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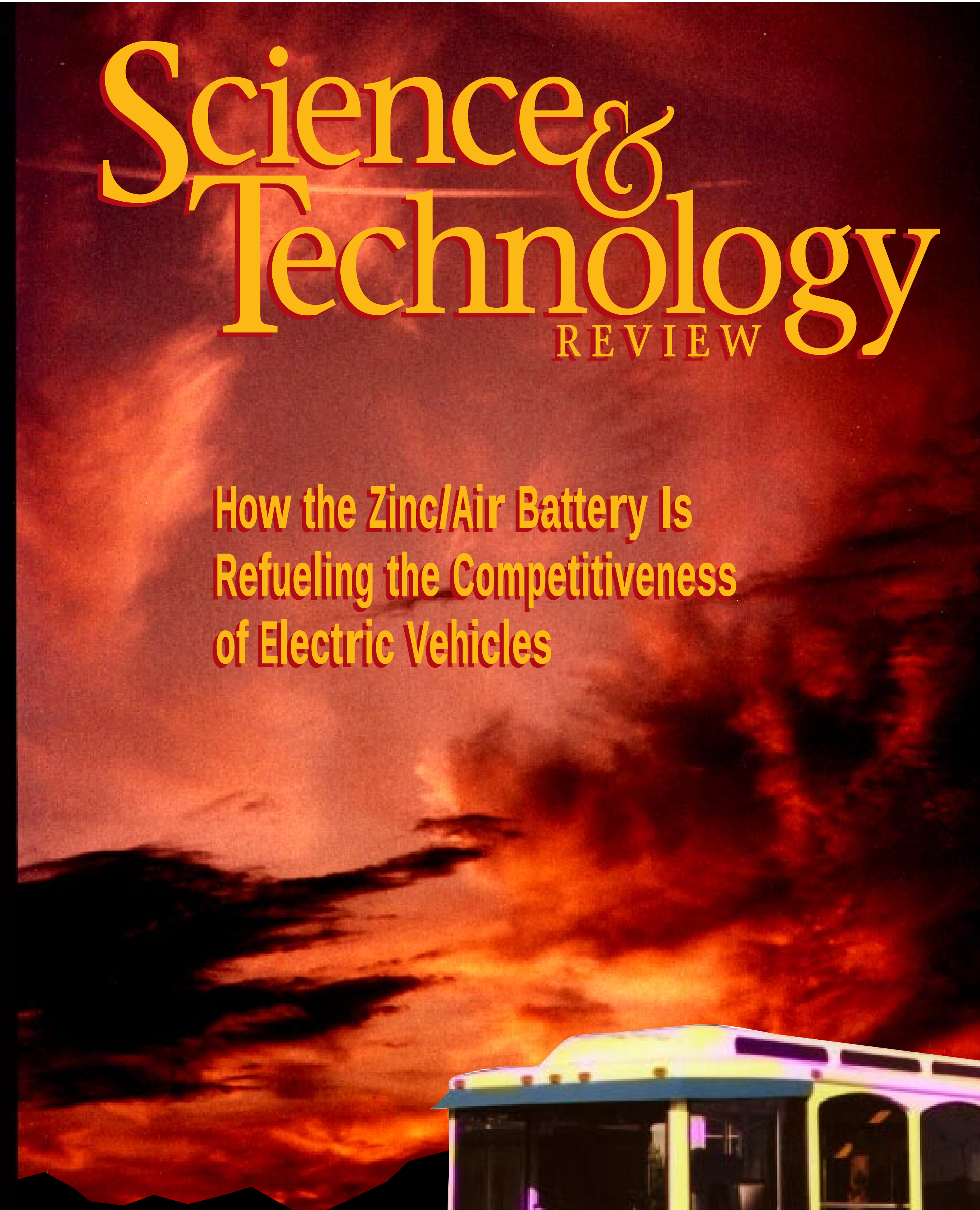
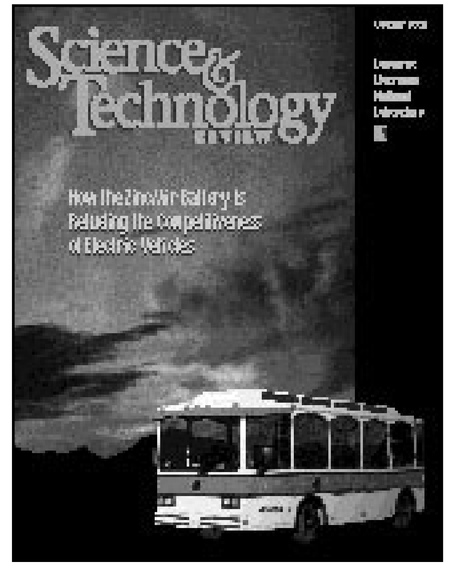


How the Zinc/Air Battery Is Refueling the Competitiveness of Electric Vehicles

About the Cover



The Laboratory is making noteworthy progress in the development of innovative energy sources for alternative transportation vehicles. This month, *S&TR* features a report about the zinc/air battery developed by Laboratory scientist John Cooper. Cooper and his colleagues recently road tested this refuelable battery in an electric shuttle bus on loan from the Santa Barbara Metropolitan Transit District in southern California. The bus, pictured on the front cover, was powered in part by the light-weight, environmentally clean zinc/air battery, which generates power from small (1-mm) pellets like those spilling across the back cover. The zinc pellets and electrolyte that fuel the battery can be recycled quickly and inexpensively. Our report on this important advance in alternative transportation, especially electric fleet vehicles, begins on p. 6.

What Do You Think?

We want to know what you think of our publication. Please use the survey form on the inside back cover to give us your feedback.

Electronic Access

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About *S&TR*

The Lawrence Livermore National Laboratory, operated by the University of California for the United States Department of Energy, was established in 1952 to do research on nuclear weapons and magnetic fusion energy. *Science and Technology Review* (formerly *Energy and Technology Review*) is published monthly to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments, particularly in the Laboratory's core mission areas—global security, energy and the environment, and bioscience and biotechnology. The publication's goal is to help readers understand the accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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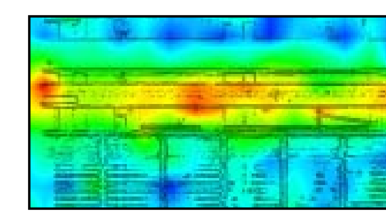

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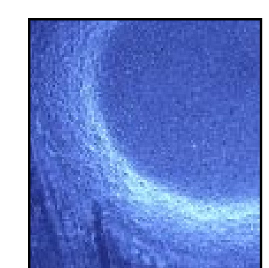

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Terawatt laser tests are prelude to petawatt

Laboratory researchers have been putting their new 100-terawatt, high-power, ultrashort-pulse laser through its paces, testing some of the basic concepts underlying a petawatt laser they plan to debut in January. Ramped up to full power for the first time on July 31, the terawatt system produced 125 trillion watts of power in an extremely short pulse—less than 0.5 trillionths of a second.

The laser was made possible by a revolution over the last few years in the ability of scientists to produce extremely short high-power and high-intensity pulses. "The regime of physics accessible with the 100-terawatt laser is only now beginning to be explored," said Mike Campbell, Associate Director for Lasers at LLNL.

The system will have applications in basic laser–plasma physics, x-ray lasers, fast-ignitor research, and many other areas, while simultaneously serving as an engineering prototype for the Laboratory's petawatt (1-quadrillion-watt) system. Initial testing of the petawatt is slated for December, when it will produce 10 to 20 times the power of the 100-terawatt laser.

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Upgraded FXR back in business this month

Shut down since June to complete a $3.5-million performance upgrade, the Laboratory's Flash X-Ray Radiography (FXR) facility was scheduled, at *S&TR* press time, to be back in business in mid-October.

In the era of science-based stockpile stewardship, FXR is viewed as a key tool to help assure the safety and reliability of the nation's nuclear weapons stockpile. In addition to its stewardship role, FXR is used for experiments on advanced conventional weapons and on shaped charges, and it is a testbed for future flash x-ray technology.

In operation since 1982, FXR was designed to provide test data for verifying computer-simulated predictions of how imploding objects behave. The 40-meter-long linear induction accelerator shoots an electron beam at a tantalum target. The target emits an intense cone of x rays aimed at a test object that is detonated on the firing table. The high-speed x-ray image produced is similar to a picture taken in 60 billionths of a second.

Prior to shutdown, the FXR was composed of 54 cells—6 injector cells that generate the electron beam and 48 accelerator cells. Modifications this summer and early fall involve adding four cells to the injector to produce a 2.5-megavolt, 3-kiloampere electron beam, a significant increase from the previous 1.2-megavolt, 2.2-kiloampere beam system. A more powerful, higher quality beam will reduce the beam spot size from 2.4 millimeters to 1.6 millimeters, resulting in a higher resolution x-ray image.

Upgrading of the FXR will permit development of a process called "double pulsing," in which two snapshots are taken in close succession. Work on double pulsing will begin in 1996.

Contact: Charles F. "Joe" Baker (510) 422-9536 (baker3@llnl.gov).

Lab scientists aid in discovery of dwarfism gene

Laboratory scientists were among members of two national biomedical science teams that earlier this year identified the genetic cause of two forms of dwarfism—pseudo-achondroplasia, or PSACH, and multiple epiphyseal dysplasia, or MED. Both conditions are marked by shortened limbs, loose joints, and the early onset of osteoarthritis.

Working over a two-year period, the research teams found that the conditions are caused by mutations of a gene located on human chromosome 19. The gene—called the cartilage oligomeric matrix protein, or COMP, gene—is important for normal bone development and joint function. The scientists' discovery is discussed in the July 1, 1995, issue of *Nature Genetics*.

One of the Livermore scientists, Greg Lennon, says that in the long run the discovery may lead "to a better understanding of joint and bone disorders—including osteoarthritis—and ways to treat them."

Lennon and his colleagues Harvey Mohrenweiser, Anne Olsen, and Susan Hoffman provided the research teams with expertise that helped localize the region of chromosome 19, with which both diseases and the COMP gene were associated. They were also resources for detailed analysis of the normal gene.

Lennon worked with scientists from the University of Texas—Houston Health Science Center, the University of Texas—Houston Medical School, the National Center for Human Genome Research at the National Institutes of Health, and Harvard Medical School. Mohrenweiser, Olsen, and Hoffman collaborated with scientists from the Cedars–Sinai Medical Center in Los Angeles and the Jefferson Medical College in Philadelphia.

Contact: Greg Lennon (510) 422-5711 (lennon5@llnl.gov).

Lab joins study of childhood thyroid disease

Members of the Laboratory's Environmental Programs directorate are on a U.S.–Ukrainian team that is undertaking what has been described as the largest and most detailed study of its kind of the effects of radiation exposure on the incidence of thyroid disease in children.

The work focuses on 70,000 children who lived in areas of Ukraine that were heavily contaminated in the 1986 accident at the Chernobyl nuclear power plant. A primary objective of the study, estimated to last 15 years, is to determine to what extent exposure to radioiodine, especially iodine-131, results in thyroid disease in children.

The scientific protocol that lays out a plan for the study was signed in May by the U.S. Ambassador to Ukraine and the acting Ukrainian Minister of Health. Work under the protocol is expected to cost roughly $1 million annually, which will be funded primarily through Department of Energy funds.

As a designated "Center of Excellence" for the epidemiological study, the Laboratory will play a lead role in the dose-reconstruction efforts and will purchase and deliver medical and other supplies needed to keep the study functioning over its 15-year lifetime.

Other U.S. participants in the study are the National Cancer Institute and the Nuclear Regulatory Agency. Ukrainian participants include the Ministry of Health of Ukraine, the Ukraine Academy of Medical Sciences, the Ukrainian Research Institute of Endocrinology and Metabolism, the Ukrainian Scientific Center for Radiation Medicine, and the Ukraine Radiation Protection Institute.

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Climate models may have ignored sulfate aerosols

Conventional climate-modeling studies may have omitted an important factor in predictions of greenhouse warming—the effects of sulfate aerosol pollutants, which result from photochemical reactions of sulfur dioxide emitted by fossil-fuel combustion.

That is the assessment of Laboratory researchers who developed a computer model to track the effects on the atmosphere of both sulfate aerosol pollutants and greenhouse gases, such as carbon dioxide emissions, from burning fossil fuels.

During the past 100 years, average temperatures have increased 0.5°C, instead of the 1°C predicted by conventional computer climate models. The predictions, however, considered the effects of greenhouse gases only, not sulfate aerosols pollutants, which tend to lower temperatures. Predictions of climate change in response to both greenhouse gases and sulfate aerosols are a closer match to actual observed temperatures, the new Livermore studies indicate. The work by physicists Joyce Penner and Karl Taylor and climatologist Ben Santer is discussed in the June 16, 1995, issue of *Science*.

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MIR crosses $1-million royalty, licensing fee mark

Teleflex of Plymouth Meeting, Pennsylvania, has become the tenth company to license the Laboratory's new radar technology—micropower impulse radar, or MIR. Originally developed by engineer Tom McEwan as part of a diagnostic system for our Nova laser, MIR has earned more than $1 million in royalties and fees.

All companies that receive a license for the radar technology are required to have their MIR-based products substantially manufactured in the U.S., thus creating jobs inside the country. Teleflex, which specializes in four industries (aerospace, marine, automotive, and medical), said it plans to construct a new manufacturing facility in Florida, partly to turn out products based on our radar technology.

In recent months, the technology has generated more than 2700 calls to the Laboratory from businesses and individuals. Because of continuing interest from business, we held the first MIR trade show in August. At press time, a second one is planned for October.

Michael Odza, publisher of *Technology Access Report*, an industry newsletter, said he believes "the Livermore radar is the fastest growing technology license in the entire federal laboratory system."

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Patents and Awards

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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Howard W. Hayden James A. Horton Guy R. B. Elliott	**Process for Continuous Production of Metallic Uranium and Uranium Alloys** U.S. Patent 5,421,855; June 6, 1995	A process for the conversion of uranium oxide and the production of metallic uranium and/or uranium-containing alloys that would be economical and result in the production of little, if any, uranium-contaminated waste products, eliminating the problem of their disposal as waste material.
Thomas E. McEwan	**Linear Phase Compressive Filter** U.S. Patent 5,422,607; June 6, 1995	A filter circuit and process consisting of a ladder or series of stages of low-pass filters in which each stage has an inductor with a voltage-dependent variable capacitor, varactor or PIN diode, to ground. The inductors and varactors are noncommensurate such that the values are accurately and independently established and made to correspond to a conventional phase-linear filter.
Joseph Farmer	**Method and Apparatus for Capacitive Deionization, Electrochemical Purification, and Regeneration of Electrodes** U.S. Patent 5,425,858; June 20, 1995	An electrochemical separation process and apparatus for removing ions, contaminants, and impurities from water and other aqueous process streams and for subsequently electrically placing the removed ions back into a solution during the regeneration process. Fluid flows through a continuous open serpentine channel between electrodes of carbon–aerogel composite.
Joel B. Truher James L. Kaschmitter Jesse B. Thompson Thomas W. Sigmon	**Pulsed Energy Synthesis and Doping of Silicon Carbide** U.S. Patent 5,425,860; June 20, 1995	A process for selective synthesis of polycrystalline beta silicon carbide from sputtered, amorphous, silicon carbide thin films using excimer laser radiation by simultaneously depositing (sputtering) a film of amorphous silicon and carbon on a fused silica substrate and directing pulses of excimer laser radiation onto the formed film to selectively crystallize areas in the film.
John C. Whitehead	**Valving for Controlling a Fluid-Driven Reciprocating Apparatus** U.S. Patent 5,427,507; June 27, 1995	An improved valve control system for a pair of free-piston pumps that use valve assemblies operatively connected to each pump and interconnected so as to have fluid pressure communication between them. The valve arrangement permits rapid switching between the pump's intake and exhaust and provides large cross-sectional areas for the flows with a short stroke as well as minimal hardware mass and size.

Awards

In mid-August, 16 Laboratory employees received **Weapons Recognition of Excellence** awards from the Department of Energy. Rear Admiral Charles Beers, Jr., DOE Deputy Assistant Secretary for Military Applications and Stockpile Support, presented the awards in a ceremony attended by over 300 people. The Awards, which represent achievements over the past three years, are as follows:

1995
Technical Excellence in Weapons Design: **David Stanfel, Leon Keller, and Gary Carlson**

Technical Excellence in Radiochemical Diagnostics: **Ronald Lougheed**

Technical Excellence in Weapons Materials: **Carlos Colmenares**

Technical Excellence in Weapons Science: **Neil Holmes**

1994
Technical Excellence in Experimental Diagnostics: **Charles McMillan**

Technical Excellence in Nuclear Design: **Jon Bryan, Dan Davis, George Kramer, Joseph Sefcik, and Peter Stry**

Technical Excellence in Computing: **Randy Christensen**

Technical Excellence in Opacities: **William Goldstein, Carlos Iglesias, Theodore Perry, Forrest Rogers, Paul Springer, and Brian Wilson**

Technical Excellence in Material Sciences: **Jagannadh Akella, John Moriarty, and Choong-Shlk Yoo**

1993
Technical Excellence in Nonnuclear Weapons Design: **Dennis Baum, Leonard Haselman, and Larry Shaw**

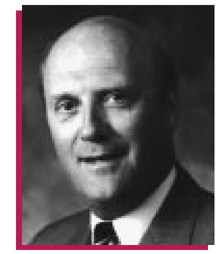
Technical Leadership in Weapons Design: **Thomas Thomson**

Technical Excellence in Weapons Disassembly: **Peter Baylacq, Patricia Billy, Lee MacLean, Albert Celoni, Thomas Devlin, Gus Grogan, William Hubbel, James Lewis, David Prokosch, James Raymond, Joseph Schmitz, and Stephen Thompson**

Technical Excellence in Weapons Design: **James Ferguson, Richard Sharp, and Jim Slone**

Technical Excellence in Weapons Codes: **Eugene Canfield, William Chandler, Lila Chase, E. Gary Corman, Ned Dairike, Gary Henderson, Samuel Stone, and Roy Swiger**

Commentary on Energy Research



Robert Schock
Acting Associate Director, Energy

LAWRENCE Livermore National Laboratory's distinguished history in energy R&D is rooted in its beginnings, when work began on harnessing nuclear fusion for energy production. This early work made our Laboratory one of the first to apply its technologies for civilian energy purposes. This work has since broadened to many aspects of energy and has had a deep impact on the energy industry. As an example, Laboratory-developed models of petroleum formation are now used routinely in the search for oil worldwide.

Reasons for emphasizing energy research in our early years were straightforward: deep convictions that energy is vitally important to society and that there is a role for government in achieving long-term goals that are partly or totally external to the marketplace. Energy is the fuel that has driven all economies since the beginnings of civilization, providing mobility, communication, comfort, and relaxation. A good example of goals external to the marketplace is proving the scientific and technical feasibility of fusion.

In the U.S., gasoline is readily available and is cheaper than it has ever been, adjusting for inflation. However, significant changes are now taking place that will affect all of us in the developed world. The economies of the developing countries are growing so rapidly that their energy use will soon tax the capacity of known energy sources. The developing countries have four-fifths of the world's population and are rapidly developing their economies. The Chinese have increased their energy use more than 50% in 10 years and have recently become the second largest energy market in the world, after the U.S. The trends mentioned above must make us seriously question whether the current situation is sustainable and what the role of the U.S. will be in future energy markets.

The Laboratory has led in advancing technologies to help sustain world economies while protecting the environment. One example is research on hydrogen as a future fuel, particularly for use in vehicles (see *Science and Technology Review*, July 1995). Conservative economic analyses indicate that hydrogen can be used as a fuel at a cost comparable to the cost of fueling today's vehicles, with essentially none of the associated detriments to air quality. Hydrogen burns very efficiently, and the product of its combustion is water.

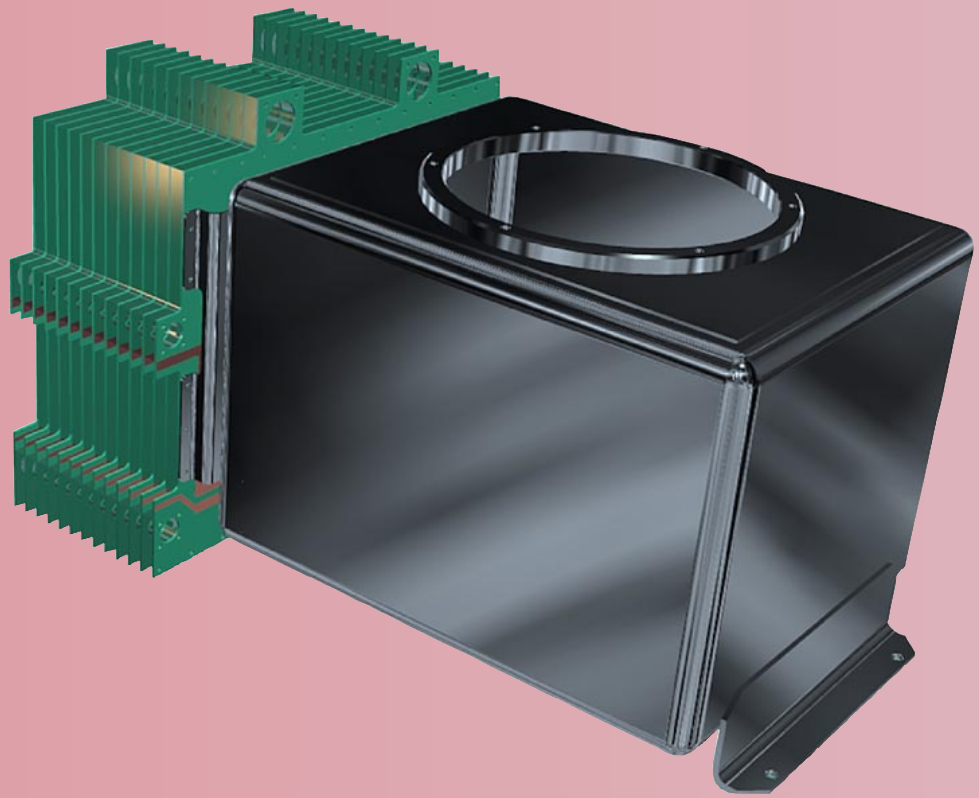
The advanced flywheels that we are developing will help store energy for advanced vehicles and allow superior power conditioning and storage in our homes and workplaces. We will no longer need to suffer power interruptions and surges. Another vehicle technology is the zinc/air power system described in this issue. Our research into the technologies used for manufacturing will result in energy savings by reducing the machining time and materials needed. These technologies will reduce our dependence on foreign oil, along with associated vulnerabilities to interruptions and price shocks.

Nuclear fission power has real potential for greatly reducing the amount of carbon dioxide we put into the atmosphere as a result of electricity generation. No one can say for sure what will be the consequences of greenhouse-gas-induced climate change, but evidence grows relentlessly that the temperature rise over the past half century is due to such emissions. We are working to resolve the technical issues inhibiting public acceptance of nuclear power as well as those relating to the prudent and safe disposition of nuclear waste.

At present there is a crisis in energy R&D, particularly over the role and size of the government's funding. Can and should the private sector do it all? Energy now accounts directly for $500 billion of the $6-trillion U.S. economy. Yet we are spending only $2 billion (less than 0.5%) on government energy R&D, and the budgets appear to be heading significantly lower. That $2 billion represents about 2¢ per every gallon of gasoline we use. By comparison, our total government R&D budget is about $60 billion; so we spend 3% of the government's R&D money on energy, which contributes 8% to the economy, clearly an underinvestment. Industry spends an amount similar to what government spends, on both energy R&D and on all research. Can we as a nation afford to spend so little on something so important to our livelihood and productivity now and in the future? If we need additional impetus, it comes from world markets for energy technologies, currently $1.5 trillion a year and growing rapidly.

For these reasons, energy R&D must continue to be an important facet of the Laboratory's mission of fulfilling the strategic objectives of the nation.

Powering Future Vehicles with the Refuelable Zinc/Air Battery



A recent road test at LLNL underscored the zinc/air battery's capacity to give electric vehicles some of the attractive features of gas-driven cars: a 400-km range between refueling, 10-minute refueling, and highway-safe acceleration.

Figure 1. Santa Barbara Municipal Transit District bus at Lawrence Livermore National Laboratory.

LABORATORY employees may have done a double take one day last February when they saw a blue-and-white bus emblazoned with the words "Downtown Waterfront Electric Shuttle" coursing around the site. The bus (Figure 1), on loan from the Santa Barbara Municipal Transit District, was being powered in part by a revolutionary new type of battery called the refuelable zinc/air battery. The battery was operated as part of the bus's power train to verify the road-worthiness of a fully engineered prototype.

Developed at Lawrence Livermore National Laboratory, the battery weighs only one-sixth as much as standard lead/acid batteries and occupies one-third the space, yet costs less per mile to operate. What's more, because the battery is easily refuelable, it promises trouble-free, nearly 24-hour-a-day operation for numerous kinds of electric vehicles, from forklifts to delivery vans and possibly, one day, personal automobiles.

The battery's inventor, LLNL electrochemical engineer John Cooper, was one of a handful of bus riders that day, monitoring the battery's performance and occasionally driving the remarkably powerful vehicle. The road test underscored the potential of the battery to give electric vehicles some of the attractive features of gas-driven cars: a 400-km range (250 miles) between refueling, rapid refueling (10 minutes), and highway-safe acceleration. The positive test results also cleared the way for discussions with a host of interested commercial partners about further development.

For all of its advancements, the chemistry of the zinc/air battery is relatively simple (Figure 2). The device combines atmospheric oxygen and pellets of zinc metal in a liquid alkaline electrolyte to generate electricity with byproducts of zinc oxide and potassium zincate. In operation, the battery consumes all of the zinc. Refueling is easily accomplished by replacing spent electrolyte with fresh electrolyte containing recycled zinc pellets.

Such a refuelable battery has clear advantages over rechargeable and reconstructible batteries. For example, it can be "topped off" and even refueled on the roadway in an emergency. Except for the alkaline electrolyte (which contains the same hydroxide found in popular liquid drain cleaners), all of the materials making up the battery are relatively safe and do not pose the environmental dangers found in other battery types containing lead, concentrated acids, flammable metals, and other toxic or hazardous materials.

Because new zinc fuel can be generated from spent zinc oxide in the electrolyte by using relatively small and simple equipment designed by Laboratory researchers, the battery needs only a modest investment to support it. Refueling would be done at a company's home base using existing maintenance personnel. Quick, easy refueling is a particular advantage for companies needing rapid refueling or extended use throughout the day for their fleets of shuttle buses, taxis, delivery vans, passenger vans, forklifts, or aircraft support vehicles.

Fast Development

The successful bus test capped a remarkably short development period for the battery. It started in 1991, when Cooper noticed a Lab energy program poster display of a proposed oil shale retort. One display pictured crushed shale rock falling by gravity through a narrow channel before it was heated for oil extraction.

"The rock formed an open matrix by bridging small gaps, which slowed the feed rate," Cooper recalls. "I reasoned that the

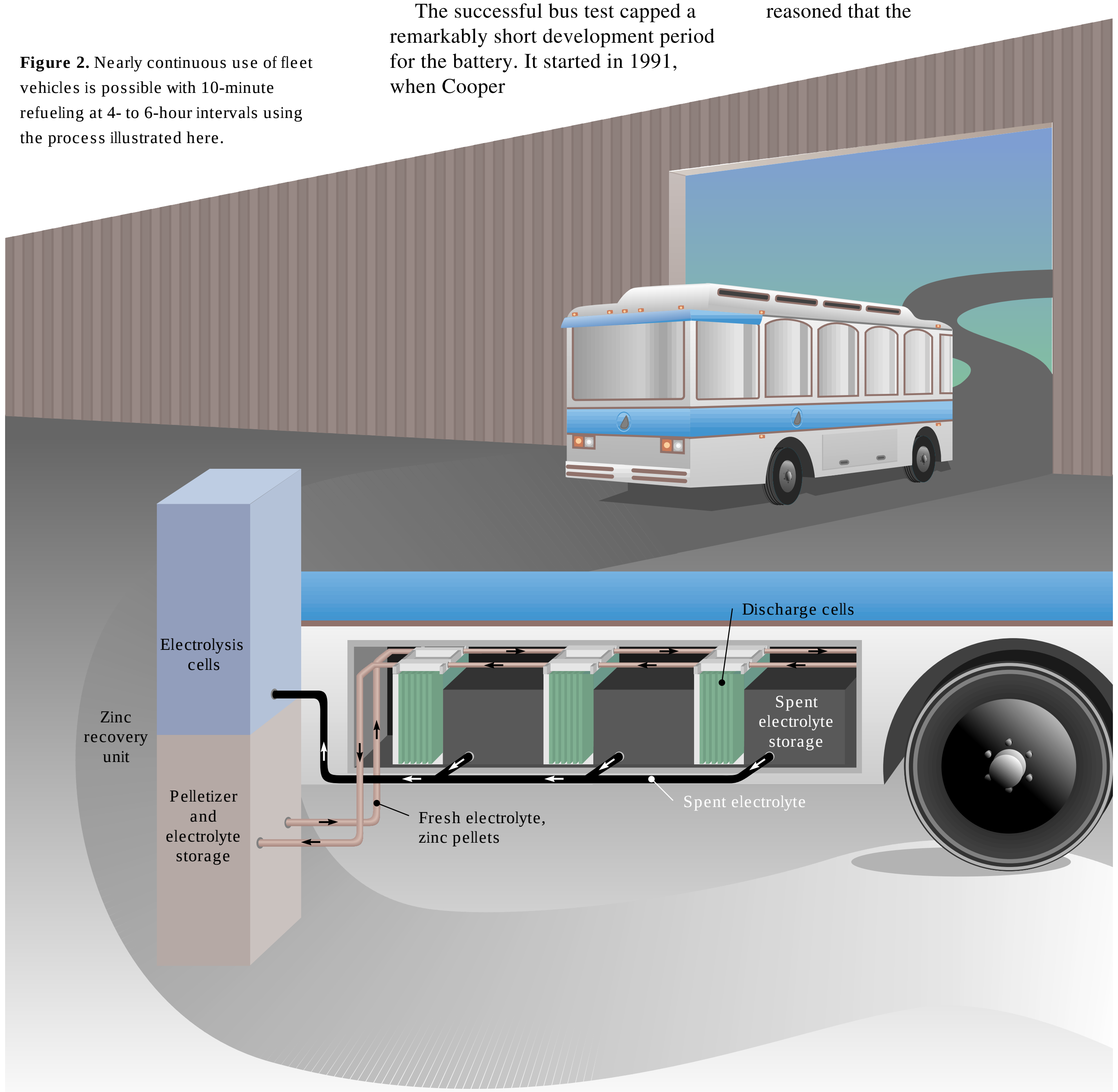


Figure 2. Nearly continuous use of fleet vehicles is possible with 10-minute refueling at 4- to 6-hour intervals using the process illustrated here.

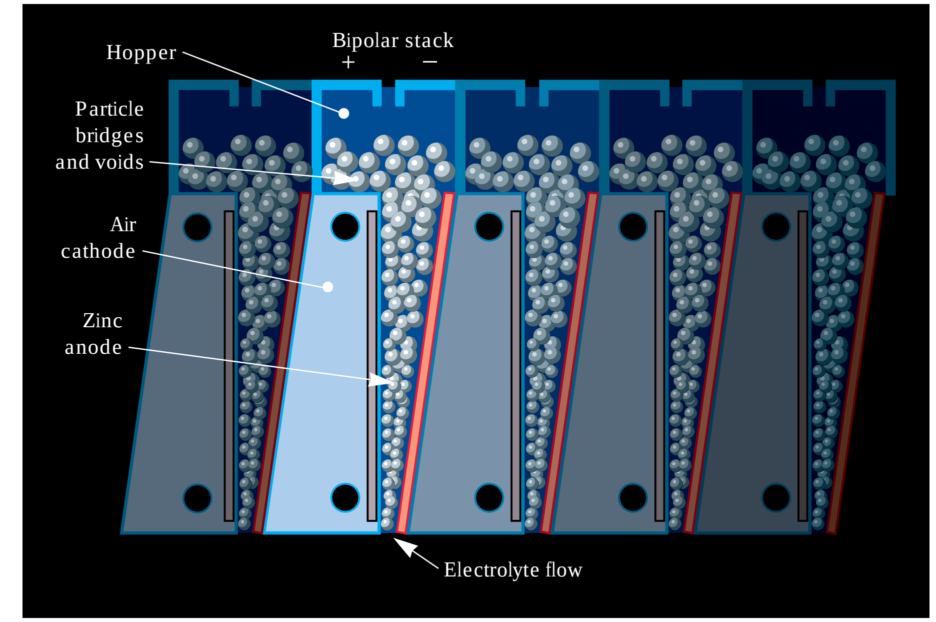


Figure 3. Zinc pellets are gravity fed from hoppers to cells.

same principle could be used to advantage in designing a particle electrode in a small gap, where we want an open matrix, allowing electrolyte to flow through freely."

Some months later, he had successfully tested a self-feeding design for a zinc/air battery, with a hopper from which zinc particles fell through a restricted opening into a reaction cell (Figure 3). This novel design, the basis for Cooper's 1993 patent on the battery (see box p. 10), solved a persistent problem with previous zinc/air battery designs, in which the zinc particles and reaction products would eventually clog the cell, preventing complete oxidation and reducing power generation.

Cooper is no stranger to battery design. In the early 1980s, he was the Department of Energy's national program leader for an aluminum/air battery development effort headquartered at the Laboratory and conducted in cooperation with five corporate partners. That program advanced to the stage where it was transferred to industry, but the battery did not see commercial development in autos because of ample and relatively cheap worldwide petroleum supplies and the battery's chief drawback—aluminum corrosion. The technology instead evolved into batteries for emergency power reserve units, submarine propulsion, and forklift trucks.

With Livermore's Laboratory Directed Research and Development funding in hand, Cooper worked for two years beginning in mid-1992 with a small team of mechanical and chemical engineers and technicians as a part of the Laboratory's Energy, Manufacturing, and Transportation Technologies (EMATT) program. The project's goals were to develop an engineering zinc/air prototype battery based on Cooper's design, optimize its energy storage and power characteristics, and show that the self-feeding cells could operate under realistic road vibrations and accelerations.

Finally, to be successful in the marketplace, the zinc/air battery had to be able to be refueled quickly, easily, and safely without the need for a new infrastructure of expensive, complex equipment. Energy researchers have long recognized that if a way could be found to refuel a battery simply and rapidly, it could provide an electric vehicle acceptable to consumers. Quick and easy refueling is important in fleet electric vehicles such as shuttle buses and delivery vans, which often must operate more than 8 hours daily.

The alternatives to refueling pose significant disadvantages. For example, exchanging batteries doubles the investment in batteries and specialized equipment; adding a gasoline or diesel engine produces air emissions; and electrical recharging takes hours to complete. (The traditional lead/acid batteries used in Santa Barbara's 12 electrically powered city buses require 4 to 8 hours of recharging after 4 or more hours of use.)

During the development phase, the battery was tested in various configurations of cells and air electrodes. Cells were tested with air electrodes of 80, 250, 600, and 1000 cm^2, with the 250-cm^2 size judged the most

Battery Design and Operation

The LLNL zinc/air battery is constructed in modular form of unit cells (see the drawing below), each of which is made up of a hopper, a self-feeding galvanic cell, and refueling ports. The cells are joined together in a battery module that is connected to an electrolyte storage tank containing electrolyte and discharge products. The hoppers in each cell act as buffers, helping to protect the fragile air electrodes from damage during refueling, handling, or road shocks.

Each cell contains a lightweight plastic frame, an electronic circuit board, and a paper-thin air electrode. The electrode is the most expensive component in the battery and accounts for half the battery cost. As many as 12 cell stacks can be combined with one electrolyte storage tank to form a battery, and Cooper envisions both a 6-cell and 12-cell basic unit, as with lead/acid batteries.

In operation, 1-mm zinc particles are pushed along the base of a horizontal fill tube by the flowing electrolyte. The zinc particles flow through slots leading into individual hoppers above the reaction cell. (Cooper likens the process to “hosing gravel down a driveway.”) The very narrow (less than 3-mm-wide) cell opening allows the particles to feed uniformly into the cell to form an open, loosely packed structure, which permits the oxidation of all of the zinc and easy flow of electrolyte. At the same time, electrolyte flows easily upward through the cell and hopper to remove heat and reaction products. Electric power to drive both air and electrolyte pumping is negligible, consuming less than 0.5% of the battery’s gross power output.

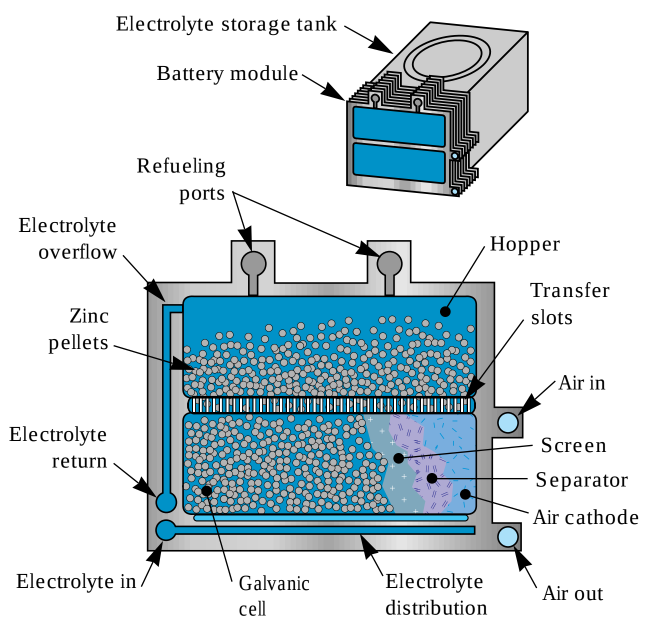
The battery’s unusual modular design permits the independent choice of the battery’s power (measured in kilowatts) and energy capacity (measured in kilowatt-hours). The very lightweight cells provide the power, and a storage tank holding the reserve of heavy electrolyte determines (along with the zinc) the total energy capacity of the battery and most of the weight. “Within broad limits, we can combine any number of cells with any amount of electrolyte and zinc, depending on the ratio of power to energy we need,” Cooper says.

Given this unique characteristic, each kilowatt of power contributes weight of 2.8 kg and volume of 3 L to the battery, while each kilowatt-hour of energy contributes 6.5 kg and 4 L. Thus, a battery with 30 kW of power and 60 kWh of energy weighs 474 kg (1040 lb) and occupies 330 L (12 ft^3). Because power and energy are independent, the traditional terms of “specific power” and “energy density” have no unique meaning in this case. Still, Cooper speaks loosely of the battery yielding 140 Wh/kg in vehicle sizes, or about five times greater than that delivered by lead/acid batteries.

During refueling, spent electrolyte containing oxidized zinc particles is drained and fresh electrolyte is added. Stacks of 12 full-size cells are refilled at a rate of 15 seconds per cell in the laboratory. A battery pack consisting of three parallel branches, each with three modules of 12 cells—108 cells in all—would be filled in parallel from a common flow in about 10 minutes. Because the batteries of any vehicle would be filled in parallel, the refueling target of 10 minutes is a reasonable goal for any combination of three-by-three battery packs.

Existing bus or delivery van maintenance facilities would operate as ready-made refueling and recycling stations. Crews would replenish the electrolyte mixture with fresh material they had recycled on site. Exhausted electrolyte (an alkaline liquid containing zinc compounds) removed at the time of refueling would be recycled to produce new zinc fuel entrained in fresh electrolyte. Recycling would be done with small-scale electrolysis equipment the size of a vending machine, which Livermore researchers designed.

The recovery equipment would be operated by the fleet’s vehicle maintenance crew and located at the fleet’s home base. The recovery unit’s cost would be about one-fifth that of a typical zinc/air battery because it would operate continuously (hence, be smaller) and would not require an expensive air electrode or heavy, expensive high-amperage power sources. The electrodeposited zinc plate would be shredded into small particles and then pressed into uniform, 1-mm pellets by a small machine.



Details of a zinc/air battery unit cell (end view)

appropriate for bus-size vehicles. Cells were operated for as long as 16 hours, with intermittent refueling. Stacks of 12 cell modules were refueled in only 4 minutes. Batteries were discharged in units of 1, 3, and 6 cells. To simulate road conditions, the research team used a vibration table for some tests.

Road Testing the Prototype

With laboratory tests complete by the end of 1994, the team prepared for a vehicle test sponsored by the U.S. Department of Transportation’s Federal Transit Administration. Early this year the Santa Barbara Metropolitan Transit District provided the Laboratory with a 6.6-m (22-ft), 5.7-metric-ton electric shuttle bus.

For the bus test, one six-cell, 7-V engineering prototype zinc/air battery was cabled in electrical parallel with a three-cell, 6-V lead/acid battery. This hybrid unit then was placed in series with the standard 216-V lead/acid battery power plant of the bus, using diodes to prevent reverse polarization of the zinc battery (Figure 4).

The bus was driven on a 1.2-km loop around the Lab for about 5 hours for a total of 120 km (75 miles), at which point the lead/acid batteries were 80% discharged. The road test validated the design of the self-feeding zinc/air cells under typical driving vibrations from starts, stops, turns, and accelerations. The self-feeding cells functioned correctly without becoming clogged with zinc particles or starved for fuel, and they operated well in the hybrid configuration. In addition, the test validated the integrity of the electrolytic air seal, the weak link in all metal/air batteries. Fatigue of this crucial seal caused by variations in full particle flow and stresses from the road surface could limit a battery’s lifespan; long-term tests will be necessary before commercialization of the battery.

The test run also indicated the zinc/air battery’s potential savings in vehicle weight, battery weight and volume, and cost to operate over a lead/acid battery. For example, replacing the lead/acid batteries in the Santa Barbara bus with zinc/air units would reduce vehicle weight from 5.7 to 4.0 metric tons, the battery weight from 2.0 to 0.35 metric tons, battery volume from 0.79 to 0.25 m^3, and electricity cost from 5.6 cents per mile to 4.7 cents per mile (Figure 5). Yet power remains the same.

The zinc/air battery is less efficient than the lead/acid battery (60% versus 70% conversion efficiency, respectively). Nevertheless, the lighter weight of the zinc/air battery cut a total of 1.7 metric tons from a 5.7-ton bus, so the total energy use is 17% less than that of a lead/acid-powered bus because of the lower vehicle mass. Additionally, the marked reduction in vehicle weight means reduced tire and brake wear, which are major cost factors in large vehicles.

The Savings Are Long-Term

When commercialized, zinc/air batteries will probably be the least expensive advanced battery on the market. Cooper estimates a unit sized

Figure 4. Developer John Cooper, left, and electronic technician Douglas Hargrove, inside the Santa Barbara bus during its test run at the Laboratory.

for a bus would cost around \$2000. The dominating cost is that of the air electrode, about \$120 per square meter in large quantities. Since the battery delivers more than 4 kW/m^2 of air electrode, the cost of this unit is only about \$30 per kilowatt. When all components are considered, the total production cost is about \$50 per kilowatt for peak-power production plus \$2 per kilowatt-hour capacity. Lead/acid units cost about \$75 per kilowatt-hour.

The cost of the recycling equipment depends on how much fuel is needed each day. For buses running 12 hours a day, the recycling unit would cost about 25% of the battery it serves. The recycling unit has no expensive components and uses metal sheets instead of the more expensive air electrode.

Although the zinc/air battery has sufficient power by itself to power large electric vehicles, combining it with another power source (lead/acid battery, supercapacitor, or flywheel) is recommended. The hybrid power plant allows better acceleration and greater flexibility in selecting routes with varing grades. Finally, with few peaks in the current, the life of the electrodes in the battery is expected to be as great as 12,000 hours. Regenerative braking, in which the considerable braking energy turns magnets to recharge a flywheel or capacitor, will decrease total energy use by another 10%.

Cooper's interest in zinc/air batteries has been shared by many energy researchers. Zinc/air batteries have been developed for both mobile and stationary power applications because of their low cost and high energy density. The batteries have found other uses in hearing aids, military field electronics, and laptop computers. In these applications, however, zinc/air batteries are very expensive for the low power they provide, and they cannot be refueled.

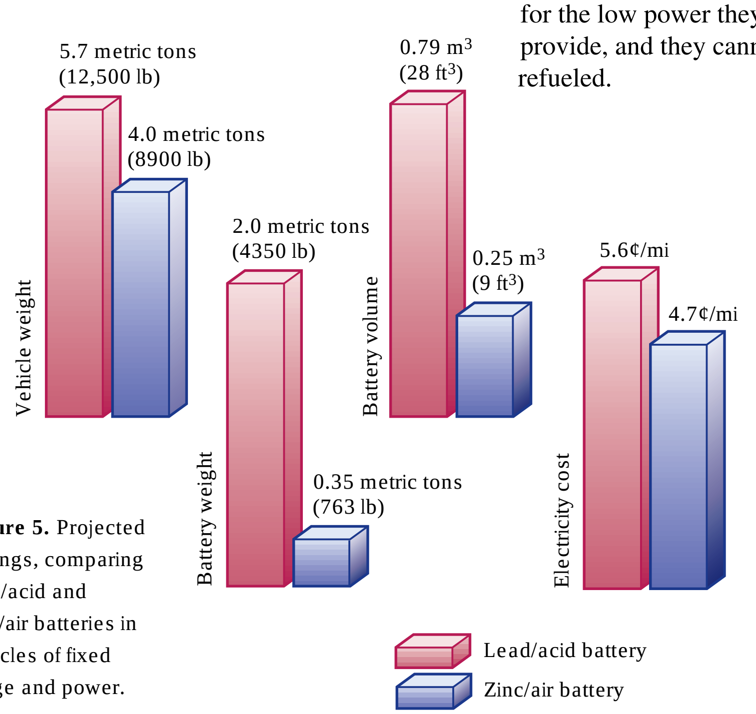


Figure 5. Projected savings, comparing lead/acid and zinc/air batteries in vehicles of fixed range and power.

Commercial interest in zinc/air batteries for powering electric vehicles has grown significantly during the 1990s. An Israeli company in 1994 demonstrated a zinc/air-battery-powered van that had a range of more than 420 km with highway acceleration and sustained speeds. However, unlike the LLNL design, that battery is not refuelable; the battery's spent electrodes must be delivered to a plant for reconstruction.

Commercial Development

The LLNL refuelable zinc/air battery is now ready for advanced development as part of a commercialization effort with one or more industrial partners. Cooper has received scores of requests for more information from battery manufacturers and potential users. Many inquiries have been in response to news articles about the battery that appeared earlier this year in the *London Times* newspaper and *Design News* magazine. "There is an enormous world market, with literally millions of units that could take advantage of the new battery," he says. "More than 90% of new battery concepts fail, so no one talks to you until you've demonstrated a prototype unit that works on the bench and in a vehicle."

Cooper cautions that before commercial units find their way into vehicles, more work needs to be done, particularly in determining the longevity of the air electrode under actual or simulated road use and how many times the zinc reaction products can be recycled. Cooper believes these challenges are not insurmountable and that full-scale production can begin as early as 2000. One strong selling point is that, because of its modular design, the battery can easily be tailored to accommodate varying needs, from small forklifts to large urban buses to silent military vehicles.

Down the road, passenger cars might also be powered by zinc/air batteries. As the cars proliferated, they could be refueled at service stations. Cooper says some oil companies are interested in the idea because it is a potential new market for their stations. In the long run, commercial zinc recovery plants could take advantage of large-scale production using electrolysis cells combining electrical and hydrogen energy to reduce zinc oxide to zinc. This process would operate with a substantial savings over the purely electrical route to recovery and would give the zinc/air battery an almost unbeatable total energy efficiency. The zinc/air battery's total energy use would be comparable to a fuel cell at one-tenth the cost.

Another factor favoring electric vehicles is energy flexibility. The U.S. transportation sector depends almost exclusively on crude oil, most of it imported. Electricity, by contrast, can be produced by power plants using a wide variety of energy sources, including coal, natural gas, hydroelectric power, solar energy, and nuclear energy.

A final argument for electric vehicles is that they require less maintenance and are easier to repair because the vehicle's "power train" is simpler than that found in gasoline-powered vehicles. In a typical electric vehicle, an electric motor powered by batteries provides torque to the front wheels. An electronic motor controller regulates current through the motor and transforms the battery's dc voltage to ac.

The switch from gasoline power plants to zinc/air batteries for passenger cars would make the most economic and environmental sense in urban areas, where gasoline-powered cars burn excessive fuel and generate significant pollution in start-and-stop driving. Such a fundamental shift to electric propulsion is no longer just an environmentalist's dream. In 1990, the state of California enacted regulations requiring 2% of all cars sold in the state to run without any polluting emissions by the year 1998. The exact benefit to the environment, however, depends on the emissions generated by local power plants that produce the electricity to build, recharge, or refuel the batteries.

Cooper says that the new technology is likely to have its greatest impact on fleets of electric vehicles. "Buses, vans, and industrial vehicles have a unique combination of high daily usage, low power requirements, and in-place service infrastructure. This combination makes their owners and operators an ideal market for refuelable zinc/air batteries."

Key Words: alternative fuel; electric vehicle; refuelable; zinc/air battery

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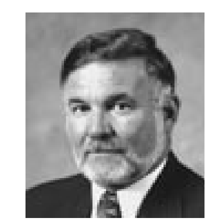
About the Engineer



JOHN COOPER holds a Ph.D. in physical chemistry with special emphasis on electrochemical engineering. For 10 years at the Laboratory, he has worked on electrochemical batteries as power sources for alternative, environmentally clean vehicles. From 1978 to 1983, he was the national program leader for the Department of Energy's efforts to develop aluminum/air batteries. His professional career has focused on active research in electrochemical process development for environmental remediation and waste processing, textile manufacturing, elecroplating, and metals recovery. Other research interests include optical crystals and processes, transport phenomena in aqueous systems, and molten salt processes. Cooper is the author or coauthor of more than 80 publications in the area of electrochemical processes and devices.

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Lawrence Livermore National Laboratory Directed Research and Development Program,
International Lead-Zinc Research Organization,
Santa Barbara Metropolitan Transit District, Santa Barbara, California,
U.S. Department of Transportation through CALSTART, Inc., Burbank, California.

Gamma-Ray Imaging Spectrometry

Laboratory scientists have developed an imaging instrument for locating and identifying nuclear materials by taking "photographs" of the gamma rays emitted by these materials. This instrument, the gamma-ray imaging spectrometer, has many potential applications as wide ranging as treaty verification, environmental cleanup investigations, gamma-ray astronomy, and nuclear medicine.

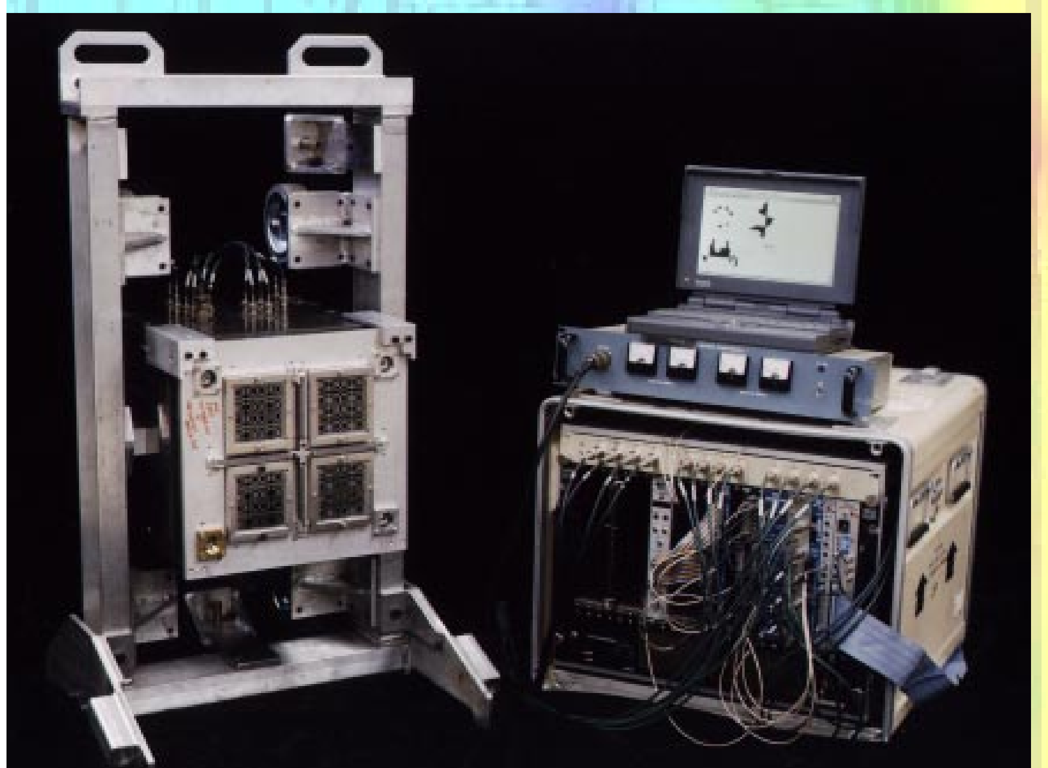

Figure 1. A Gamma-ray imaging spectrometer (GRIS) configured for work in gaseous diffusion plants. On the left, the GRIS imager head has four independent gamma-ray imagers. On the right is its data-acquisition system.

ONE of the challenges facing today's world is to keep track of the nuclear material generated during the Cold War. Some of the materials are radioactive isotopes that fuel nuclear weapons; others are used in the nuclear power industry. At Lawrence Livermore National Laboratory, we have developed an instrument that can help locate and identify these materials.

One of the characteristics of many nuclear materials, including those used in weapons, is that they emit gamma radiation. Each isotope emits a unique spectrum of gamma rays that can penetrate substantial amounts of ordinary matter without being scattered or absorbed like visible light. This radiation is imagable and can be used to indicate the presence and specific type of nuclear material.

Although nonimaging, nondirectional gamma-ray radiation detectors have long been used to monitor the presence and general location of nuclear materials, gamma rays have been poorly exploited to provide information about the precise location of the nuclear material. Recent advances in position-sensitive detector technology, coupled with advances from gamma-ray astronomy, have allowed researchers to design and build a gamma-ray camera capable of taking gamma-ray "photographs" that quickly characterize radiating materials. When these images made with invisible radiation are combined with visible-light images, they clearly show the exact location of the gamma-ray emitting materials.

Looking at Gamma Rays

The gamma-ray imaging spectrometer (GRIS) we have assembled comprises four coaligned, independent imagers, each with its own detector and coded-aperture mask (Figure 1). Each detector "sees" incoming gamma rays only through its mask, which serves as the imaging optic for the gamma rays (see box, pp. 18-19). This mask is mounted on a movable mask plate in front of the detector plane; moving the plate provides different levels of zoom for the gamma-ray images.

At the back of the housing are the electronics that take the relatively weak signals from the detectors and amplify them before they are sent to the data-acquisition system, which can be located remotely. Our system currently consists of a commercial electronics module, whose data are read out by a notebook computer (Figure 1). Coaligned with the gamma-ray imagers is a video camera. Images from this provide both a visual aim point and visible light images that can be overlaid with the gamma-ray images to pinpoint the location of the radioactive material.

Applications and Results

Although the spectrometer was developed to control the special nuclear material (SNM) associated with nuclear weapons, there are a myriad of applications in other areas, including environmental cleanup, astronomy, medicine, the nuclear power industry, and any other enterprise where radioactive sources are used.

Arms Inspection

GRIS was initially designed for use in arms inspections called for by the Strategic Arms Reduction Treaty (START)—specifically, to count the number of warheads on board a missile without requiring either close access to the missile or its disassembly. Inspections would be conducted remotely, based on the premise that the gamma-ray signature from the on-board warheads, although weak, is strong enough to be detected through the top of the missile. GRIS was constructed with four detectors to decrease the time it takes to obtain a good image approximately 10 m from the source. Figure 2 shows GRIS being used to inspect a Peacekeeper missile in its silo; the missile's ten warheads in the GRIS image are easily seen in Figure 3.

Confidence through Transparency

As the U.S. and Russia strive to reduce their respective nuclear stockpiles, each must have the ability to identify and verify the location of the other's weapons components throughout the demolition process. Each

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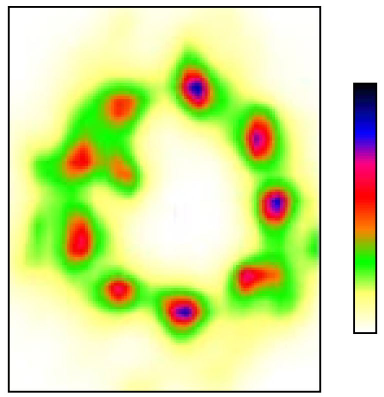


Figure 3. This enhanced gamma-ray image is from an emplaced Peacekeeper missile. The warheads are shown in a ring of nine, with the tenth inside the ring at the 10 o'clock position. The colors represent radiation intensity contours.

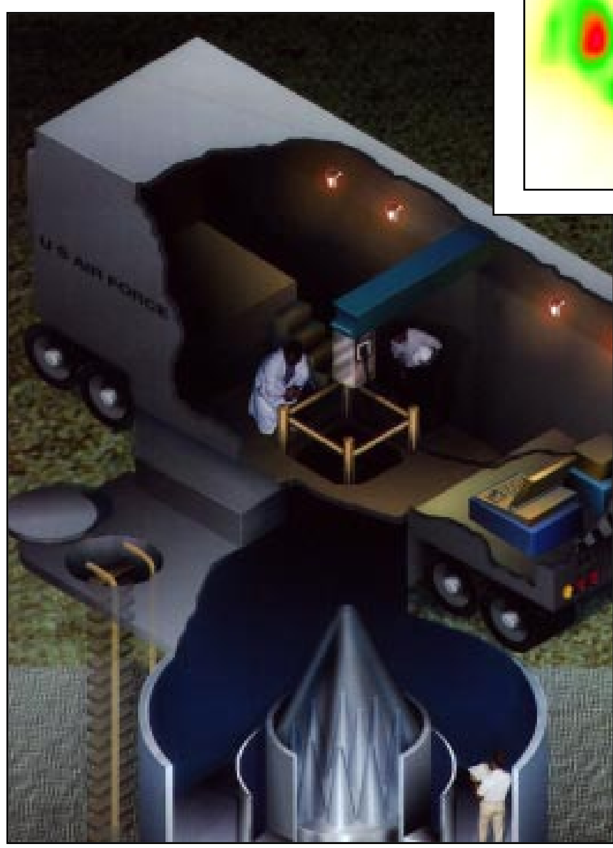


Figure 2. Rendering of the configuration used for gamma-ray imaging of a Peacekeeper missile. The GRIS imaging module is suspended above the open silo door and generates an image from the radiation given off by the warheads at the top of the missile.

must have confidence that the SNM in the other's storage vessels is associated with nuclear weapons components but must be able to develop that confidence without performing an inspection that is sufficiently detailed to raise classification issues. This ability, or confidence, is called transparency.

In a recent joint U.S.–Russian demonstration at LLNL, we obtained data with a conventional, nonimaging gamma-ray detector and with GRIS. The data were collected from a radioactive source hidden inside a typical weapons component storage container. Both detectors possessed similar energy resolutions and could identify the type of material present. However, in a single measurement, the non-imaging detector could not verify the quantity of SNM present or the likelihood that the material was a weapons component. Such information could only be obtained from the nonimaging detector by scanning it across the storage vessel in small steps. Although this generated a crude image of the object that allowed identification, it also required most of a morning to complete. By comparison, the inspection with GRIS took half an hour—a time which could be easily reduced to a few minutes. The GRIS images taken from two directions 90 degrees apart (Figure 4) clearly show that a disk of plutonium and not a weapons component is in the storage container.

Related applications that take advantage of GRIS's ability to "see" behind shielding occur in nuclear waste disposal and in the characterization of nuclear weapons. Figure 5 illustrates such an application. Here, we placed a rectangular shape made from plutonium rods inside a storage drum. To simulate shielding, we placed a depleted uranium plate about 3 mm thick outside the drum. The uranium serves as shielding, as a source of confusing radiation, and as a different radioactive isotope.

Figure 5 indicates both the energy resolution of the system and how images using data from different spectral regions can show the locations of different materials. The image obtained using only the data in the region of the spectrum shaded blue is on the left. This image represents emission from uranium and shows only the large uranium plate. On the right is the image obtained using data in the region of the spectrum shaded pink. These data are characteristic of plutonium and reveal the rectangular figure behind the uranium inside the container.

Safeguarding Weapons

When nuclear arms and their components are secured and stored, the primary concern is to verify that no material is removed from a storage area. In addition to armed guards, an inventory control system that constantly

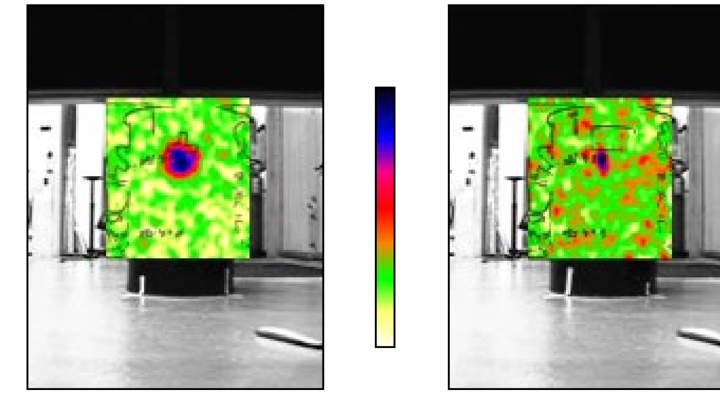


Figure 4. Overlaid on a video picture, a color gamma-ray image shows the difference between a face-on (left) and an edge-on (right) image of a plutonium disk. The images were obtained at a distance of 1.8 m and a position resolution at the source of 3.8 cm. Black represents the highest radiation intensity.

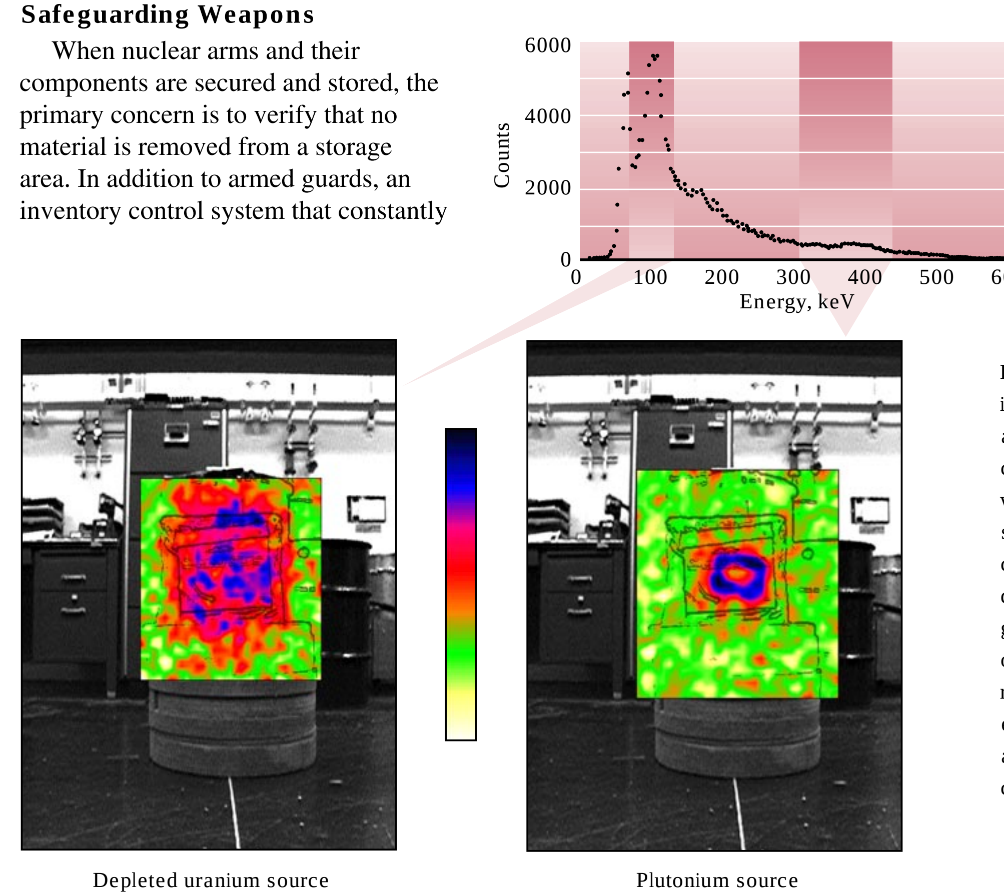


Figure 5. Demonstration of gamma-ray imaging and energy discrimination in applications for arms control transparency, contaminated waste identification, and weapons forensics. The plutonium source is distributed inside a storage drum can be clearly seen, even through 3 mm of depleted uranium. The image at left is generated from 100-keV gamma radiation of the depleted uranium; the image on the right is generated from the plutonium energy band at about 400 keV. With the appropriate energy selection, the plutonium can be seen through the uranium.

How the Gamma-Ray Imaging Detector Works

Astronomers have worked on the problem of imaging gamma rays for about 30 years. Although cosmic sources of gamma rays are extremely bright, they are also exceedingly far away, so the problem is how to image dim sources in a relatively large background. In principle, a pinhole camera could be used, but only a small fraction of the available radiation would reach the film or detector. In the late 1960s, it was recognized that one could improve the pinhole camera by punching more holes in the blocking sheet. Each hole projects its own image on the detector, and the different images overlap. If the hole pattern is known, one can mathematically recreate a faithful reproduction of the scene.

Although initial attempts showed that the technique worked, they also showed that the pattern had to be selected carefully, or false sources would appear in the image. The research on pattern effects was largely completed in the 1970s when a class of patterns called uniformly redundant arrays was created. These patterns possess a unique property: the information present in the shadow pattern from any one source in the image is not affected by the presence of gamma-ray sources in other parts of the image.

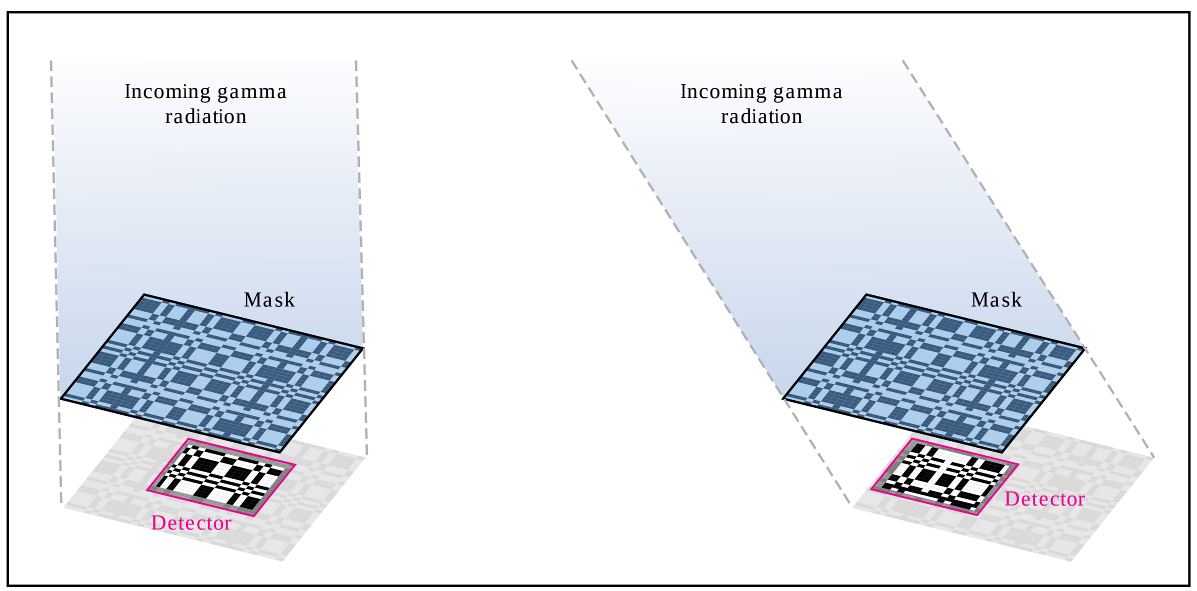
In the schematic of the imager (see the illustration below), we assume that radiation is coming from a very distant source. The light rays from this source are parallel, so a shadow of the mask is projected on the detector much the way it would be projected by the sun. Each pixel (the smallest picture element) in the image is represented by parallel gamma rays incident from one direction that project a detector-sized portion of the mask pattern onto the detector. The pattern is selected such that each projection is unique and independent of all other projections.

The image is recreated by a cross-correlation technique: the complete detector pattern is summed against each unique mask position by adding counts to the sum if the mask is open at this position and subtracting them if it is closed. Physically, counts are added if they could have come from that direction and subtracted if they could not. If no source is present, any detector-sized portion of the mask pattern has the same fraction of open and closed area relative to all other portions of the mask of that same size, so the sum is zero (except for statistical fluctuations). If a source exists at the particular location being summed, then every time there is an opening there will be counts, and the sum will recreate the true flux (amount of signal per unit time) from the source.

The advantage of this technique is that half the detector area is exposed to each of the sources in the field of view. The rest is behind closed mask elements. Compare this with a pinhole camera, in which the open area is only one pixel's worth. For a point source, the signal-to-noise ratio increases as the square root of N, where N is the number of open holes. For our system, N is approximately 200, meaning a 14-times-greater signal strength and significantly reduced data-acquisition time.

Unfortunately, because all the counts in the detector are used at each image location, the more sources there are in the field of view, the less one gains from this technique. It reverts to one with the same sensitivity as a pinhole camera if the whole field of view glows at the same intensity.

The resolution of a coded-aperture camera is just what it would be for a pinhole camera. For each pixel, the angular offset in incoming radiation is the basic hole size divided by the focal length (detector-to-mask spacing). To obtain the resolution at the source, one must multiply this angle by the distance to the source.



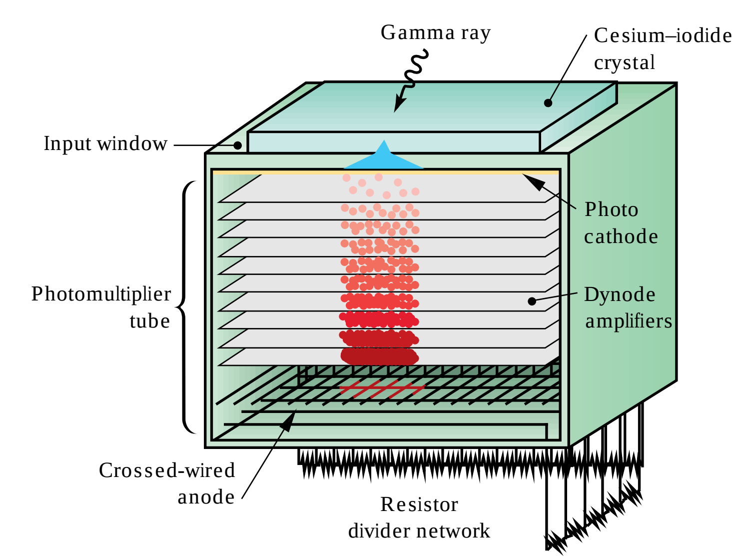
Uniformly redundant-array coded apertures produce an image by having each source pixel cast a unique mask shadow pattern on the detector. The mask is four times the area of the detector. On the left is the system response for a source in the center of the field of view. On the right, is a response for a source near the left edge of the field of view.

Position-Sensitive Detector

Converting the signal to a visual image requires a position-sensitive detector. Moreover, the position resolution must be comparable to the mask hole size; otherwise the pattern washes out. Because typical position-sensitive detectors (known as Anger cameras) for gamma rays of energies from 20 kiloelectron volts to greater than 1 megaelectron volt have position resolutions of the order of 1 cm, an imager must be quite large to have a reasonable number of pixels across the detector. An imager made with such a detector must also have a long focal length to achieve even modest position resolutions at the source

Our development of a gamma-ray detector with a position resolution of about 1 mm allowed the full exploitation of the coded-aperture technique in a compact system. In the schematic of the detector at the left, a position-sensitive photomultiplier tube is combined with a thin cesium–iodide crystal. When a gamma ray hits the crystal, it causes a brief flash of light, which is converted to an electronic signal by the photomultiplier tube. The tube is unique in that it allows the position of the light flash to be determined from its four output signals. The amount of light is proportional to the energy of the gamma ray and is also measured by the photomultiplier tube. The 4- × 5-cm active area of the detector yields about 40 pixels across its face, allowing for a mask pattern about 20 × 20 pixels (ideally, one oversamples by a factor of two.)

This schematic of the GRIS detector shows how it locates gamma radiation. A sodium-doped cesium–iodide crystal emits a flash of light when struck by a gamma ray. This light is converted to electrons and amplified by the photomultiplier tube on which the crystal is mounted. The tube uses a unique mesh dynode structure and a crossed-wire anode to determine the location of each event over the face of the tube.



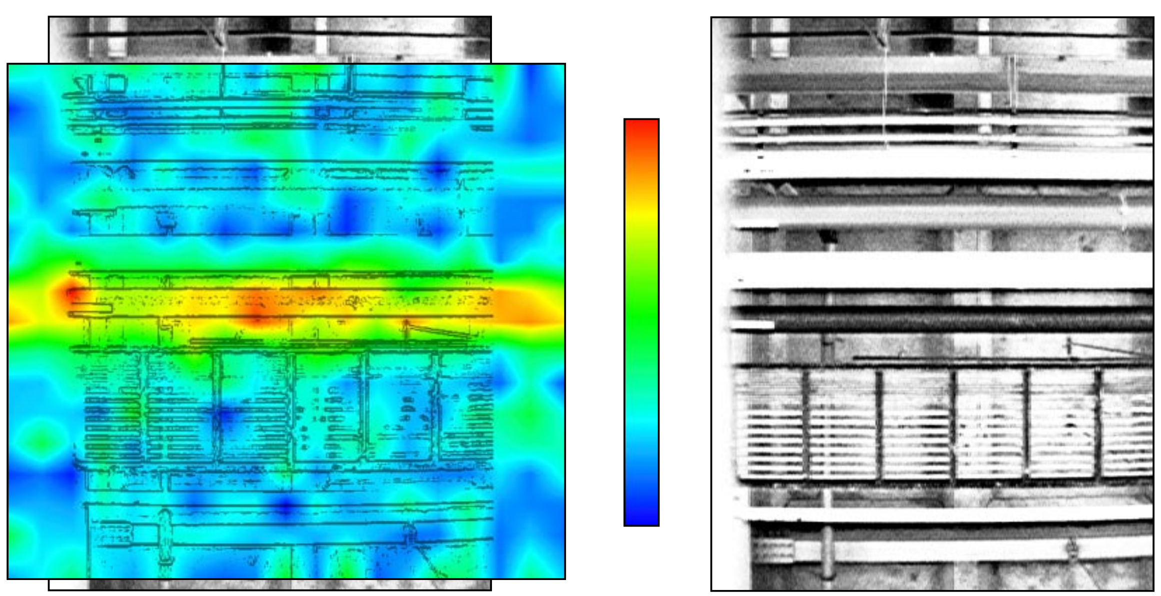
monitors the radiation from each radioactive component is desirable. However, such a level of security is not always possible. Particularly in establishing an interim storage area, the costs and time required to make individual security monitors for each location can be prohibitive. However, the need for such facilities will be particularly important as U.S. and states of the former Soviet Union dismantle nuclear warheads. In this case, a GRIS-type imager can be a relatively inexpensive and very rapid way to establish inventory control.

Although we have not fielded such an application, the implementation is straightforward. The gamma-ray imager is installed so that it can "see" all sources, and a baseline image is taken. Then, the imager is set on a timer to take that image over and over again. A mathematical comparison of each successive image to the original can be used to sound an alarm should something be moved; we developed suitable algorithms to do this in the course of analyzing the Peacekeeper data. The advantages of using an imager in this case are that it can be set up very quickly, personnel need not leave the room, and visible light is not required.

Locating SNM in Process Plants

GRIS has been demonstrated at two U.S. gaseous diffusion, uranium-enrichment plants—K-25 at Oak Ridge, Tennessee, and the Portsmouth plant near Portsmouth, Ohio. The images we obtained from these plants demonstrate the utility of gamma-ray imaging in a number of complex situations.

Gaseous diffusion is used to separate the useful uranium-235 isotope from the predominant uranium-238 isotope present in natural uranium. Uranium-235 is the fissionable material used both as nuclear fuel in reactors and as weapons components. In the gaseous diffusion process, uranium metal is combined with fluorine to make uranium hexafluoride (UF_6), which is a



Gamma ray image   Video image

Figure 6. Video (right) and composite gamma-ray/video overlay (left) of a contaminated pipe at the K-25 gaseous diffusion plant at Oak Ridge. The gamma-ray image clearly shows which of the pipes overhead is contaminated.

gas at elevated temperatures. Separation takes advantage of the fact that the gas, composed of the lighter uranium-235 isotope, diffuses at a slightly higher rate than the gas containing heavier uranium-238. The UF_6 is enriched in heated equipment and piping contained within insulated housings.

Occasionally, because of leakage of wet air or environmental changes in the housing, solid UF_6 deposits develop. Such deposits routinely occur in an operational plant and must be located and identified. This task is not trivial. Many different pipes share the same heat shielding in the miles of pipe galleries. To enter these enclosures, workers must don protective gear to avoid radioactive contamination from possible residual leaks from more than 30 years of operation. In addition, some facilities—including those going through decontamination and decommissioning—contain highly enriched uranium, which could cause a criticality accident if a deposit of uranium-235 becomes too large.

Current characterization of the uranium deposits in these plants is performed primarily using sodium-iodide-based radiation detectors. These are carried through the plant, and readings are taken at fixed intervals to map the radiation fields. If a "hot" region is found, workers must either enter the heat-shield-enclosed area or take many measurements with a collimated version of the detectors to try to locate the deposit. Both are time-consuming, expensive, and potentially hazardous tasks. GRIS avoids these problems by generating images from outside the heat shielding that definitively locate the hot material.

Our first use of GRIS in this environment was at the idled K-25 plant. GRIS was mounted on a cart to look up some 4 m at the pipe galleries overhead that range in width from a few meters to more than 12 m across. Each gallery, enclosed in heat shielding, contains pipes ranging in size from a few centimeters to more than a meter in diameter. The building had been entirely scanned by K-25 personnel walking under and on top of the galleries using an uncollimated radiation detector; the results from this survey were used to select sites of interest for application of the GRIS imager. The first image was a pipe used to exhaust the building's many vacuum pumps. We selected this pipe because the lack of heat shielding allowed us to verify that the gamma-ray and video images identified the hot pipe (Figure 6).

A second exposure was taken of a more representative location where an isolated deposit of material was known to exist. After an initial wide-field image was taken to see the complete deposit, we moved the imager under the hot spot and zoomed in on this region. Figure 7 shows a deposit in a 1.2-m-diameter pipe, where an expansion joint exists. The deposit is probably uranium oxide, formed when a leak developed in the expansion joint.

The images from the next location, although they are nearly featureless, clearly demonstrate the power of the technique. We took GRIS to a location where we expected to find a series of radioactive pipes running the length of the area covered in the image. Two exposures were needed to cover the full width of the 12-m-wide pipe gallery. The resulting images (Figure 8) revealed only a few hot spots, not the contamination expected from the standard analysis.

1.9- ¥ 1.7-m field of view

5.2- ¥ 4.6-m field of view

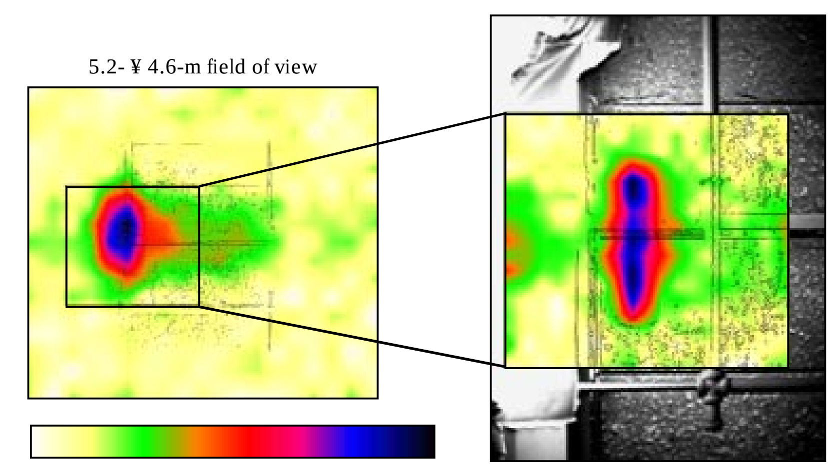


Figure 7. Overlay of gamma-ray intensity as a function of position for wide-field (left) and zoom views (right). The gamma-ray image on the right, which is overlaid on a video image, was taken after the imager was moved under the hot spot initially identified from the image on the left. The radiation is emitted by a uranium deposit inside a 1.2-m-diameter steel pipe hidden behind heat shielding.

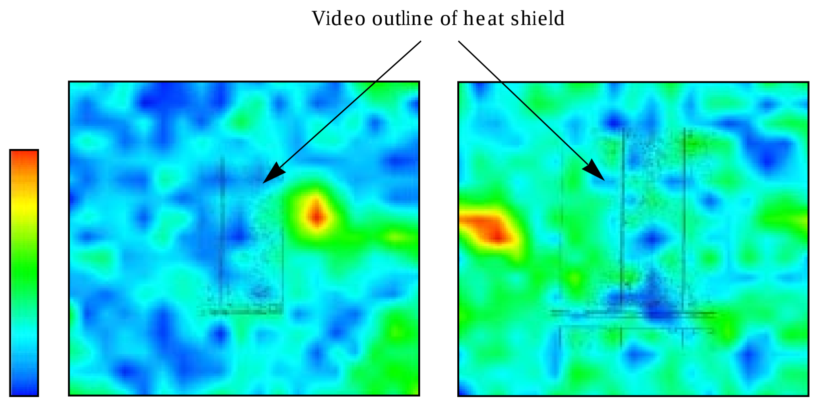


Figure 8. A powerful example of the advantages of gamma-ray imaging, this image shows little contamination within the heat shield. Instead, the image shows that the contamination is in a nearby area.

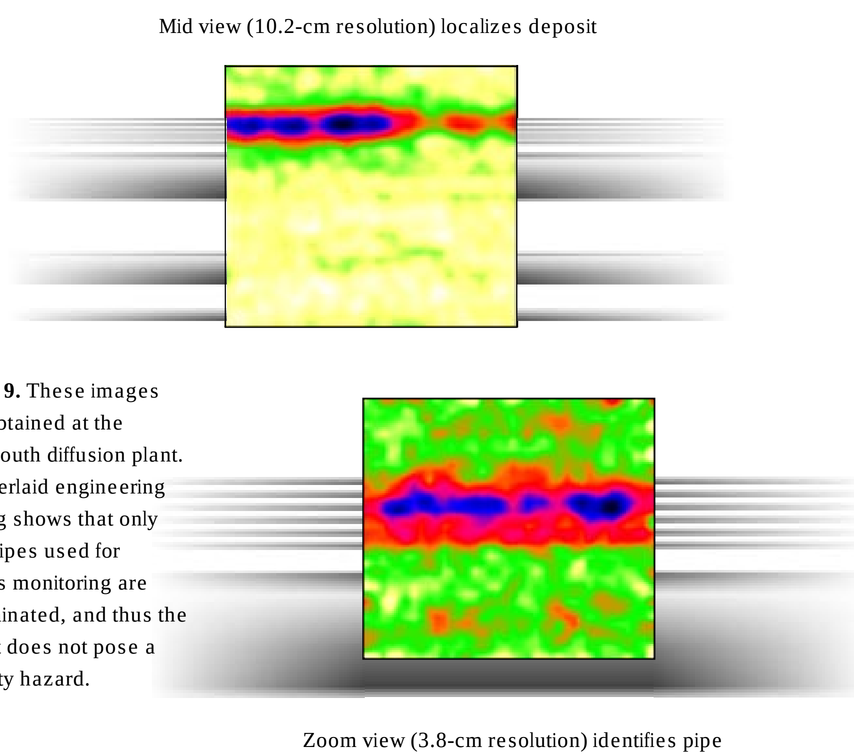


Figure 9. These images were obtained at the Portsmouth diffusion plant. The overlaid engineering drawing shows that only small pipes used for process monitoring are contaminated, and thus the deposit does not pose a criticality hazard.

Following the K-25 visit, we took GRIS to the diffusion plant at Portsmouth. There we made two measurements of note. The first was taken to determine the exact location of a known deposit of highly enriched uranium. There were concerns that a criticality accident was possible if the deposit was in the main 20- or 30-cm-diameter pipes of the gallery. One image (Figure 9) shows that this was not the case and that the deposit was in much smaller instrumentation pipes. The second image (Figure 10) shows a deposit in a diffuser cell, a large heat-shield-enshrouded area about 25 m × 6 m. The image, overlaid onto a plant blueprint, clearly shows plant personnel where the deposit is located before someone enters a cell.

In addition to its usefulness to personnel who operate and clean up these facilities, gamma-ray imaging also promises to be very useful to the International Atomic Energy Agency's safeguards programs for monitoring reactor fuel production facilities around the world. One of the major uncertainties in inspecting such plants is the nuclear material remaining in the process equipment. The ability to take images of both deposits and gas in the equipment can significantly increase the accuracy of the estimates of the quantity of material present. In addition, the settings of valves and the flow of gas through a plant can be independently verified.

Other Applications

Other GRIS applications are being considered. For example, a private company working for the nuclear power industry is studying the feasibility of using the gamma-ray/video overlay imagery to direct workers away from

areas of particularly intense radiation.

In a similar application, GRIS could be used to find "lost" radioactive sources. Intense radioactive sources are sometimes used for materials characterization in construction and maintenance. If these sources are lost from their holders, they present a significant radiation hazard.

Finally, nuclear medicine could potentially benefit from application of a gamma-ray imager with capabilities similar to those of GRIS. The gamma emissions of several well-known radionuclides used in medicine fall within the range of energies GRIS exploits.

Spectrometry and the Stars

In addition to the programmatic imaging work described so far, we have collaborated with the University of California at Berkeley and at Santa Barbara to combine our unique detectors with a novel implementation of coded-aperture imaging to build the world's highest angular-resolution, gamma-ray telescope (Figure 11). Constructed with Laboratory Directed Research and Development funding, GRATIS (gamma-ray arc-minute telescope imaging spectrometer) comprises 36 individual imagers specifically tailored to work in the astronomical energy band from 20 to 200 keV. Our high-position-resolution detectors combined with a 4-m focal length allow GRATIS to achieve an unprecedented angular resolution of 2 arc-minutes (arc-min). By providing each of the 36 detectors with its own one-dimensional coded-aperture mask (Figure 12), we provide better overall performance at lower manufacturing cost than a more conventional telescope of similar size. Every one of these

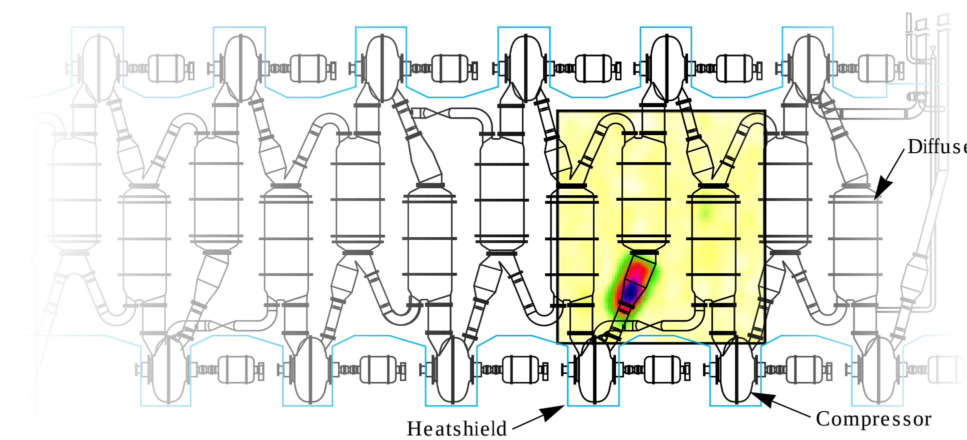
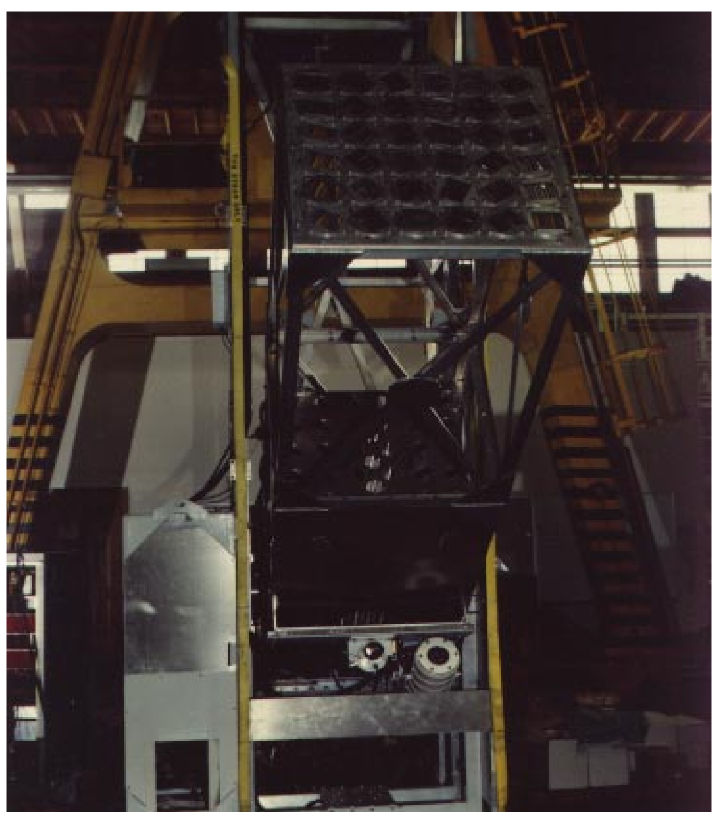


Figure 10. Overhead view of process equipment at the Portsmouth, Ohio, facility overlaid on engineering drawings of the area. The gamma-ray image clearly localizes the deposit to one length of pipe. The cylindrical diffusers are spaced about 2 m apart.

Figure 11. GRATIS is held by the launch vehicle as it is transported to the launch site at Palestine, Texas. Although significantly larger in size, the telescope is operationally very similar to the GRIS system developed for LLNL programmatic work.

Figure 12. Close-up view of the GRATIS mask plane. There are 36 individual one-dimensional masks, each rotated with respect to all the others. The resulting rotated individual images are combined mathematically to give a two-dimensional image.



telescopes produces a one-dimensional picture of the sky; the images are combined mathematically to give a full two-dimensional image.

GRATIS provided a special challenge because viewing radiation from the cosmos requires that the telescope be above all but the most tenuous portions of the atmosphere. Thus, GRATIS is hung from a helium balloon, and the pointing system is operated by remote control. To keep a source in the center of the field of view requires that the pointing system be stable to 1 arc-min. To reconstruct the images properly requires that we know where the telescope is pointing to an even higher accuracy, which is obtained by using a coaligned star camera and a gyroscope system that allow us to reconstruct the pointing after the flight to approximately 20 arc-seconds.

GRATIS was first flown successfully in spring 1994 from Palestine, Texas. During its 11-hour flight, we observed three scientific targets: Cygnus X-1, Cygnus X-3, and Her X-1; we are in the process of analyzing the data. Meanwhile, GRATIS is on the ground in Alice Springs, Australia, ready for its next flight this fall, when we will observe the center of our galaxy.

Continuing Development

Our ongoing efforts in gamma-ray imaging include improvements in the detectors and in image-generation techniques. We are building a new detector that takes advantage of the rotated one-dimensional imaging used in GRATIS to extend the useful energy range of this work and to significantly lower the cost per unit area of detector. Called the Gamma-Ray Bar Imaging Telescope (Figure 13), GRABIT achieves these advances by separating the energy- and position-resolving functions of the detector.

A series of scintillator bars is mounted on a nonimaging photomultiplier tube. Most of the scintillation light from a gamma-ray event is collected by this tube, the signal from which is used to determine the energy of the gamma ray. To determine where the gamma ray hits, we pick off a small fraction of the light with a fiber-optic bundle and transmit it to an imaging device such as the photomultiplier tube used in GRIS. By observing which fiber end glows and knowing its arrangement on the imager, we can determine which bar is hit by the gamma ray.

To understand how this feature improves the system performance, note that the GRIS detectors determine an event's position by finding the center of the light footprint at the input to the photomultiplier tube. However, as one makes the crystal thicker, the average event size will increase because the light spreads out more before it reaches the tube, thus decreasing the ability to find the flash location. By dividing the crystal into bars, we remove this problem: the position resolution is limited only by the width of the bar. The costs are lower because the unit area of nonimaging tubes is only about one-tenth that of imaging tubes. By reading out a bar with a fiber optic, we effectively increase the expensive imager area some 40 times. We are currently assembling a laboratory prototype of this detector system.

Our previous imaging work clearly demonstrates the advantage of generating images using different parts of the energy spectrum. Unfortunately, the energy resolution of the cesium iodide currently used is only about 10%, not enough to distinguish commercial (reactor-grade) plutonium from weapons-grade plutonium. Higher energy resolution makes this distinction possible because it separates the different gamma-ray energy lines of the various plutonium isotopes.

Another advantage of improved energy resolution is the ability to obtain information from a strong source that lies behind a significant thickness of other material. In such a case, the overlying material acts much like the diffuser in front of a light, scattering the radiation and blurring the image. However, unlike visible light, the scattered radiation at these higher energies is also shifted to a lower energy. By restricting the image to photons, which are in a known spectral line from the source, one can remove this type of blurring. With these advantages in mind, we plan to develop position-sensitive, solid-state detectors such as germanium- or zinc-doped cadmium telluride, both of which provide much better energy resolution.

Because it was developed for gamma-ray astronomy, the coded-aperture imaging technique as it has been applied by others assumes that the source is very far away. In the close imaging work we have described, this assumption does not hold. We have applied several techniques to compensate for this difference and are continuing to make improvements to the imaging techniques.

We are investigating the application of more advanced imaging algorithms to the coded-aperture data. These techniques rely on iterative approaches, based on Bayesian logic, that seek the

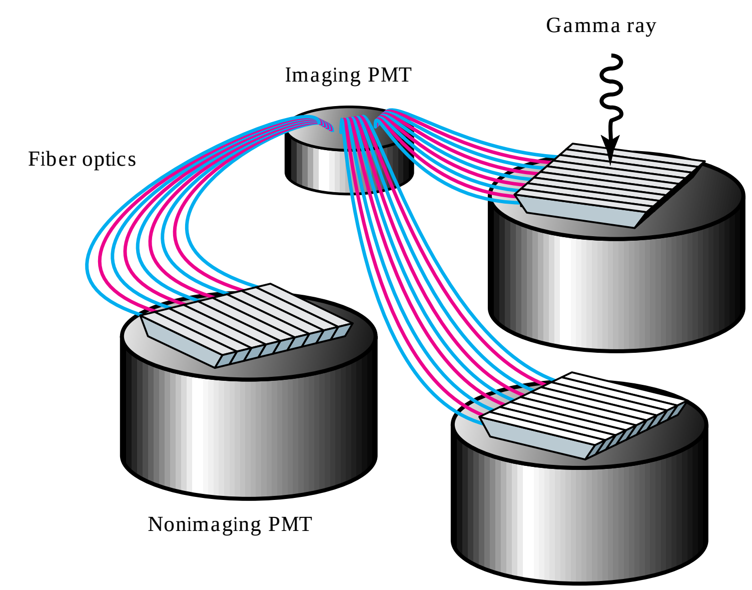


Figure 13. This schematic of the GRABIT detector shows how the position- and energy-resolving functions are separated. The light collected from the bottom of the bar arrays provides the energy information for an event. The small amount of light transported to the image tube by fiber optics allows one to determine which bar was struck.

best image on the basis of prior knowledge of the source and instrument. We are already applying one such technique, known as maximum entropy, to obtain the two-dimensional image from our set of one-dimensional images in GRATIS data. This technique selects the "flattest" image (the one with the least structure) commensurate with a statistical goodness-of-fit indicator based on the known instrument properties. In this case, we assume that the scene nature supplies will not have a lot of rapid variations in counts versus position.

Key Words: gamma rays—gamma-ray arc-minute telescope imaging spectrometer (GRATIS), gamma-ray astronomy, gamma-ray bar imaging telescope (GRABIT), gamma-ray camera, gamma-ray imaging spectrometer (GRIS); special nuclear material (SNM); Strategic Arms Reduction Treaty (START).

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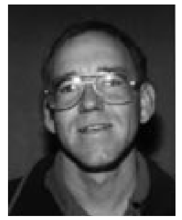
About the Scientist



KLAUS-PETER ZIOCK came to Lawrence Livermore National Laboratory 10 years ago as a post-doctoral scientists in V Division. Since 1988, he has been a staff scientist in V Division's Laboratory for Experimental Astrophysics. He received his Ph.D. in Physics from Stanford University in 1985 and his B.A. from the University of Virginia in Physics and Chemistry in 1978. His primary area of scientific research is low-energy gamma-ray astrophysics. He has been involved in the development of GRIS, GRABIT, GRATIS, GRB (a gamma-ray burst detector), and SXRP (an x-ray polarimeter).

His numerous publications to date (about 40) are in the area of atomic physics, including high-atomic-number systems, positronium spectroscopy, and instrumentation development for astrophysical research.

Positioning Health Care Technologies for the Needs of the 21st Century

LAST year, expenditures for health care reached about 14% of the U.S. gross domestic product, or a staggering $1 trillion. Many experts agree that the annual bill for health care will grow even larger in the next few years. Moreover, the effects of escalating costs extend beyond the domain of health care per se; they are reflected in added costs of U.S. manufactured products, in labor–management relations, and in many other ways that are not always obvious.

Can the trend be reversed? In some industrial fields, such as electronics, technological innovation is part of an effective strategy to reduce costs without decreasing quality. In marked contrast, investment in technology development accounts for only a tiny fraction of national health care spending, and even medical research and development represents only about 3% of its overall spending. LLNL is marshaling its world-class technology base to help the nation to contain escalating costs for health care.

Over the last decade, a broad spectrum of Livermore research projects has explored new or improved health care technologies that can potentially reduce health care costs. We are developing better imaging systems, such as pulsed x-ray lasers, improved instrumentation and information systems, and advanced sensor and detection systems, such as accelerator mass spectrometry. Other efforts around the Laboratory—often interdisciplinary and involving external collaborators—are already having an impact on the frontiers of research or treatment in maladies such as cancer, heart disease, stroke, diabetes, osteoporosis, and repetitive strain injury as well as in specialties such as ophthalmology, dentistry, and prosthesis design and manufacture.

To coordinate these activities, we established the Center for Healthcare Technologies at LLNL. Its goals are to:

- Continue to pursue the high-quality science and technology efforts that are already directed toward improved health care.
- Become better known in the health care community.
- Propose LLNL initiatives in health care that are more integrated than others'.
- Promote a national focus for federal activities in health care technology.

The Center has an external advisory committee of senior health-care professionals and an internal coordinating and advisory committee.

Perhaps most importantly, the Center represents a single point of contact through which interested organizations outside the Laboratory can gain access to the LLNL individuals or groups that are most appropriate for addressing specific health-care needs.

Our current strategy entails three phases of activities, which we have launched in parallel.

In Phase I, we are delivering results on current projects and gaining recognition for our accomplishments in health-care technologies. More than two dozen projects at the Laboratory are currently funded at about $6 million per year. The box illustrates developments from one of our most recent and exciting initiatives—the prevention of hemorrhaging in stroke-damaged blood vessels.

During our first year, we contacted more than 80 medical, industrial, and governmental organizations. We are identifying and coordinating projects that extend LLNL core competency in the multidisciplinary focus of biotechnology, helping to meet future DOE Defense Program requirements and providing cost-effective medical technology at the same time.

In Phase II, we are initiating and participating in larger health-care projects through multidisciplinary teams of collaborators. For example:

- Digital Mammography Systems is a proposed team of military, government, and industrial partners led by an Army medical center. Livermore would be responsible for system integration at 14 sites, for data integrity and archiving, and—with Sandia National Laboratories, Livermore—for new algorithms for computer-assisted diagnosis.
- This year, we have been asked to define and coordinate potential roles for the DOE laboratories in Testbed'95, which will set up a telemedicine system. The Center is a partner in the health-care working group of the National Information Infrastructure Testbed (NIIT), a consortium of telecommunications, computer, and other companies. In September 1994, we participated in a successful, one-day NIIT telemedicine demonstration, Testbed'94, held at the Congressional Office Building in Washington, D.C.

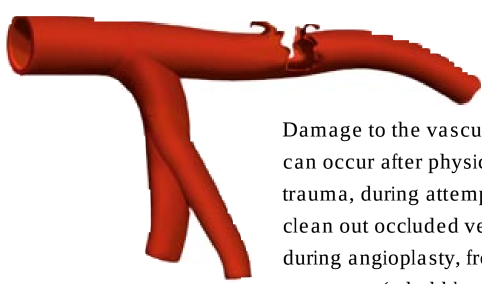
• In a concept paper, we proposed development of minimally invasive medical technology, an area in which the medical industry has great interest and which is now being considered as a government focus area.

Our Phase III activities seek to establish a national strategy for health care technology programs. The focus is on reducing costs without reducing access or quality of service. We have proposed a government organization operating under the National Institutes of Health (NIH). We envision this new agency as a forward-looking, expert organization that pursues the best technical solutions from the best sources combined with the medical expertise of the NIH. We have presented our concepts to the largest health care, medical research, and industrial organizations in the U.S., to Congressional staff members, and to members of the Clinton Administration. *Science and Technology Review* will report on developments and feature important technological advances as they occur.

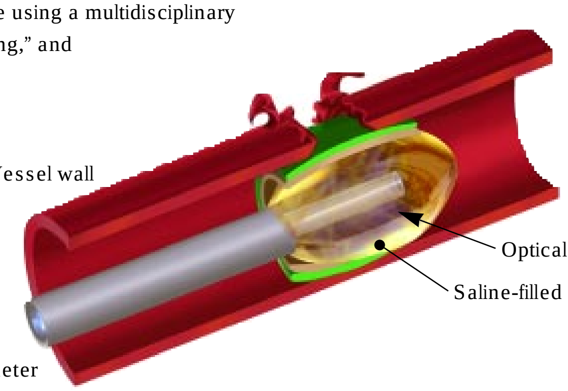
For further information contact J. Patrick Fitch or any member of the Center for Healthcare Technologies (510) 424-4806 (healthcare@llnl.gov).

Patch Welding for Damaged Blood Vessels

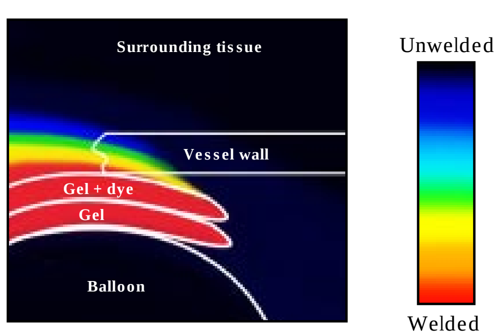
Every year in the U.S., over three million Americans are victims of stroke. The annual cost of care for stroke patients is about $30 billion. When the brain is deprived of oxygen, cell death can begin in a matter of minutes. Now, a change in treatment is coming. To promptly restore blood flow and oxygen supply, we are using a multidisciplinary approach to characterize vessels and occlusions, to do “clot busting,” and to “weld” damaged vessels, as illustrated here.



Damage to the vascular wall can occur after physical trauma, during attempts to clean out occluded vessels, during angioplasty, from an aneurysm (a bubble on the vessel wall), or as a consequence of other conditions.

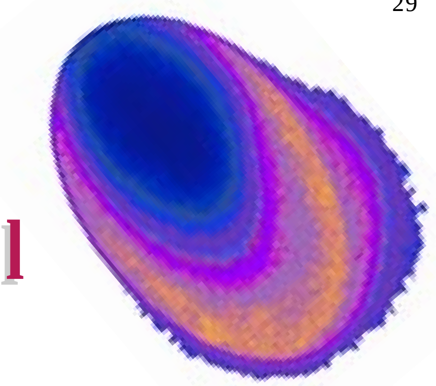


A tiny saline-filled balloon is inflated in the vessel until a biocompatible gel (tan) and the patch or “solder” material (green dye) make contact with the damaged vessel wall. Within the balloon is an optical fiber. Pulsed laser light from the tip of the fiber is absorbed by the dye until the ideal patch-welding temperature is obtained.



In the first six months of this project, we developed a modeling code, LATIS, to control and localize temperature when heating tissue. This code (similar to those used in inertial confinement fusion research) allows us to select the right combination of laser pulse duration, repetition rate, and number of pulses to obtain the ideal temperature (see red zone) for patch welding a blood vessel. At the wavelength we use, about 65 pulses every 200 microseconds are optimal for repairing a vessel without damaging the surrounding soft tissue.

The Short-Pulse Laser: A Safe, Painless Surgical Tool



THE very best surgeons possess exceptional skill and dexterity, but most have not had access to what sounds like the best of high technology tools—a medical laser. Medical lasers have been used successfully in some procedures such as repairing detached retinas, breaking up kidney stones, and removing port wine stain birth marks. However, their remarkable ability to simultaneously cut and cauterize has not caused them to eclipse steel or electrosurgical tools because they have lacked predictable precision with body tissue and have been too large and expensive to be a practical part of medical offices and operating rooms.

Recent advances by Livermore researchers are changing the capabilities of surgical lasers so that they may fulfill their promise to become the “blade of choice,” especially in surgical procedures on organs and tissues that bleed profusely when cut. By applying chirped pulse amplification to solid-state lasers, researchers have built systems that may increase the use of laser surgical techniques in operating rooms. The techniques are expected to revolutionize dentistry and are particularly well-suited to precision microsurgery on corneas, delicate ear bones, and the brain.

Limitations of Earlier Lasers for Surgery

Since their advent about 30 years ago, lasers have been observed to induce damage in transparent solids, such as defect-free dielectrics (electrical insulating materials used during laser beam amplification and as mirrors to direct beams). For pulses longer than a few picoseconds,* the generally accepted theory of bulk damage to these materials is that the incident radiation heats electrons (those in an atom’s conduction band, to be exact), and these electrons transfer thermal energy to other electrons and atoms in the lattice. In other words, the dielectric material is damaged by the melting, boiling, and thermal shock that result.

Similarly, a fundamental limitation of past surgical laser systems was the heat caused by the beams—either a continuous beam or one made up of multiple, 1000-ps pulses, or “bursts.” As a result, laser surgery was soon found to be unexpectedly complicated. Lasers affect irradiated tissue through absorption of the light energy, and the absorption is determined largely by the properties of the material being irradiated, such as its color. Consequently, a surgeon might be cutting tissue quite effectively with the laser at the proper specific energy when the beam suddenly hits a different kind of tissue. If the tissue has different absorption properties, the cutting rate and heat generation can suddenly increase or decrease dramatically—by orders of magnitude. Surgeons have had to worry about how much energy the beam deposited and the degree to which the irradiated tissue absorbed or reflected the light. They might irradiate tissue with no apparent effect, only to discover that the light was being reflected or transmitted and absorbed by other tissues and causing undesired burning at these sites.

Indeed, this collateral damage has been a real concern with conventional laser-surgery pulsed systems. For example, laser cutting can significantly heat material some distance from the area being irradiated, causing either desiccation of the material or, if there is water below the surface, explosive vaporization resulting in torn tissue.

There has been a clear need for a tool better than the scalpel, but one that does not require continuous adjustment or present the possibility of catastrophic mishap. Introduced about the same time as lasers, electrosurgical tools, which use radiofrequency waves to interact with tissues, have become the tools of choice for many applications in which lasers proved disappointing. Electrosurgical tools, for example, can simultaneously cut and cauterize; they are also less expensive than lasers, are easier to use, and cut much faster. They are, however, not suited to microsurgery, and they too can cause collateral tissue damage.

Ultrashort Pulses Provide the Answer

Recently, however, laser technology has cleared some hurdles. By applying chirped-pulse amplification to solid-state lasers, Livermore researchers have built systems producing

* One picosecond (ps) = 1 trillionth of a second or 10^{-12} s.

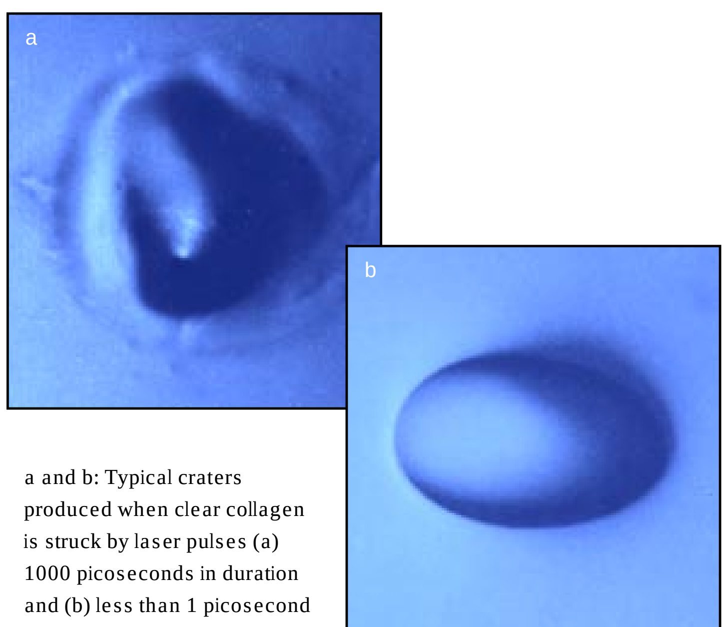
terawatt (10^{12} W) pulses with ultrashort durations—well under a picosecond. (Chirped-pulse amplification is described in some detail in the article on multilayer dielectric gratings in the September 1995 issue of *Science and Technology Review*.) According to theory, subpicosecond durations are far too short for appreciable electron energy to be transferred to surrounding material. As a result, less laser energy is absorbed by the tissue, so material should be able to be removed by subpicosecond pulses with essentially no collateral damage. Theory also predicts that the energy absorption mechanism for ultrashort pulses makes material removal by laser much less sensitive to tissue type than is the case with longer pulses.

To confirm the theoretical promise of ultrashort pulses, we performed a series of experiments on various materials. These extensive experiments, with materials such as fused silica and calcium fluoride, yielded results that agreed well with theory. We then produced "phantom tissues"—materials whose properties mimic the densities and effective atomic numbers of living tissue. We mixed gelatin and water to make collagen gels (collagen is a fibrous protein found in all multicellular animals), and we mixed aqueous solutions of cupric chloride in different concentrations to produce a range of light-absorption properties.

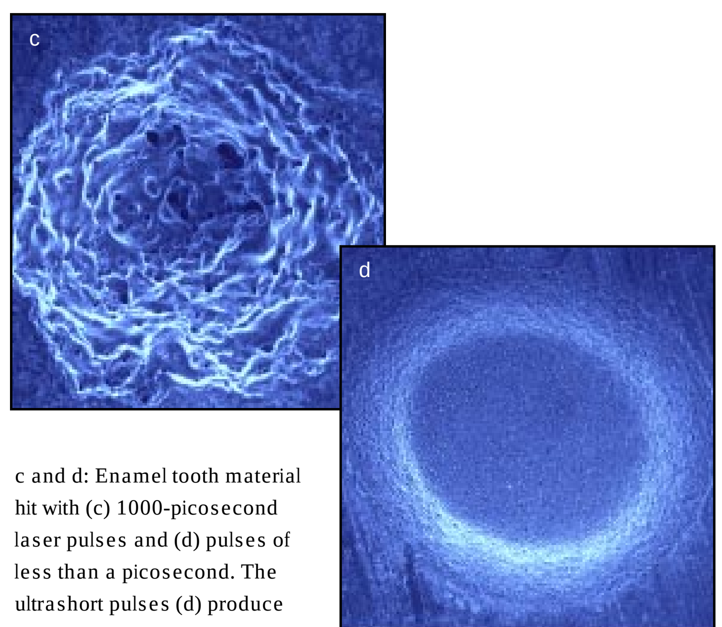
We then performed ablation measurements—measurements of how much material was removed by being "blown off," or ablated. We used a chirped-pulse amplification laser to obtain pulses of continuously adjustable duration from 0.3 ps to 1000 ps, with a laser spot size of 0.5 mm in diameter (about the size of a period). After irradiating the sample, we inspected it for formation of an ablation crater. The smallest craters we could observe were approximately 1 micrometer in diameter, 500 times smaller than the area the laser had ablated. We determined the ablation threshold for a given pulse width. Then, to determine the ablation efficiency, we measured ablated crater depth and diameter after 10 to 100 laser pulses, recording the energy of each pulse. Now we could predict how the laser was "cutting."

The figures below show typical craters produced by 1000-ps pulses and by pulses of less than 1 ps in a clear collagen gel (a and b) and in tooth enamel (c and d). Much more thermal damage appears with the longer pulses (a and c). For ultrashort pulses, collateral damage is practically absent, and a clean, smooth crater is produced (b and d).

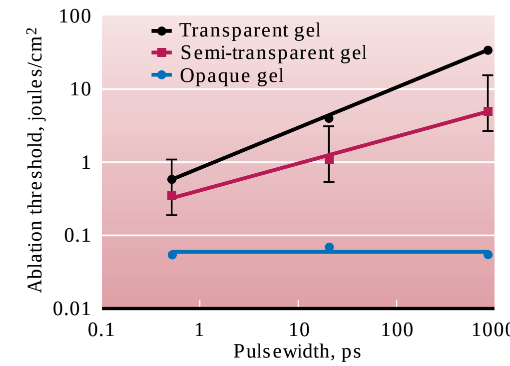
The figure on page 31 presents the results of ablation threshold measurements for collagen gels dyed to have different linear absorptions. The ablation thresholds for collagen gels follow the trends that we predicted. The ablation threshold for clear gels, which are similar to corneas, in the 1000-ps pulse width range (75 joules/cm^2) is about 1000 times higher than the ablation threshold for black gel (0.074 joules/cm^2). In the subpicosecond pulse width range, this difference decreases to only a factor of six. Thus, the ablation thresholds for transparent and nontransparent tissues converge at shorter pulse widths.



a and b: Typical craters produced when clear collagen is struck by laser pulses (a) 1000 picoseconds in duration and (b) less than 1 picosecond in duration. The shorter laser pulses (b) ablate the tissuelike collagen cleanly and precisely and produce less collateral damage than the longer pulses (a).



c and d: Enamel tooth material hit with (c) 1000-picosecond laser pulses and (d) pulses of less than a picosecond. The ultrashort pulses (d) produce less collateral damage than the longer pulses (c).



Short pulses cause highly localized, shallow energy deposits, and each one removes only a thin layer of material (less than 1 micrometer). Varying the number of pulses controls how much material is removed. High repetition rates (greater than 100 Hz) achieve high average removal rates (greater than 1 mm during 10 seconds). This method of tissue ablation has several advantages:

- It is efficient. With decreasing pulse width, the energy density needed to ablate material decreases.
- Minimal collateral damage occurs because ablation is efficient with the short pulse and because the ablated tissue carries away a large fraction of the deposited energy from the laser.
- The ablation threshold and ablation rate vary only slightly as tissue type and state change.
- Ablation depth can be controlled with extreme precision because a small amount of tissue is ablated per pulse and because the number of pulses can be controlled.

With ultrashort laser pulses, the absorption threshold and ablation rate (depth of material removed per pulse) are relatively insensitive to factors such as laser wavelength and tissue state (e.g., structure, hydration, and oxygenation). Because an ultrashort laser pulse (0.005 ps to more than 20 ps) is medically useful by virtue of its duration rather than its wavelength, a variety of lasers operating over a wide range of wavelengths can be used, such as lasers based on dyes, excimers, or solid-state materials. However, solid-state infrared lasers such as those used at the Laboratory offer the advantages of safety and convenience.

Our experimental results are still preliminary; further research is needed to understand what happens to the energy after it is deposited by the laser. How the energy couples to the atoms of the tissue, how the tissue is ablated, how the stress wave is generated, how the stress wave propagates into the tissue, and how the collateral damage occurs all warrant further investigation.

Practical for Surgery

Ultrashort-pulse lasers have an important niche in surgery. The precision ablation of these lasers allows microsurgeons to perform intricate operations, such as drilling holes through small middle ear bones, for which they use microdrills. Likewise in brain surgery, which also puts a premium on accuracy and control and on minimizing thermal collateral damage, a system with a high pulse-repetition rate could allow a surgeon enough speed and control to virtually "sculpt" the tissue.

An added benefit of lasers to surgery is the fact that the pulses can be transmitted by fiber optics. Laser energy can be delivered to many remote locations within the body through fiber-carrying catheters. In the future, instead of making large incisions to gain access to certain organs or cavities, surgeons will use more endoscopic and laproscopic techniques. Fiber-delivered lasers are already being used to break up kidney stones, for example, and are performing better than ultrasound for this purpose.

Ultrashort-pulse laser systems also have great potential in dentistry to replace the dentist's drill for cavity and root-canal work. The drill produces pain chiefly by heat—the drill gets the tooth very hot—and secondarily by mechanical vibration. We have demonstrated that the ultrashort-pulse lasers produce minimal heat and vibration and virtually no collateral damage to surrounding enamel.

The Laboratory is not alone in developing ultrashort-pulse laser systems. However, the critical step, once their medical utility has been conclusively proven, will be to make them compact and inexpensive. We have been developing the technology to make comparatively compact, easy-to-use high-power optical systems that produce pulses with flexible durations and wavelengths. Essentials for practical use are very high beam quality and reproducibility, in which the Laboratory has long-standing expertise. Using recent advances, we can design high-power, ultrashort-pulse systems small enough to be practical—and affordable—for surgeons and dentists.

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Powering Future Vehicles with the Refuelable Zinc/Air Battery

Developed at Lawrence Livermore National Laboratory, the zinc/air battery weighs only one-sixth as much as standard lead/acid batteries and occupies one-third the space, yet costs less per mile to operate. Further, because the battery is easily refuelable, it promises trouble-free, nearly 24-hour-a-day operation for numerous kinds of electric vehicles, from forklifts to delivery vans and possibly, one day, personal automobiles. The test of a Santa Barbara Municipal Transit bus with a hybrid of zinc/air and lead/acid batteries capped a short development period for the zinc/air battery. The test run indicated the zinc/air battery's potential savings in vehicle weight from 5.7 to 4.0 metric tons, in battery weight from 2.0 to 0.3 metric tons, in battery volume from 0.79 to 0.25 m^3, and in electricity cost from 5.6 cents per mile to 4.7 cents per mile. The power, however, remains the same.

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Gamma-Ray Imaging Spectrometry

At Lawrence Livermore National Laboratory, we have developed an instrument that can help locate and identify special nuclear material (SNM) and other radioactive materials. Recent advances in position-sensitive detector technology, coupled with advances from gamma-ray astronomy, have allowed researchers to build the gamma-ray imaging spectrometer (GRIS), capable of collecting the radiation and generating an image of its source. Such images of invisible radiation can be combined with visible-light images to clearly show the location of the materials. The gamma-ray energy information from different parts of the image can uniquely identify the type of material present. Although GRIS was developed to control the SNM associated with nuclear weapons, we have tested the instrument in several of a myriad of applications in other areas, including environmental cleanup, astronomy, medicine, the nuclear power industry, and any other enterprise where radioactive sources are used.

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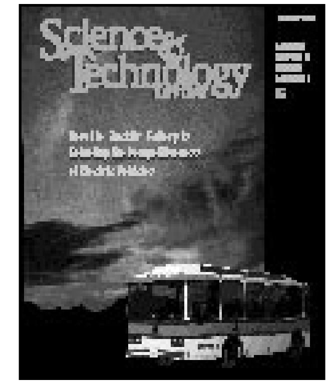

Science & Technology Review FAX Survey

What Do You Think?

This issue of *Science and Technology Review* (formerly *Energy and Technology Review*) represents a modified approach to communicating the work of the Laboratory. The intent of our changes is to make this publication more interesting to a broader audience. Please give us your reactions to our changes by answering the questions in sections 1 and 2 below and faxing them back to us at (510) 422-8803. You can also mail your response to the address below. If you photocopy this form first, you won't have to remove it from the publication.

Also note that this form can be used to ask for more information, to change your address, to stop your free subscription, or to add a colleague to the circulation. If you are requesting any of these, be sure to include your name, etc., in section 5.

1. Rate your interest

How interesting did you find the following articles?

	very interesting	interesting	minimal	none
Zinc/Air Battery	❑	❑	❑	❑
Gamma-Ray Imaging	❑	❑	❑	❑
Center for Healthcare Technologies	❑	❑	❑	❑
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How would you rate the technical level of the content?

	acceptable	too high	too low	didn't read
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Gamma-Ray Imaging	❑	❑	❑	❑
Center for Healthcare Technologies	❑	❑	❑	❑
Medical Lasers	❑	❑	❑	❑

How interesting and valuable do you find our new sections?

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