield significantly higher-quality images than ever before.

X-rays that can penetrate the heavy metal in a weapon mockup are typically made at an electron accelerator. An electron beam moving at near the speed of light is smashed into a tungsten target. The electrons are yanked off course by the strong electrostatic pull of the positively charged nuclei in the tungsten atoms, and their sudden change in direction causes them to give off energy in the form of high-energy x-rays.

Scientists already knew how to use a short burst (pulse) of high-energy electrons (rather than a continuous beam) to make a short pulse of high-energy x-rays. The new challenge was for the accelerator to deliver a very large number of electrons in a single pulse—several thousand amperes of electric current (household circuit breakers blow at 20 amps)—to generate a *super*-intense x-ray flash that could penetrate the mockup late in the implosion. That's when the heavy metal surrogate comes close to the density at which nuclear reactions in a real weapon start to build up in the fuel.

The 3-foot-diameter induction cells of DARHT's first axis.

(top right) A static test object placed between the DARHT first-axis x-ray source (cone-shaped projection at right) and a camera system (left). The sphere is used to test the strength of the x-ray pulse.

Furthermore, to increase the image quality, the electron beam-pulse would have to be ultrashort and focused to a very small spot on the tungsten target. As with the hole in a pinhole camera, the smaller the beam spot, the more point-like the area producing x-rays, and the sharper the resulting image. Also, to achieve stop-action shots of materials barreling inward at thousands of meters per second, the electron pulse (and resulting x-ray flash) needed to be shorter than 100 billionths of a second, about a million times shorter than exposures achieved with a high-end conventional camera.

That combination was a very tall order. But Lawrence Livermore National Laboratory in California had already developed an advanced electron accelerator for its own x-ray hydrotest facility, and that machine, known as a linear induction accelerator, met many of DARHT's requirements. In 1987 Los Alamos chose the same type of accelerator for its facility, but with more stringent requirements (see "How It Works" on the next page).

When completed in 1999, the first-axis accelerator could readily produce one short electron pulse (60 billionths of a second), of extreme intensity (2,000 amps) and with an energy of 20 million electronvolts. And it could focus the beam to a 2-millimeter-diameter spot on the target. It was the smallest spot size and shortest pulse length ever achieved at that intensity.

As a result, the overall image quality was 10 times higher than ever before achieved at a Los Alamos facility and about 3 times higher than was possible at Livermore's x-ray facility.

Beginning in December 1999, Los Alamos weapons designers were privy to the clearest single views ever made of the inside of a hydrotest object. The views helped validate new descriptions of implosion physics used in computer simulations of weapons performance.

The Drive for Multiple Pulses

By the time Los Alamos knew that the second-axis acclerator needed to produce multiple x-ray pulses, the environmental impact statements for the entire DARHT facility had already been approved, and construction of the twin buildings was complete. The long narrow hall for the second-axis accelerator was empty and waiting. But now it was the wrong size.

Making multiple x-ray pulses from a single-pulse induction accelerator would require creating a single electron pulse about 2 millionths of a second long—33 times longer than the pulse in the first axis. It would then be chopped into four shorter pieces that would reach the target sequentially.

But boosting that longer-lasting pulse to high energy would require an accelerator four to five times longer than the space planned for it!

With the second-axis building already complete, the scientists had to find a way to squeeze a long accelerator into the much shorter space—a kind of "square peg in a round hole" problem. It could be done, but only by leaving behind some well-honed accelerator design principles.

A Bold New Design

A single-pulse linear induction accelerator like that planned for both DARHT axes consists of a long row of doughnut-shaped magnetic induction cells, each connected to a high-voltage generator (see "How It Works"). At the instant of firing, each generator discharges its power, creating a pulse of electric current through its induction cell, which in turn creates a large voltage difference across the gap separating that cell from its neighbor.

Simultaneously, electrons injected into the beam line—the aligned "holes" in the induction-cell "doughnuts"— speed through the vacuum at the center of the cells, getting an energy kick at each gap.

Clearly, the voltage pulses across the cell gaps would have to persist for as long as the electron pulse did, so the scientists had to greatly slow the rate at which the power was discharged from each generator. But the voltage pulse quits when the induced magnetic field in the core of each induction cell builds up to saturation (the induced magnetic field can increase no more).

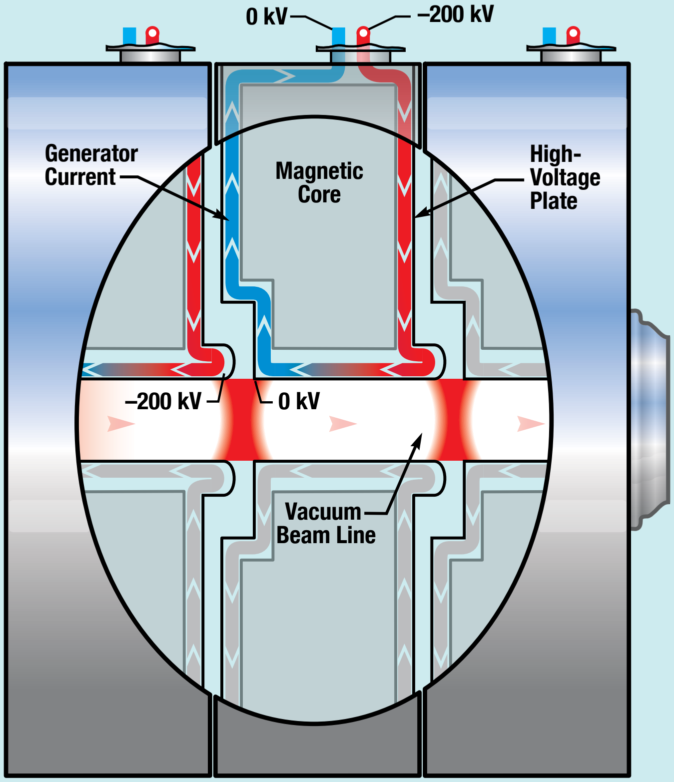
Since the time to saturation grows in proportion to the cross-sectional area of the magnetic core, the only

How It Works: Linear Induction Accelerator

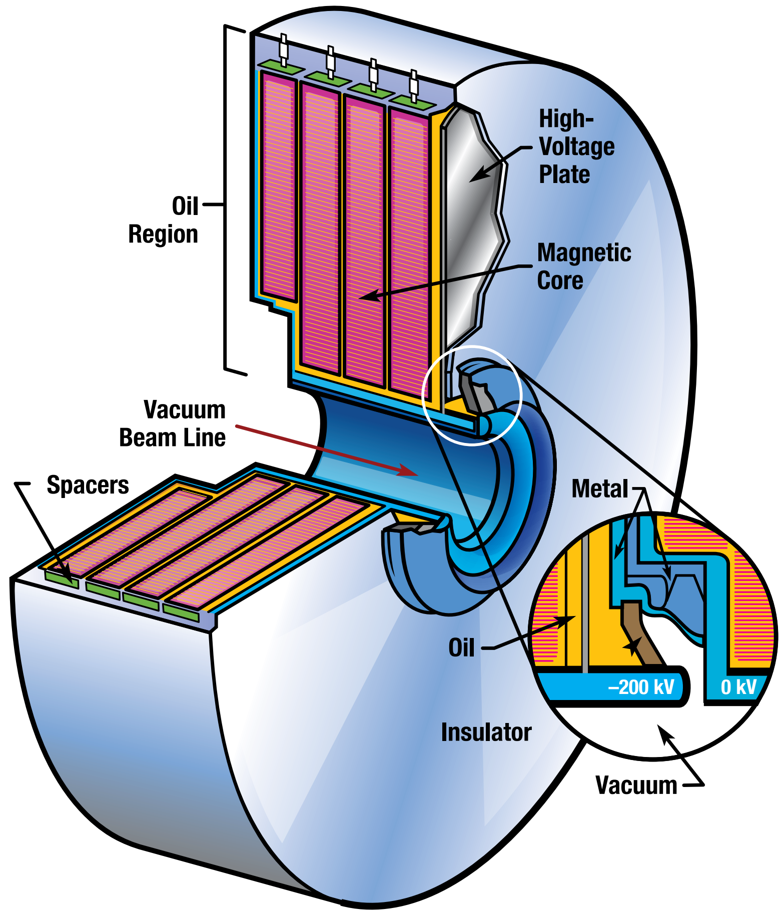
The single-pulse linear induction accelerator in each DARHT axis consists of a long row of doughnut-shaped induction cells (only three are shown here in this two-dimensional view) with a large accelerating voltage difference, –200 kilovolts (kV), across the gap between each pair of neighboring cells. The electron beam-pulse travels through the central bore of the cells, receiving a 200-kiloelectronvolt energy kick each time it passes though a gap.

To create the accelerating voltage across the cell gap, a negative voltage pulse from a generator enters each cell (red) and travels down the high-voltage plate, which connects to the inner cylindrical surface of each cell. Together, the high-voltage plate, the cell end plate, and the inner and outer cylindrical surfaces form a conducting cavity. The voltage pulse returning to ground (zero volts) generates a current (red-to-blue transition) around the magnetic cores and an increasing (inductive) magnetic field (not shown) within them.

If the cavity were empty, it would act like a short circuit, drawing too much current from the generator and reducing the voltage pulse length to a few billionths of a second. When filled with the annular magnetic "cores" surrounding the central bore, the cavity acts like an inductance, resisting the flow of current from the generator.



This three-dimensional cutaway view shows the two regions of a single induction cell—(1) the oil-filled region containing the high-voltage plate and the magnetic cores and (2) the inset region where vacuum, metal, and high-voltage insulator meet. Electrical breakdowns were observed in both regions. Each induction cell weighs about 15,000 pounds and contains four narrow magnetic cores saturated with oil.



way to prolong the voltage across the cell gaps for a relatively long time—2 millionths of a second—was to add more magnetic material to the cores. But the accelerator could not be lengthened along the beam line, so the only choice was to increase the diameter of the magnetic cores.

A design team from California's Lawrence Berkeley National Laboratory and Los Alamos ventured boldly into this unexplored design territory, designing new magnetic cores that were twice the diameter of the first-axis cores.

The team kept the increase to a minimum by replacing the material (ferrite) used in the first axis cores with metglas—paper-thin ribbons of amorphous iron tape. The maximum magnetic field strength (saturation point) in metglas is five times higher than in ferrite.

The magnetic tape was insulated by thin (less than a thousandth of an inch) layers of mylar and wound up into a roll of 20,000 turns to make mammoth six-foot-diameter cores, each four inches wide and weighing more than one and a half tons. Four cores went into each induction cell.

Sparks Fly — What's the Problem?

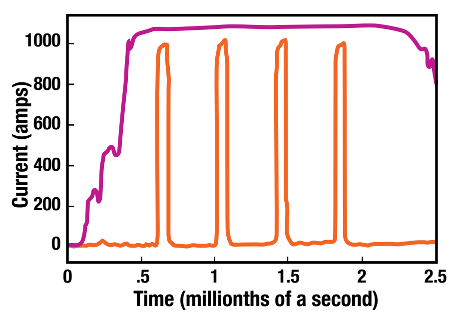
In early 2003, after fully assembling the accelerator, with its 78 induction cells, and successfully testing it with the cells at a lower voltage, the DARHT team was ready to crank the machine up to full power.

And then the unthinkable happened. Electrical breakdown! As the cells fired in sequence, they began to spark.

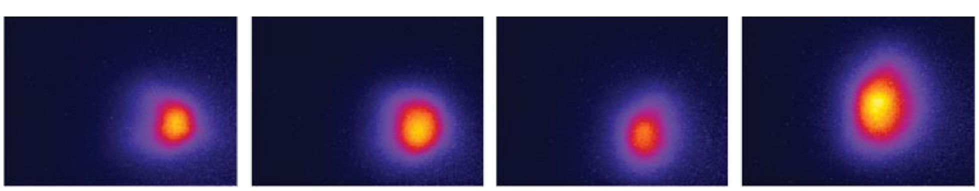
After recovering from the initial shock, Los Alamos gathered a team of the best accelerator and pulsed-power scientists and engineers from Los Alamos, Lawrence Berkeley, and Lawrence Livermore National Laboratories, as well as industry experts. This team launched an all-out effort to identify the problems and find solutions that would allow the machine to be re-engineered *without* adding new materials and components.

The origin of the high-voltage electrical breakdown turned out to be unexpectedly high electric fields between the high-voltage plate and the oil-insulated magnetic cores and at sites where metal, high-voltage insulator, and vacuum meet in the vacuum side of the cell (see the inset to the figure above).

Why wasn't the danger of high-voltage breakdown identified in the original design of the cells or detected during the original fabrication and testing phase? Because unbeknownst to the developers, the equipment for calibrating the test voltage was faulty.



Kurt Nielsen, the lead pulsed-power scientist for refurbishment of the cells, describes how the team began to turn things around. "Tens of fixes, both high-voltage and mechanical, were identified,



(left) Images of four electron-beam spots produced by the Scaled Down Accelerator and (above left) the corresponding electron pulses (orange) chopped out of a single pulse (majenta).

thoroughly tested, and implemented." The most dramatic change was lengthening each cell by one inch, which redistributed the electric fields in the oil-filled magnetic core region and reduced their magnitude—but also reduced by four the number of cells that would fit in the building. Another was modifying the high-voltage vacuum insulator that separates the magnetic core region of each cell from the vacuum beam line to ensure that it prevents the high voltage from leaking across the cell accelerating gap.

The Proof Is in the Testing

To check that the fixes would work, the team went through a series of rebuilds, called pre-prototypes, solving technical problems along the way and then testing the final configurations at high voltage.

Six prototype cells were then built and tested by being fired hundreds of thousands of times at 20 percent over the required voltage of 200 kilovolts. Not a single breakdown!

At the same time, the team launched an experimental campaign using the original cells but operating them at lower voltage (100 kilovolts) to produce electron pulses with lower energy (about 7–million electronvolts). The experiments tested the stability of a 2-millionths-of-a-second, 1-thousand-amp electron pulse, the longest pulse ever at such intensity. The results of the experiments put to rest lingering questions about stability, showing definitively that the long pulse did not break up or start corkscrewing as it traveled down the accelerator.

By July 2005 the team had entered the second phase of the project: to develop and implement a plan to disassemble and refurbish all the cells. As Juan Barraza, the lead mechanical engineer, says, "We introduced lean manufacturing, a production line approach, and it worked so well it's become a model for other Lab projects."

Final proof of the design came in the form of the Scaled Accelerator, a scaled-down version (test stand) of the full-energy machine. Twenty-six of the 74 refurbished cells, along with the "kicker," the component that would chop the long pulse into four short ones, were put together with the target system. The Scaled Accelerator was then ready for a first-time test at an energy of 8-million electronvolts.

The moment arrived in October 2006. The team fired up the Scaled Accelerator and watched in jubilation in the control room as four ultrashort, super-intense, rapid-fire x-ray bursts, made from a single electron pulse, flashed on the monitor panels. It was the first time ever anywhere in the world.

This first success was followed by a series of further tests that were just completed in February 2007. All the evidence suggests that x-ray intensity, pulse length, and spot size will easily scale to meet specifications when operating at full energy.

The Future

"A group of talented folks worked tirelessly in the face of skepticism. The result is a cell whose performance exceeded the original specifications," says Project Director Ray Scarpetti.

Scarpetti's deputy, Subrata Nath, sums up the significance of their work by saying, "The ability to produce multiple pulses with varied intensities in a pre-set time sequence means that the weapon designers will get to *specify* what they want to see, and DARHT will be able to deliver."

In June the DARHT team will start full-energy commissioning of the entire second-axis accelerator.

DARHT Project Director Ray Scarpetti (left) and Deputy Director Subrata Nath, standing proudly beside the long rows of refurbished cells now being installed in the second axis.

Cibola Takes Flight

The latest satellite from Los Alamos presages an era of supersmart space-borne sensors.

"Go Atlas!" The team in the launch control room shouted encouragement as the Atlas V rocket arced gracefully through the sky. After months of schedule changes and launch delays, Diane Roussel-Dupré and her Cibola Flight Experiment team were at last seeing their Cibola satellite—a sophisticated box no bigger than an armchair—ferried into space.

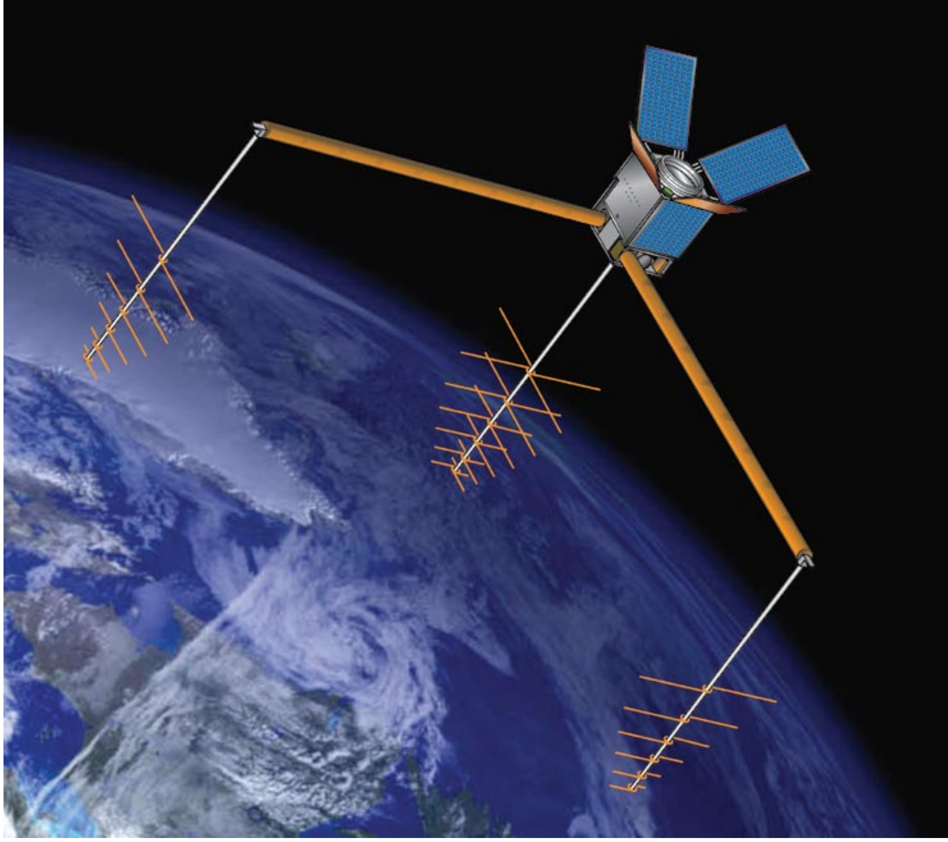
Cibola (pronounced *SEE-bo-lah*) is the newest satellite from Los Alamos National Laboratory. Its primary goal is to prove that an innovative supercomputer—developed over the past six years by Roussel-Dupré s close-knit team—can perform reliably in the harsh, radiation-filled environment of near-Earth space. If successful, the supercomputer could have a huge impact on the next generation of space-borne sensors.

As part of DoD's Space Test Program, an Atlas V rocket carried aloft two Defense Advanced Research Projects Agency satellites and four small, experimental satellites, including Cibola. An innovative "launch adapter ring" allowed the four small spacecraft to "piggyback" into space.

BEN COOPER/LAUNCHPHOTOGRAPHY.COM

A technology "pathfinder" for the Department of Energy (DOE), Office of Research and Development, Cibola will test eight new technologies that DOE, the Department of Defense (DoD), and NASA are considering for future space missions. The boxy satellite is carrying a new kind of high-density lithium-ion battery pack, a new type of power supply, inflatable radio antennas that harden when exposed to the cold of space, and the supercomputer.

"Los Alamos is in a unique position to field these pathfinder missions, which are necessary to validate new technologies," says Roussel-Dupré. "The DOE, DoD, NASA, and commercial enterprises cannot afford to fly something that may fail. The Laboratory has a very successful track record validating new technologies with the ALEXIS and FORTÉ satellite projects, two previous space-validation experiments undertaken at Los Alamos."



Artist's conception of Cibola in orbit. The three radio antennas beneath the satellite are designed to sense the electromagnetic pulse generated from aboveground nuclear detonations as well as collect data about lightning storms.

The March 8 launch from Cape Canaveral, Florida, marked the end of a three-year marathon to prepare Cibola for space flight. Los Alamos was responsible for the entire mission. It built the all-important supercomputer payload and proved the satellite was space-ready with a series of exhaustive tests. The Laboratory even monitored the contract for the spacecraft. The satellite body itself was built in just 27 months by England's Surrey Satellite Technology, Ltd.

At this writing, the diminutive spacecraft is safely in orbit. Systems are being methodically activated, and the ground crew is learning the ins and outs of flying its "bird."

The shakedown hasn't been exactly storybook. There were a few surprises uncovered after launch. But that's par for the course.

"Several are not problems, just 'undocumented' features," remarks Roussel-Dupré. "Actually, everything is functioning reasonably well, and the satellite is proving to be quite robust. But, yes, I do have a few more gray hairs."

(Left to right) Scott Robinson, Kimberly Katko, Diana Esch-Mosher, and Steve Knox watch the launch from the Laboratory's Satellite Operations Center.

Nuclear Lightning?

Underpinning Cibola's pathfinder mission is the desire to improve the ability of the United States to detect and locate above-ground nuclear explosions. A nuclear weapon emits a burst of radiation—neutrons, x-rays, and gamma rays—when detonated. The gamma rays in particular can collide with atoms in the atmosphere, freeing electrons that become accelerated in Earth's magnetic field. Those electrons emit a broad spectrum of radio waves known as an electromagnetic pulse, a portion of which (30–300 megahertz) will penetrate clouds and Earth's upper atmosphere and can be detected by a satellite.

Unfortunately, ordinary lightning is a similar pulse of energy. To be effective, nuclear-detection sensors have to be able to distinguish lightning from a true weapon-generated electromagnetic pulse. The task is sufficiently complex to require analysis by a supercomputer.

On most detection satellites, the computing power is too limited to analyze the mass of data generated by either event. Thus, FORTÉ—Cibola's immediate predecessor—relayed its data back to Earth for processing and analysis. But the communication could take place only when the satellite passed over a ground station, and there was only one such station. It's a dish antenna located on the roof of the Laboratory's Physics Building. Between transmissions, the satellite stored events in its computer memory.

"We would fill FORTÉ's memory in several seconds with a good lightning storm," says Roussel-Dupré. "Then we couldn't do anything else for the rest of the orbit, until it saw the ground station again and downloaded its data."

Cibola likewise has a downloading problem in that it talks to the Los Alamos ground station for only 10 minutes at a time, 6 times a day. But Roussel-Dupré and her collaborators envisioned a way to stretch the satellite's memory: use an on-board supercomputer to extract and save the cream of an event, then discard the rest. Send only the processed data down to Earth.

It was a great idea, except for one thing: supercomputers don't work well in space. Not well at all.

Chips in Space

Space is a harsh environment. Far from being empty, the ethereal region surrounding Earth is filled with radiation, primarily energetic charged particles from the sun and the ever-present cosmic-ray background.

Computer chips like the ones found in a desktop computer fare poorly in this harsh environment. The high-energy particles can smash into a chip and cause permanent damage.

The chips can also experience another type of radiation trauma known as single-event upsets. These are "soft errors," wherein no physical damage occurs, but the output of a memory bit (or some other chip feature) changes, say, from 1 to 0. The result could be benign or, if the upset occurs in the wrong bit at the wrong time, radically change the outcome of a calculation. The latter did not bode well for the reliability of an orbiting computer.

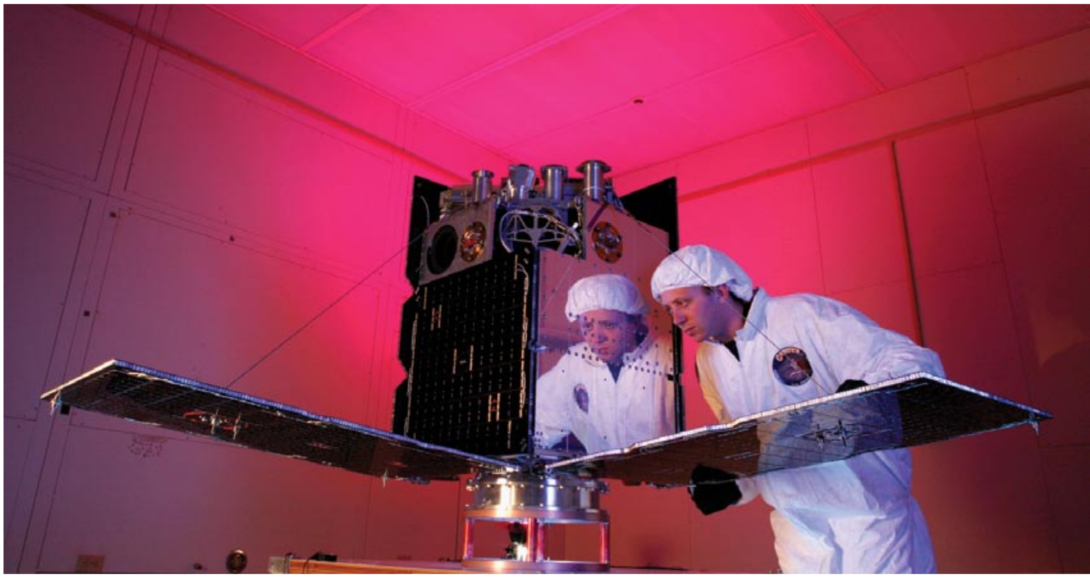
Lightning can mimic the electromagnetic pulse of a nuclear explosion. Cibola's on-board supercomputer will analyze detected events and determine which is which. PHOTO BY HARALD EDENS, © 2003, WWW.WEATHERSCAPES.COM

One way to eliminate single-event upsets is to "harden" chips to radiation damage by giving them larger features. Unfortunately, that strategy lowers the overall chip speed and increases power consumption. Additionally, all satellite components need to be in final form years before launch, so by the time they reach space, hardened satellite computers are at least 10 if not 20 years behind their ground-based counterparts in both speed and functionality.

"We wanted to have a fast, reliable computer in space," says Michael Caffrey, the payload computer's chief engineer, "but also take advantage of the technology and cost advantages coming out of the commercial chip industry." So in order to have their chips and launch them too, Caffrey's team spearheaded a new approach to the computing-in-space problem.

A Space-Capable Computer

The idea was to investigate the use of an off-the-shelf, commercial chip known as a "field-programmable gate array" (FPGA). An FPGA can host millions of elements wired together into cells that carry out logic functions. By linking various cells, one can "configure" an FPGA to perform more-complex tasks that, in turn, can be strung together to create a data-analysis program.



Daniel Seitz inspects Cibola's solar panels. The four deployed and two body-mounted panels on average provide 110 watts of precious electric power, barely enough to power a bright light bulb.

One of Cibola's radio antennas during the satellite's testing phase. Once Cibola was in orbit, a 2.3-meter-long antenna successfully deployed from the gold-colored canister.

The beauty of the FPGA is that the internal linking isn't permanent but is established through programming. By optimizing the links, one can make the computer run very efficiently. Thus, Cibola's FPGA-based supercomputer is very fast—roughly 100 times faster than what is currently available for space flight. Plus, the linking can be "tweaked" *while the satellite is in orbit* if better ways are found to differentiate lightning from a true electromagnetic pulse.

Furthermore, the computer can be reconfigured in less than a second to tackle a completely different science mission. So Cibola was planned with several missions in mind, to study lightning, for example, as well as to understand how conditions in the upper part of the atmosphere—the ionosphere—affect radio communications and other space operations.

Still, there was a hitch. "The FPGAs are not radiation hardened," says Caffrey. "They will have single-event upsets."

Could they be hardened? Collaborating with teams from Brigham Young University and Xilinx, the FPGA manufacturer, Caffrey's team worked for three years to study the problem, develop strategies, and test ideas.

The solution involved a clever tactic known as "triple modular redundancy." Suppose you could run an analysis program simultaneously on three identical (redundant) computers. Then, assuming that no more than one computer at a time can be corrupted by a single-event upset, you could compare the three outcomes to identify the correct result. In other words, you take a vote.

Limited in volume and power, Cibola could not carry three computers. But Caffrey and his team could identify critical *points* within the analysis program where a single-event upset would affect the result. They could then configure redundant computational pathways and "voter" circuits at those points and thereby harden the analysis program.

But finding the critical points is challenging, often requiring months or even years of software design time. So Caffrey's team and the Brigham Young team developed a software tool (the Brigham Young, Los Alamos triple modular redundancy tool, or BLTMR) to analyze FPGA configurations and produce a program appropriate for use in space. Caffrey states confidently that the BLTMR's output "is not only space-qualified but also is more reliable than a program produced by a software engineer."

The BLTMR can also be applied to programs used on Earth. Massively parallel supercomputers, with thousands of processors all working simultaneously, are also subject to single-event upsets from terrestrial neutrons, a problem that will only get worse as chip features get even smaller and more numerous. The semiconductor industry is very interested.

Cibola is flying at the relatively low altitude of 350 miles and will likely stay in orbit for three to five years, depending on the amount of solar activity. Solar flares eject huge numbers of charged particles into Earth's upper atmosphere. Those particles increase the drag on objects in low Earth orbit, causing them to lose energy and altitude until they eventually fall and burn up in a fiery descent. With any luck, Cibola will not meet this fate too soon, but it all depends on the sun. And no one can program that.

Diane Roussel-Dupré is the project leader for the satellite. "I am honored to have been a part of the Cibola team."

Plutonium Superconductivity and Hidden Magnetism

For decades magnetism was thought to be immutably hostile to superconductivity—the absence of electrical resistivity. Now Los Alamos discoveries have shown that some surprising materials disprove that assumption and point the way toward finding a room-temperature superconductor.

A small magnet levitates above a superconductor, which repels the tiny pellet's magnetic field. The superconductor—a material that offers no resistance to the flow of electrical current—would lose its superconducting power in the presence of a much stronger magnetic field, thus seeming to verify the conventional theory that magnetism and superconductivity never mix. Researchers are finding holes in that theory.

Superconductivity is the closest thing to a perpetual motion machine that nature has to offer. Picture an electric current circulating for years in a closed loop of superconducting wire, with no loss of energy, and you will have the right idea.

Most metals are good conductors of electricity, but in a normal metal, the electrons that carry the electric current (the conduction electrons), gradually slow down, losing energy to heat through friction as they bump against the stiff lattice of positively charged ions that forms the metal's structure. This conversion of electric energy to heat is known as *resistance*.

Los Alamos scientist Eric Bauer heats a small metal sample to 1600 degrees Fahrenheit as the starting point for growing large single-crystal samples of unconventional superconductors.

In 1911, a Dutch physicist named Heike Kamerlingh Onnes discovered that resistance in metals decreases as temperature drops and that when certain metals are cooled to near absolute zero (a very chilly *minus* 460 degrees Fahrenheit), the resistance miraculously disappears. The electrons seem to move through the metal as if the lattice were not there. The metal has changed from being a normal conductor to being a superconductor.

John Sarrao, Los Alamos physicist, explains why we should care: "Ever since this miraculous flow of current was discovered, scientists have been searching for a room-temperature superconductor with the hope of achieving enormous energy savings in electric power applications. In the U.S. electric power grid alone, 40 billion watts of electric power are continuously converted to useless heat because of the normal electrical resistance in transmission lines. A grid made of superconducting cable would save much of that energy."

Conventional Superconductivity—Up Against the Low-Temperature Barrier

When a metal turns into a superconductor, trillions and trillions of conduction electrons suddenly pair up and become very gregarious, forming a collective state in which the pairs glide in unison through the superconductor like couples in a well-rehearsed ballroom dance.

Unfortunately, the Nobel Prize–winning theory of the 1950s that explained how and why the electrons pair up in this unusual way also suggests that this phenomenon can occur only at extremely low temperatures and only in metals that are entirely non-magnetic.

For decades the theory was borne out in hundreds of pure metals and simple alloys that were good conductors at room temperature and became superconductors only when cooled with liquid helium to near absolute zero.

Unlikely Candidates

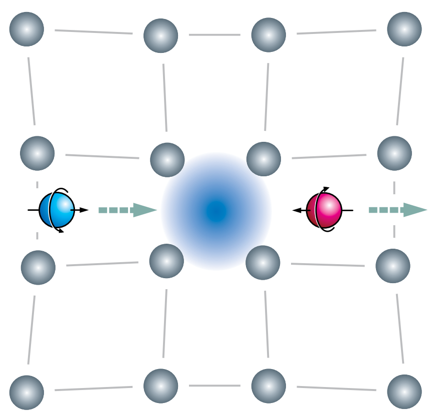
Then in the 1980s, a revolution occurred. J. Georg Bednorz and Karl Alexander Mueller of IBM tried something new, looking for superconductivity in very complicated crystalline materials. These had a layered structure made up of two or three different metallic elements as well as oxygen.

Their search was a long shot, but it led to the discovery in 1986 of a new class of copper oxide superconductors called cuprates, which broke all the rules of the conventional theory.

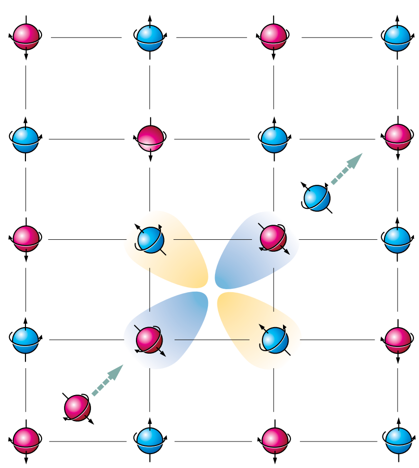
At room temperature, the cuprates are brittle, ceramic-like materials that conduct electricity very poorly and show a tendency to become magnetic. But somehow these unlikely candidates become superconductors at temperatures way above those of conventional superconductivity, temperatures that can be attained through cooling with liquid nitrogen, a cheap refrigerant compared with liquid helium.

At long last superconductivity could be turned into a practical tool. The very next year, Bednorz and Mueller won the Nobel Prize in physics, and the research effort in high-temperature superconductivity went into high gear. It has remained there ever since.

The goal is not only to find a material that superconducts at room temperature, but also to understand how the supercurrent forms at what is, for a superconductor, such a high temperature.



In conventional superconductivity, the vibration of the metal's structural lattice provides a symmetrical attraction (fuzzy blue region) between two electrons. In this artist's conception, a passing electron causes the positively charged ions (gray) to pull together, which attracts a second electron that has its magnetic pole pointing in the opposite direction.



In heavy-electron superconductors, electron pairing is caused by magnetic forces involving electrons that are bound to the structural lattice (localized). The localized electron magnets are antiferromagnetic, or alternating in direction from one lattice site to the next. A passing conduction electron causes the localized magnets to rotate and form attractive (blue shading) and repulsive (yellow shading) forces relative to a second conduction electron that has its magnet pole pointing opposite to that of the first.

What Makes Superconductivity?

In all superconductors discovered so far, the pairs of electrons making up the supercurrent are held together by a special attraction, which acts as a glue. Moreover the glue works only if the magnetic poles of the paired electrons are lined up in parallel or, more commonly, antiparallel directions—parallel but with their north poles at opposite ends. (Each electron is like a tiny spinning magnet, with north and south poles analogous to Earth's north and south magnetic poles.)

In conventional low-temperature superconductors, the glue is the very gentle vibrational motion of the material's structural lattice. The vibration acts through electrical forces to create the attraction between the paired electrons (see figure at left).

But at high temperatures, the vibration becomes so vigorous that it breaks up the pairs instead of binding them together. So what could possibly provide the glue in high-temperature superconductors?

Many suggestions have been made, but the puzzle has been unyielding for the last 20 years. Scientists, at Los Alamos and elsewhere, have only recently begun to recognize the ingredients that could lead to the solution.

"In high-temperature superconductors, several competing forces battle to dominate the behavior of the conduction electrons—electric forces and magnetic forces among the electrons, as well as lattice forces," explains Alexander Balatsky, theorist at Los Alamos. "At certain values of pressure, temperature, and applied magnetic field in the metal, the competing forces become equal in strength and the electrons can exist in more than one state, or phase. These conditions define the so-called *critical point*, and any slight change in them will produce a very large response in the material."

This extreme sensitivity is seen in water at its tri-critical point, the combination of pressure and temperature at which water's three material phases—liquid, ice, and vapor—exist together. Even the slightest change in the pressure or temperature pushes the system toward one phase or another.

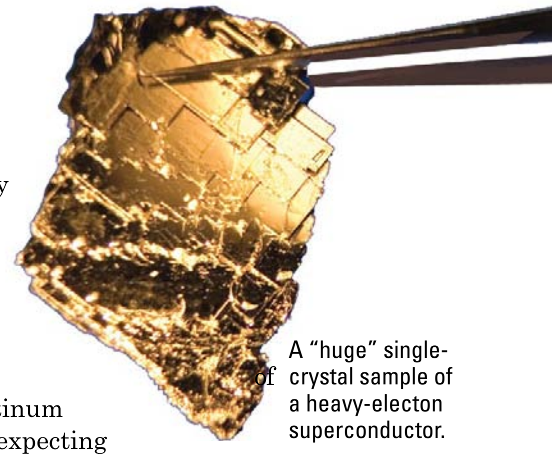
Balatsky continues, "Most materials that become high-temperature superconductors have critical points that allow the conduction electrons to exist in multiple phases at once, and it is just in the vicinity of those critical points that we find the superconducting phase. While the exact mechanism of electron pairing is still unknown, there are good reasons to expect that an interplay between magnetism and other more conventional electron-pairing forces is at the center of the high-temperature superconductor mystery."

Says Sarrao, "From all we've learned at Los Alamos, it is clear that magnetism plays an important role in the pairing mechanism of high-temperature superconductivity."

The First Unconventional Superconductors

More than 20 years ago, scientists at Los Alamos were the first become aware of an "unconventional" superconductor, one in which lattice vibrations could not explain the electron pairing, and magnetism was implicated instead.

It was a "heavy-electron" superconductor, part of a large class of low-temperature superconductors in which the conduction electrons, weighed down by the drag of the competing forces among them, act as if they have masses up to a thousand times heavier than that of normal electrons.



A "huge" single-crystal sample of a heavy-electon superconductor.

Jim Smith, a co-discoverer of heavy-electron superconductivity along with Zachary Fisk and Jeff Willis, recalls, "In 1984 we were studying a single crystal of the uranium-platinum compound UPt_3, expecting it to become nearly magnetic at very low temperatures. Before trying to measure its magnetic properties, we cooled our tiny whisker of a sample and measured its electrical resistance to check its purity. Suddenly, at about a half degree above absolute zero, its resistance disappeared. It seemed to us that superconductivity and magnetic behavior could coexist on the very same electrons."

That apparent co-existence of magnetism and superconductivity (which was soon confirmed by other researchers) came as a monumental surprise. Conventional theory had taught that magnetism *destroys* superconductivity by flipping the intrinsic magnet of one of the paired electrons, thereby breaking the pair apart. But for these very-low-temperature heavy-electron superconductors, magnetic forces seem to produce a glue that binds the conduction electrons into pairs. Moreover, the magnetic forces arise from some of the conduction electrons that become *localized*, or bound to the ions making up the lattice, as was argued by theoretical physicist David Pines and others early on (see lower figure on opposite page).

Connection to High-Temperature Superconductivity?

From today's perspective, recognizing the presence of competing electrical and magnetic forces is a crucial ingredient in understanding heavy-electron superconductor behavior.

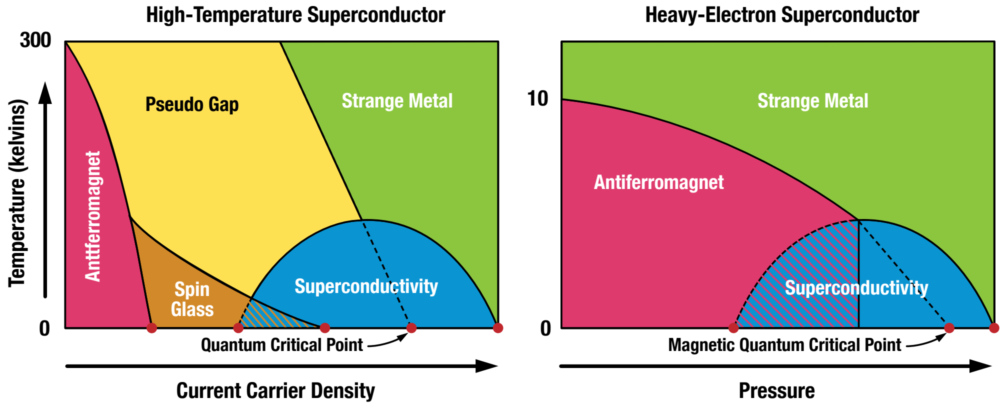
At low temperatures, magnetic forces win out, pulling the conduction electrons to localize at lattice sites and causing their tiny magnets to line up in an ordered pattern known as antiferromagnetism. In this magnetic phase, the magnetic poles of the localized electrons alternate in direction from one lattice site to the next.

At higher temperatures, electric forces dominate, pulling electrons free of the lattice sites (delocalizing them) to wander through the crystal, forming a normal metal.

In fact, researchers speculate that this competition

John Sarrao led the discovery of the first plutonium superconductor.

between localization and delocalization of conduction electrons may signal the presence of a critical point (actually a *quantum* critical point, defined as a critical point occurring at zero temperature) and may explain the co-existence of magnetic and superconducting phases in heavy-electron superconductors.



Both heavy-electron and high-temperature superconductors have an antiferromagnetic region, a dome-shaped region of superconductivity, and a region of strange metallic behavior characterized by magnetic fluctuations. Also both have quantum critical points at zero temperature (red dots) that influence their electronic behavior at much higher temperatures.

Speculation became reality when Los Alamos scientists Joe Thompson and Tuson Park looked for and found a quantum critical point in their studies of a cerium compound made of cerium, rhodium, and indium, $CeRhIn_5$. The compound is a member of a new family of heavy-electron superconductors that Fisk, Sarrao, and Thompson had discovered earlier. This family has a layered crystal structure like that of the famous high-temperature cuprate superconductors.

Thompson and Park found that their single-crystal sample was magnetic when cooled to low temperatures but became superconducting when pressure was applied.

What happened to the magnetism? Was it still there? Thompson explains, "To check, we turned on an external magnetic field, and suddenly the electrons became ordered into a magnetic state even though superconductivity was still present. The magnetic state was hidden behind the superconducting state, and at a certain pressure, both superconductivity and magnetism became manifest, depending on the strength of the applied magnetic field. At absolute zero temperature, this is just what we might expect at a magnetic quantum critical point."

It now appears that the cuprates, which superconduct at about 100 degrees above zero, share many of the same features as the heavy-electron superconductors, which superconduct at about 1 degree.

Both classes of materials support a push-pull between different competing phases: magnetism and other ordered states versus delocalization and conduction. The outcome of that push-pull can be shifted by temperature, pressure, and magnetic fields and also by the material's exact composition. Both cuprates and heavy-electron superconductors exhibit similar regions of magnetic, metallic, and superconducting phases as well as quantum critical points (see figure above).

The similarities between cuprates and heavy-electron superconductors give rise to the next burning question concerning the mechanism of electron pairing: Is the magnetic glue that binds electron pairs in the heavy-electron superconductors also making pairs in high-temperature superconductors?

Plutonium Superconductivity—A Provocative Link

Surprisingly, plutonium, the radioactive metal that forms the explosive core of most nuclear weapons, provides a link between heavy-electron and high-temperature superconductors.

During World War II, Manhattan Project pioneers learned that although plutonium metal is brittle and very hard to work with at room temperature, it becomes ductile like aluminum when heated or when small amounts of impurities (aluminum or gallium) are added to it. The reasons, however, were controversial.

Fast forward to the present and the discovery of an amazing fact—plutonium's complicated metallurgy originates from the same electronic push-pull between magnetism and conductivity that gives rise to high-temperature and heavy-electron superconductivity.

It has been known for some years that plutonium's conduction electrons are poised between localizaton and delocalization, giving plutonium an "almost magnetic" character as well as an ability to take on many structural phases. But would that competition between localization and delocalization allow or prevent superconductivity?

John Sarrao thought the best candidate for a plutonium superconductor would be a crystal of the plutonium-gallium compound, $PuGa_3$, since it would have an electronic (or chemical) structure similar to Smith's whisker of UPt_3.

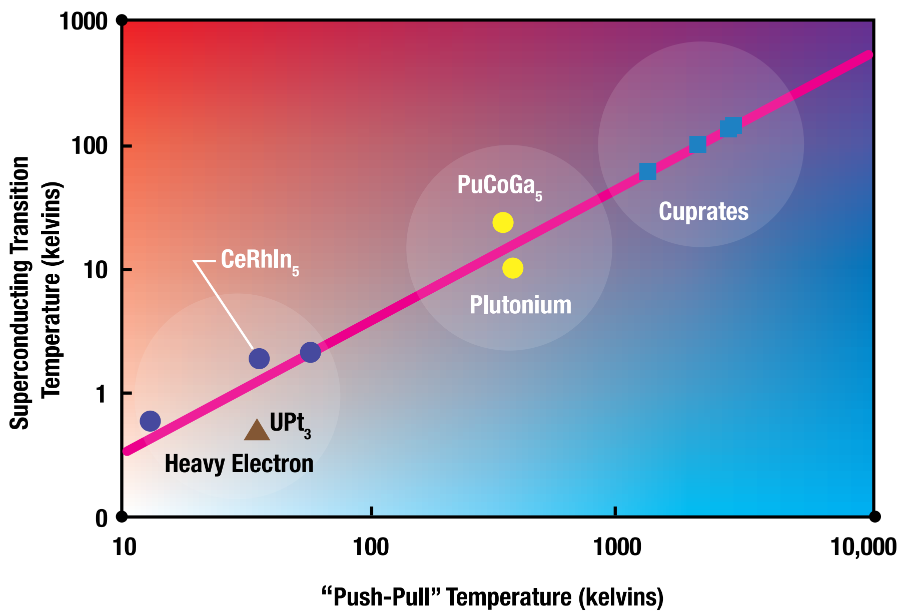
Sarrao's recipe for making large $PuGa_3$ crystals was to include some cobalt in the mix, but the result was unexpected: a huge crystal of the plutonium-cobalt-gallium compound $PuCoGa_5$. This crystal has a layered structure like that of the family of heavy-electron superconductors that he, Fisk, and Thompson had discovered earlier. Curious to learn its properties, Thompson and Sarrao cooled the big crystal down and watched it turn into a superconductor at a relatively high temperature, in between the transition temperatures of the heavy-electron and high-temperature superconductors.

Los Alamos scientist Nick Curro then showed that the plutonium superconductor was almost magnetic and that its pairing mechanism was unconventional, like that in the heavy-electron superconductors.

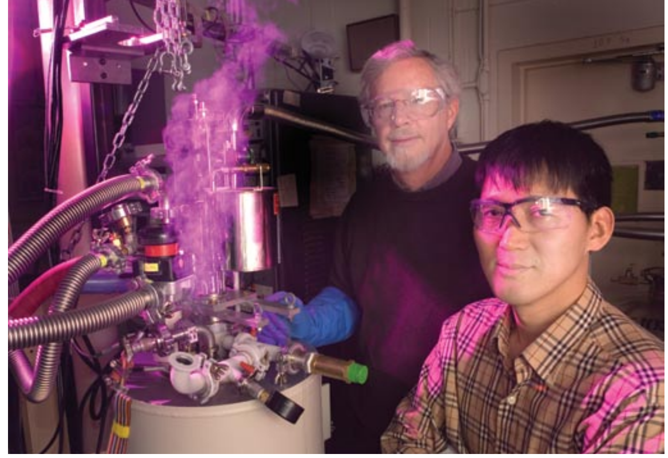
Following this discovery, the Los Alamos group looked more generally to see if the magnetic behavior of superconductors was related to their superconducting transition temperature.

Surprisingly, the answer seems to be yes. Materials that are more nearly magnetic have higher superconducting transition temperatures in the presence of competing forces. In fact, if one makes a graph of push-pull behavior versus transition temperature, the new plutonium superconductor lies smack in the middle of the line connecting the heavy-electron superconductors and the high-temperature cuprate superconductors (see figure below).

It's a strong indication that, in all these materials, the pairing occurs through magnetic forces.



The plutonium superconductors lie right in between the heavy-electron and high-temperature superconductors. The line indicates that materials with a greater tendency toward magnetism in the presence of competing forces become superconductors at higher temperatures.



Joe Thompson and Tuson Park discovered a new example of a magnetic quantum critical point in an unconventional superconductor.

Future Directions

It turns out that the crystal structure of $PuCoGa_5$ is a layered version of the easy-to-work-with form of plutonium that proved so helpful during the Manhattan Project. At Los Alamos one of the new Grand Challenges is to explore the push-pull behavior of plutonium's electrons and how that behavior might illuminate the pairing mechanism in high-temperature superconductors.

While new material discoveries are most commonly the result of accident and serendipity, Sarrao is optimistic. "We at Los Alamos have learned that special combinations of crystal structure, electronic structure, and mechanisms for making electrons pair point to likely avenues for discovering new high-temperature superconductors."

Indeed, the future looks bright from many angles. Los Alamos researchers at the Superconductivity Technology Center are already making enormous progress in taming the brittle cuprates for electric power applications. They are also conducting readiness reviews for all three national demonstration projects that are using copper-oxide superconducting power cables to deliver higher-quality electricity at higher density and more efficiently and reliably than is possible with current copper wire.

And since the physics community no longer believes in a fundamental limit on the possible superconducting temperatures, the prospects for finding a room-temperature superconductor are greater than ever.

NOT FOR THE BIRDS

Some birds species fall prey to West Nile virus while others are resistant. Finding out why may help humans combat their own diseases.

Late afternoon at the Los Alamos landfill—that's the best time and place to catch ravens. When the facility closes, the ravens show up to pick through the day's refuse. Wednesdays are ideal. That's when the restaurant garbage arrives.

Jeanne Fair knows all about the ravens' scrounging habits. Fair, an ornithologist (a scientist who studies birds) from Los Alamos National Laboratory's Earth and Environmental Sciences Division, makes regular trips to the county landfill in search of the big black birds. She's working on a study of the immune systems of several northern New Mexico bird species. Fair and Babetta (Babs) Marrone, a molecular biologist from the Bioscience Division, are principal investigators for the Laboratory project. The study combines Fair's work in the field and Marrone's expertise with an advanced analytical technique called flow cytometry, with which she examines blood samples taken from the captured birds.

Fair and Marrone are seeking evidence of the birds' response to West Nile virus, a mosquito-borne pathogen that appeared in the United States in 1999. It was first seen around New York City but has now traveled to all 48 contiguous states. It has also been found in Canada and Mexico.

West Nile infects mostly birds but is a zoonotic (pronounced *zo-oh-NOT-ic*) disease, one that can move from species to species and, in particular, from animals to humans. It has already affected small mammals and horses. In 2003, the Centers for Disease Control documented more than 9,800 human cases in the continental United States. In severe cases the virus causes meningitis and encephalitis, diseases characterized by inflammation of the brain and surrounding tissues.

Among the birds, those in the family Corvidae (the corvids), which includes magpies, ravens, crows, and jays, are the most susceptible and have the highest mortality rate. The virus has killed 95 percent of the magpies around the northern New Mexico towns of Española, Pojoaque, Nambé, and Chimayo, making the birds' once-familiar flashes of black and white quite scarce. It has also caused a significant die-off of crows and ravens across the country.

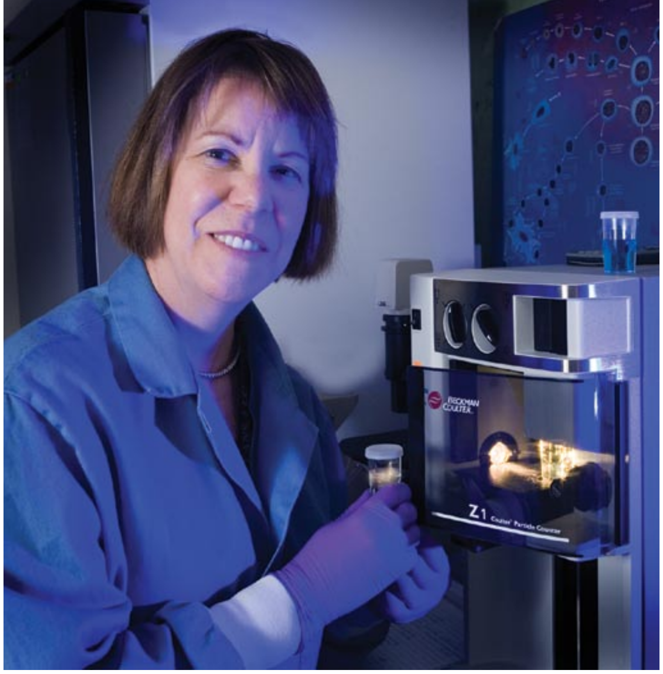
Strangely, while the corvids are susceptible to the virus, other bird species are resistant, meaning they may harbor the virus without getting sick. Domestic chickens, for example, are resistant to the virus, much to the relief of the poultry industry. In the wild, pigeons and the western bluebird are resistant as well.

Lucas Bare, an experienced bird handler, holds a raven captured at the Los Alamos landfill. Ravens are susceptible to West Nile virus and often succumb to the disease.

Fair and Marrone are trying to understand how the immune system of one bird species can resist the virus while another succumbs to it. If that difference can be understood, that knowledge may lead to intervention methods that could halt West Nile's spread through bird populations.

But there's a larger picture in the recognition that birds are a reservoir for diseases that can affect humans. Says Fair, "West Nile virus is a model system for understanding zoonotic diseases in general. The big fear is that something like the avian flu will become zoonotic, and we need to prepare for that. If we focus only on humans, we'll never get at the root cause."

Birds delight us with their songs, colorful plumage, and aerial artistry. But they also harbor diseases that can be transmitted to humans.



Back to Basics

Fair and Marrone wanted to investigate the susceptibility versus resistance issue by studying how a portion of the avian immune system, specifically a class of white blood cells known as lymphocytes, responds to the virus. Such studies would be a common strategy for understanding the issue in humans, but they had never before been attempted for birds.

Lymphocytes play crucial roles in the human immune system, and likely in all animals. Cells known as B lymphocytes produce antibodies, specialized proteins that stick to bodily invaders such as viruses and help neutralize them. Another lymphocyte, the helper T cell, activates and directs other cells of the immune system, while yet another, the cytotoxic, or "killer," T cell, attacks cells that have been infected by viruses.

The T cells are the primary regulatory cells within the human immune system, and characterizing how their numbers change in response to an infection is a natural diagnostic for all kinds of diseases. For example, the AIDS virus resides within and eventually kills helper T cells, and that particular lymphocyte is often used to monitor disease progression in AIDS patients.

Procedures for learning about a bird's T cells have traditionally been crudely quantitative. One technique involves a researcher injecting a protein called phytohemagglutin (blessedly known as PHA for short) into the flap of skin under a bird's wing (the wing web). PHA activates the T cells, causing them to divide. The researcher measures the wing web before the injection and again the day after. The increased thickness relates to the amount of T-cell multiplication and so reveals T-cell vigor, which relates to the strength of the bird's immune system.

A much more accurate tool used for counting cells is flow cytometry, Marrone's field of expertise. Marrone is working at the Bioscience Division's flow cytometry center, the National Flow Cytometry Resource, which is supported by the National Institutes of Health.

The idea is to tag each type of lymphocyte with its own marker (see illustration on opposite page), the marker often being an antibody. For example, the surface of all helper T cells is studded with a protein known as CD4, which the cell uses to recognize molecules presented to it by other immune system cells. Killer T cells are studded with the protein CD8, while other lymphocytes have their own unique proteins. An "anti-CD4" antibody will stick only to CD4 and uniquely tag the helper T cell.

The challenge Marrone faced in applying flow cytometry to avian studies was that proven markers were unavailable. A set of markers had been developed from chicken antibodies, but they had not been used for cell counting. It needed to be rigorously demonstrated that the marker set could tag the different lymphocytes reliably.

Using chickens as her test species, Marrone—along with co-workers Kirsten McCabe and Yulin Shou—developed and demonstrated the first-ever lymphocyte subpopulation measurement in birds.

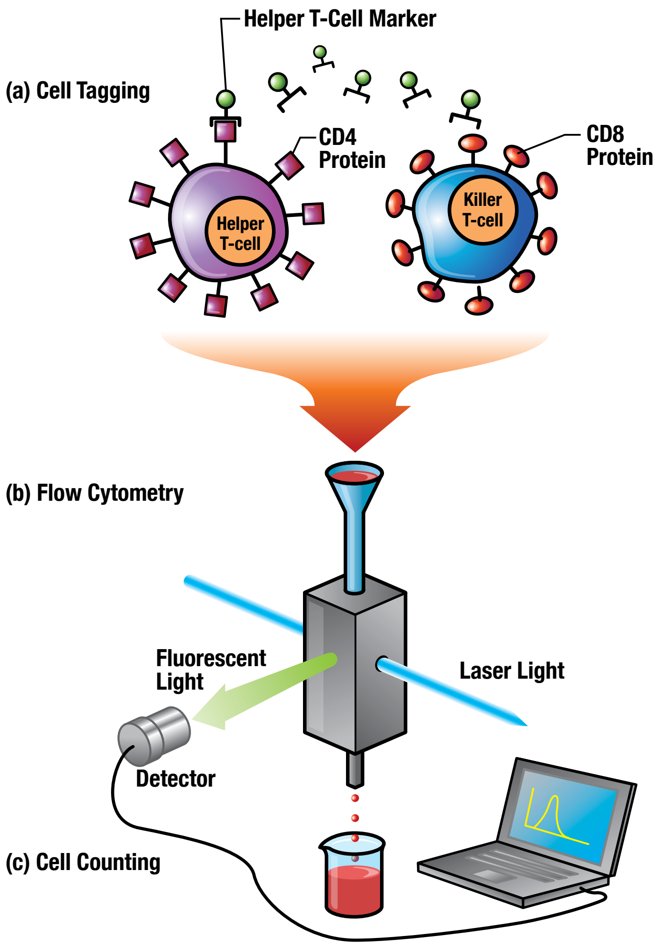
Elated, the researchers trained their sights on pigeons, a potentially critical reservoir for the virus because of the bird's omnipresence among people. It was not clear that the antibody markers, developed

(top left) Babs Marrone's expertise in flow cytometry supports her studies of how birds' immune systems respond to West Nile virus. (top right) Jeanne Fair, an ornithologist and expert on bird diseases, hopes to close the gap in knowledge concerning bird/human disease interactions. She oversees Los Alamos's Avian Nest Box Monitoring Network, a system of about 800 nesting boxes situated around the Laboratory. Researchers use the system to check for the birds' possible exposure to contaminants from Laboratory projects.

to stick to chicken proteins, would bind to the corresponding pigeon proteins. But the markers seemed to work, in that measurements of pigeon lymphocytes were in the expected proportions.

But then came a surprise. There seemed to be few differences in the lymphocyte subpopulations between infected and healthy pigeons. The researchers were again surprised when they tried to examine raven lymphocytes. The markers didn't seem to tag anything, so the researchers have yet to acquire any raven data.

"It appeared that the immune cells were more distinct between the different bird species than we had anticipated," explains Marrone. "That's making our job much harder. It's the nature of research."



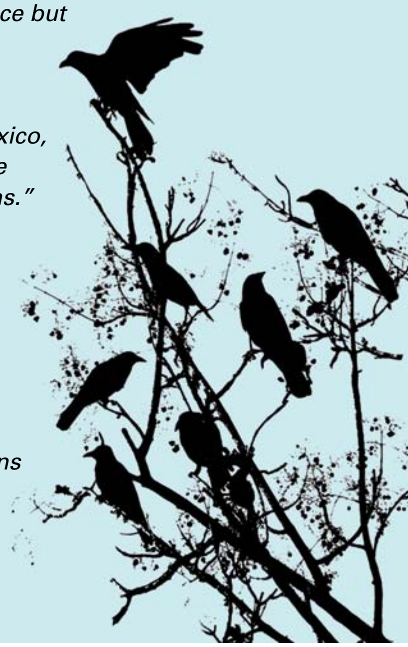
Developed at Los Alamos, flow cytometry is a method of counting thousands of cells per second. (a) Cells are tagged with a marker that lights up, or fluoresces, when it and its host cell pass through the brilliant light of a laser beam. The markers are often artificial antibodies that bind to proteins found only on the cells of interest. (b) The tagged cells are suspended in fluid and run through the cytometer, which sends them single file through the laser beam, where they light up. (c) A detector sees the fluorescent light and tells the computer, which tallies the number of tagged cells.

Birds Not of a Feather

"Ravens are the challenge of this project," says Jeanne Fair. "They're smart. We use a compressed-air cannon to fire a net at the birds to catch them. The ravens don't like it, so they stay out of sight. They even remember what vehicle we were driving the last time we came to the landfill, so we have to change cars for each trip.

"Pigeons are much easier. We simply put a baited trap—a cage with an entrance but no exit—on the roof of a business plagued by too many of the birds: the car wash in Pojoaque, New Mexico, for example. By nightfall the trap is crowded with pigeons."

All of the birds are released after the Los Alamos researchers take their samples for analysis. The ravens are returned to their original location. Happily for businesses like the car wash, the pigeons are released far from their point of capture.



Marrone and Fair are in the process of developing the means to culture avian lymphocytes in the laboratory, thereby making them readily available for further studies. The two have already established procedures to directly detect West Nile virus from a bird's blood sample and to determine whether a bird's immune system is making antibodies to the virus. They are also looking at developing ways to measure immune response that are less species specific than their previous efforts were.

The Los Alamos researchers hope that what they learn about birds' immune systems will someday lead to vaccines against the new diseases. In the meantime, their procedures that allow them to reliably test for immune responses to West Nile virus can be used to help predict where and how quickly the disease may spread through host bird populations and, by extension, through human populations. So their work isn't just for the birds. It's for all of us.

The "Nano" World—Where Less Is More

DIALOGUE

Toni Taylor, associate director of the Los Alamos Center for Integrated Nanotechnologies (CINT—http://cint.lanl.gov/), specializes in measuring the novel effects produced by tiny amounts of matter. Theoretical physicist Alexander (Sasha) Balatsky of Los Alamos leads the center's effort to understand and even predict those effects.

1663: How would you define nanotechnology?

Taylor: Nanotechnology is about using bits of matter—nanoblocks about 10 to 1000 atoms on a side—to build devices with specific properties that are designed for, say, transferring energy efficiently or detecting pathogens or making stronger structures.

1663: Will nanoscience become a defining factor in practical technologies?

Balatsky: Very likely. By looking at how matter behaves in very small regions, we are discovering totally unexpected properties and truly novel ways to make things work.

One driver for nanotechnology is the high-tech industry's desire to continue miniaturizing computer chips. Have you wondered why cell phones have more and more functions? It's because the number of transistors per computer chip is doubling every 18 months. But that trend, which has continued since 1965, will run into a steep wall in about 2015 when the transistor reaches the atomic scale.

Taylor: Even now we're running into size limitations. Some computing elements are already at the nanometer scale, containing only a thousand atoms and only a hundred or so free electrons to carry the electric current. (By comparison, a cube of matter a centimeter on a side contains about a trillion trillion atoms.) The number of free electrons always varies, but with the total number so small, the variation can affect how well the element performs.

1663: Does nanotechnology provide a way around the size limitation?

Taylor: Yes, but not by making smaller and smaller transistors. In nanotechnology we try to find the smallest structure—a nanoblock—that can produce the specific function we need. It could be a single molecule, and it could be organic, inorganic, or biological.

Balatsky: Here's an example that Toni is working on at CINT.

Imagine you want to design a hand-held sensor to detect airborne molecules. And let's say the sensor consists of a solid-state laser shining light on a tiny surface and a detector that looks at the light that's scattered, or deflected, from molecules that land on the surface.

If you pattern the tiny surface with a set of shaped, nanometer-size objects, they will interact with the molecules to create an electric field that amplifies by a millionfold the scattered light intensity from the molecules. Now you have an ultrasensitive molecular sensor.

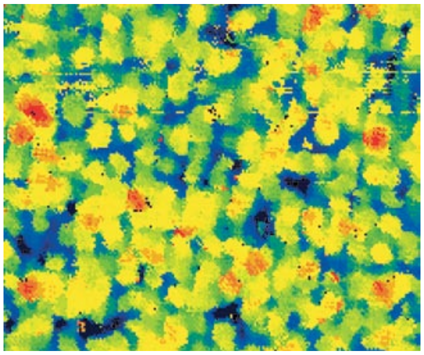
This enormous amplification of the signal came as a surprise, but surprises are common when you look at small groups of atoms. The nanoscale is a new sandbox for scientists, and we don't really have any theories to guide us.

Taylor: Another big surprise came when Victor Klimov (the CINT nanophotonics thrust leader) and his team tried to convert sunlight into electric current with quantum dots, bits of material made from a few hundred atoms. They discovered that one photon (or quantum unit) of sunlight can loosen and potentially free up to seven electrons in a quantum dot. If they can make those electrons carry electric current, quantum dots would be seven times more efficient at converting sunlight to electric current than standard solar cells.

Sasha Balatsky (left) and Toni Taylor.

1663: That would revolutionize the solar energy industry.

Balatsky: Another novel aspect of nanomaterials is their phenomenal strength. A cutting tool made from nanometer-thick layers becomes ultrastrong because it has many natural boundaries where it can relax under stress instead of cracking. A single crystal made of exactly the same stuff has fewer ways to relieve stress and cracks much more easily.



Nanoscale domains of a high-temperature superconductor as seen by an atomic microscope.

1663: Are these ultrastrong materials being made at CINT?

Taylor: Yes. We are also engineering metamaterials, materials that respond to incoming light in new ways because we've patterned their surfaces with tiny structures (see the Spotlight "T-Ray Vision" on page 25).

Balatsky: By applying either laser light or a voltage, you can, in a trillionth of a second, switch this metamaterial from *transmitting* most of the incoming light to *reflecting* most of it. So it can be a very fast switch.

Taylor: Ultimately, I think these kinds of metamaterials will be used as interconnects on chips, allowing light to carry information from one part of the chip to another. When electrons carry the information, they generate heat, which is why your computer needs a fan. Optical interconnects like these reduce the overall heat load.

1663: Is nanotechnology only about building tiny objects?

Taylor: Extremely short times are also very important—processes that occur in trillionths of a second or even a thousand times faster (femtoseconds). We have a big effort at CINT to look at ultrafast phenomena on the nanoscale, phenomena like the response of quantum dots to sunlight.

Balatsky: And of course to develop the properties of objects at the nanoscale, you have to have tools to measure what is happening at very short time and length scales. One of CINT's strengths is our world-class suite of experimental tools. Users from universities and industry can come here and find everything in one place. There are important new principles to be discovered, but only if you have the tools to look at materials in new ways.

Taylor: We use tools like atomic microscopes that see individual atoms, but we also need to marry those microscopes to other devices that measure changes in properties from one atom to the next and from one moment to the next because those changes really do occur.

Sasha, working with Seamus Davis at the Cornell University, has shown that exotic materials like high-temperature superconductors and colossal magneto-resistive materials are not at all homogeneous. Instead they're like a patchwork quilt of nanoscale regions (see picture at left) with distinctly different characters, basically different material phases living side by side in one material.

Balatsky: Yes, and the coexistence of different phases may explain the exotic properties of these novel materials. Without the computerized instrumentation to measure and record the properties of thousands and thousands of atoms in a reasonable amount of time, we would never have discovered those tiny, separate domains.

Taylor: CINT's combination of instruments and scientists makes the facility unique. We have complete laboratories where it becomes possible to combine concepts like metamaterials, nanolayered structures, quantum dots, and so on.

Bringing these exotic materials together in an integrated form is where we are heading. That's what the "I" in CINT is about—integrating different kinds of nanotechnologies to come up with functional devices and systems.

The nanotech revolution is still in the formative stage, but in 10 or 20 years, we can expect it to have a major impact on every area of technology, from pharmaceutical delivery systems that affect only the targeted organ to advanced methods for cleaning up the environment. Also, the environmental impact of nanotechnology is just beginning to be looked at. That is potentially another area in which CINT can become a leader.

Entrance to the CINT gateway at Los Alamos. The CINT core facility is at Sandia National Laboratories in Albuquerque.

SPOTLIGHT

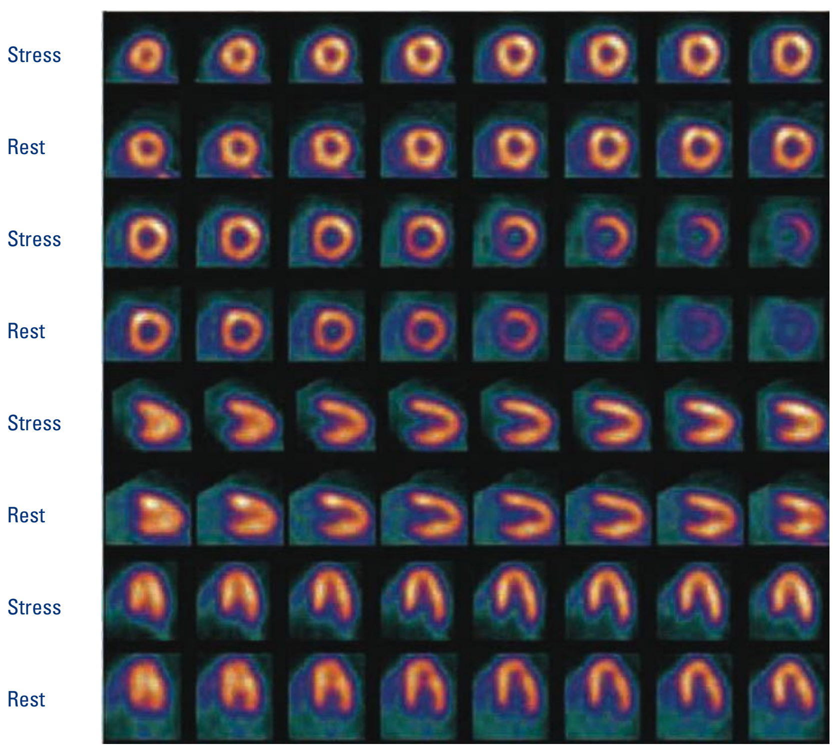
Have a Heart

The medical profession uses the radioactive isotope strontium-82 in a technology called positron emission tomography (PET) to diagnose heart disease. Nationwide, U.S. hospitals use PET on about 400 patients every day. Los Alamos recently helped avert a critical shortage of this medically important radioisotope.

Radioactive decay cuts the supply of strontium-82 in half about every 25 days, so new material must be made continually. The Laboratory's accelerator-based isotope production facility is one of only two in the United States capable of producing the isotope. The other is at Brookhaven National Laboratory in New York. Internationally, there are several similar facilities, including one in Russia and one in South Africa.

The rise in heart disease and the demand to diagnose it is rapidly increasing the global need for strontium-82. It is becoming harder for the isotope-production facilities to find time to shut down for maintenance. This year was a case in point for the Laboratory's facility. A disruption in foreign supply threatened strontium-82 shortages in the United States. With the nation's stockpile running out, the U.S. Department of Energy's Office of Nuclear Energy requested that Los Alamos postpone maintenance at its isotope production facility and stay operational for 14 extra days to make the critical isotope.

"We had to work 24-7 for 2 weeks to do it," says Kevin John, the Los Alamos program manager for the National Isotope Program. "But by staying in production, we produced a 5- to 6-week supply, enough to support 10,000 to 14,000 patients."



PET scan of a healthy heart. PHOTO FROM GENE PETERSON, C-DO

More Scallops, Please.

The U.S. Atlantic scallop fishery has become one of the largest in the world, with last year's catch earning about $400 million. Sustaining such a valuable—and delicious—resource requires the National Oceanic and Atmospheric Administration (NOAA) to set limits on yearly scallop catches, which entails carefully monitoring the mollusk population.

But how do you count scallops in their habitat on the ocean floor? You use a boat, an underwater camera, and image-recognition software developed by Los Alamos National Laboratory.

Sriram Swaminarayan and Lakshman Prasad developed Benthist 1.0, a software tool that enables the efficient analysis of oceanographic imagery. The Woods Hole Oceanographic Institute, which has been photographing scallop populations for years, has licensed Benthist to process more than 200 terabytes (200,000 gigabytes) of digital images.

Running on a standard computer, Benthist can process approximately 1.5 images per second and count scallops with accuracy greater than 85 percent without human intervention. The previous technology the institute used took between 90 and 120 seconds per image, required significant human interaction, and achieved less than 40 percent accuracy. On high-performance hardware, Benthist can process images at an even faster rate and provides the means to analyze textures and shapes. Thus, Benthist has opened up the possibility of more fully characterizing the ocean's many habitats.

Counting scallops is part of a larger

effort to study and monitor the health of marine habitats in the face of global warming and deep-sea commercial fishing. The data will help the NOAA regulate fisheries. For information on Woods Hole's ocean floor mapping, see http://www.whoi.edu/oceanus/viewArticle.do?id=15526.

Dipstick Update

The last issue of *1663* highlighted development of the "flu dipstick," a fast, reliable, and inexpensive way to identify flu and flu-like pathogens. The dipstick project has since received a three-year grant of more than $2.6 million from the National Institute for Allergies and Infectious Diseases. The money will help further the development team's research.

The dipstick will primarily be used in hospitals and clinics for medical diagnosis and infectious disease screening—determining, for example, the difference between avian flu and SARS. But the self-contained, hand-held device is so easy to use that emergency personnel will be able to make on-the-spot diagnoses in the field, a valuable frontline capability for those trying to contain an epidemic.

T-Ray Vision

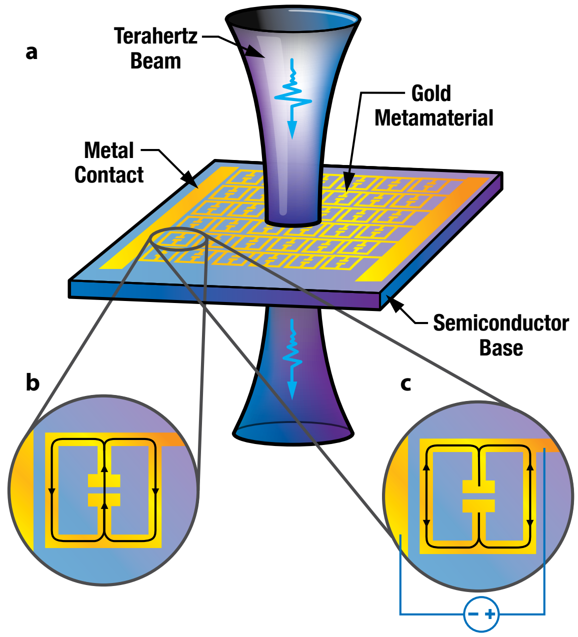
Along the electromagnetic spectrum, tucked in between the infrared and microwave frequencies is the region of terahertz radiation. Like microwaves, terahertz radiation, or T-rays, can penetrate a wide variety of non-metallic materials like paper, plastics, wood, and ceramics.

Because they can "see" through plastics and cardboard, T-rays have the potential to be used in manufacturing for such tasks as inspecting packaged objects for quality control or process monitoring. But the T-rays don't have enough energy to knock electrons from atoms so, unlike x-rays, will not damage DNA. Therefore, they might be a safer alternative for certain types of medical and dental imaging.

The problem with putting terahertz radiation to use, however, is that although devices for generating and detecting T-rays are well along in their development, techniques for manipulating the high-frequency radiation have lagged behind.

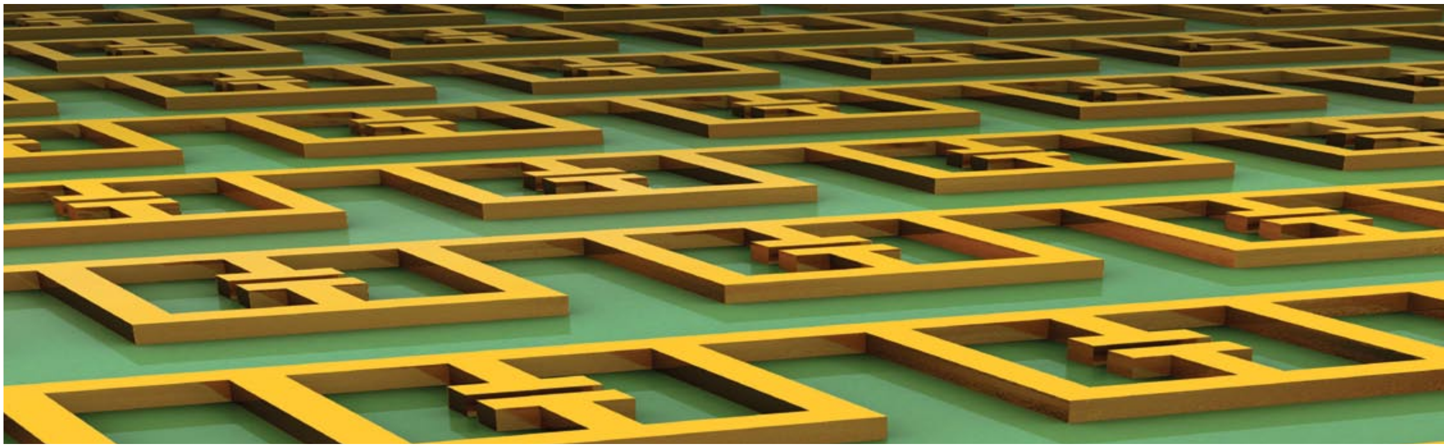
As reported in the November 30, 2006, scientific journal *Nature,* Los Alamos scientist Hou-Tong Chen and his colleagues have now developed metamaterials (artificial materials with properties derived from their subwavelength structures instead of their compositions) that can be used to efficiently modulate terahertz radiation.

To create the metamaterial, Chen and his colleagues used the micro-fabrication resources of the Los Alamos-Sandia Center for Integrated Nanotechnologies (CINT) to lay down an array of gold structures on top of a semiconductor base. The metamaterial and the semiconductor together form a device that can modulate the intensity of the T-rays by up to 50 percent when a voltage is applied to the gold structures. The experimental demonstration of the device exceeds the performance of existing electrical terahertz modulators. The team hopes to further improve the device's performance in coming months.



(a) T-rays shine through the modulator.
(b) With no voltage applied, electrons can flow across the gap in the gold structure. The electrons absorb a few T-rays as they flow easily around the two loops. (c) Applying voltage prevents electrons from crossing the gap. But they absorb far more T-rays as they slosh back and forth between the upper and lower halves of the structure. Fewer T-rays pass through the device.

FIGURE ADAPTED BY PERMISSION FROM McMILLANPUBLISHERS, LTD: *NATURE* 444, 30 NOVEMBER 2007



Terahertz metamaterial. Each box-like structure is about 36 millionths of a meter on a side. ILLUSTRATION BY VICENTE GARCIA

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