University of California
Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

Nonprofit Org.
U. S. Postage
PAID
Albuquerque, NM
Permit No. 853

Printed on recycled paper.

About the Cover

Each year, in a worldwide competition, *R&D Magazine* chooses the year's top 100 industrial inventions. In 2003, Livermore researchers received six of these coveted awards. The cover shows an R&D 100 plaque. Highlights of the winning entries begin on p. 6. Since 1978, Laboratory researchers have won 97 R&D 100 awards.

On September 9, 2003, Lawrence Livermore co-founder Edward Teller passed away at the age of 95. On pp. 2–3, *Science & Technology Review* pays tribute to Dr. Teller (who is also shown on the cover).

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the World Wide Web at www.llnl.gov/str/.

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National Nuclear Security Administration

Prepared by **LLNL** under contract No. W-7405-Eng-48

Science & Technology REVIEW

October 2003

Lawrence Livermore National Laboratory

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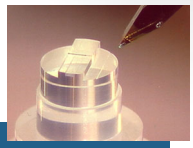

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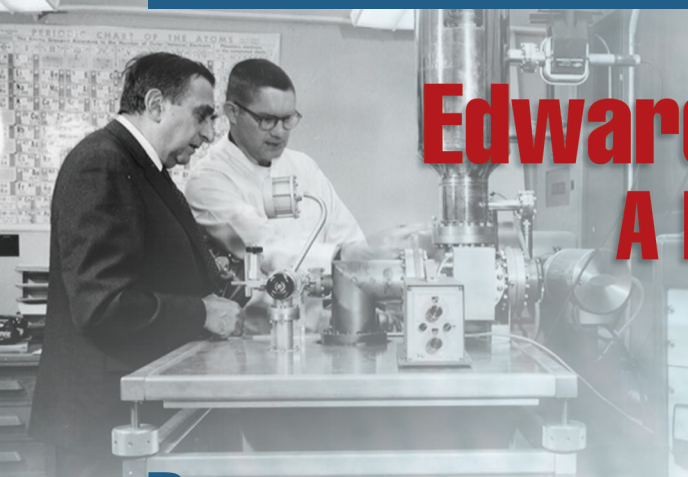
S&TR, a Director's Office publication, is produced by the Innovative Business and Information Services Department under the direction of the Office of Policy, Planning, and Special Studies.

S&TR is available on the Web at www.llnl.gov/str/.

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-52000-03-10
Distribution Category UC-99
October 2003



Edward Teller (1908–2003)
A Life Dedicated to Science

DR. Edward Teller, world-renowned physicist, co-founder of Lawrence Livermore National Laboratory, and a lifelong advocate for education, died September 9, 2003. He was 95.

"The loss of Dr. Edward Teller is a great loss for this Laboratory and for the nation," said Livermore Director Michael Anastasio. "He was a passionate advocate for science, for technology, for education, and for Lawrence Livermore National Lab. He put his heart and soul into this Laboratory and into ensuring the security of this nation, and his intense dedication never wavered."

Since he embarked on his scientific career, Teller's life has intertwined with myriad heads of state, dignitaries, and other elected officials. He met with every U.S. president since Franklin D. Roosevelt as well as with Pope John Paul II.

Less than two months before his death, Teller was awarded the Presidential Medal of Freedom, the nation's highest civil honor, during a special ceremony conducted by President George W. Bush at the White House.

Although Teller could not attend that ceremony—his daughter Wendy accepted the medal on his behalf—he was touched by the honor. "In my long life, I had to face some difficult decisions and found myself often in doubt whether I acted in the right way," he said, commenting on the award. "Thus, receiving the medal is a great blessing for me."

Throughout his long life, Teller often found himself at the forefront of some of the 20th century's most dramatic and history-making endeavors. Born in Budapest, Hungary, in 1908, Teller received a Ph.D. in physics at the University of Leipzig. It was Teller who drove Leo Szilard and Eugene Wigner to meet with Albert Einstein, who together would write a letter to President Roosevelt urging him to pursue atomic weapons research before the Nazis did.

Teller went on to work on the Manhattan Project at the fledgling Los Alamos National Laboratory and eventually became assistant director. His efforts were instrumental in creating the Livermore site of the University of California Radiation Laboratory in 1952. Teller strongly advocated development of the hydrogen bomb and promised and delivered a submarine-launched nuclear weapons system. He served as director at Livermore for two years and then as associate director for physics.

> ***"Edward Teller played a pivotal role in ending the Cold War. He has been a strong advocate for national defense and the cause of human freedom. The United States honors him for his excellence in science and in education, and his unwavering commitment to the nation."***
>
> *—President George W. Bush, during his presentation of the Presidential Medal of Freedom to Edward Teller on July 23, 2003*

"I always think of Edward Teller as passionately patriotic American with a deep Hungarian accent and a dry sense of humor," said Duane Sewell, a Teller colleague and friend for more than 50 years. "He was committed to doing every thing in his power to create a strong America, and in my eyes, he went a long way toward achieving his goal. In my eyes he was a kind, caring human being."

To Teller, science and education always went hand in hand. He taught physics at the University of California (UC), then created and chaired the UC Davis Department of Applied Science, which is located at the Livermore site.

He often admitted that knowledge was dangerous, but warned that ignorance "can be incomparably more dangerous." He was an advocate for education, believing that education was vital to the U.S. if the nation is to maintain its leadership role in the world.

In 1975, Teller was named Director Emeritus of the Laboratory and was also appointed Senior Research Fellow at the Hoover Institution. In the 1980s, he served as a determined advocate for the development of a ballistic missile

defense system to protect the nation from nuclear attack. These efforts contributed to the end of the Cold War.

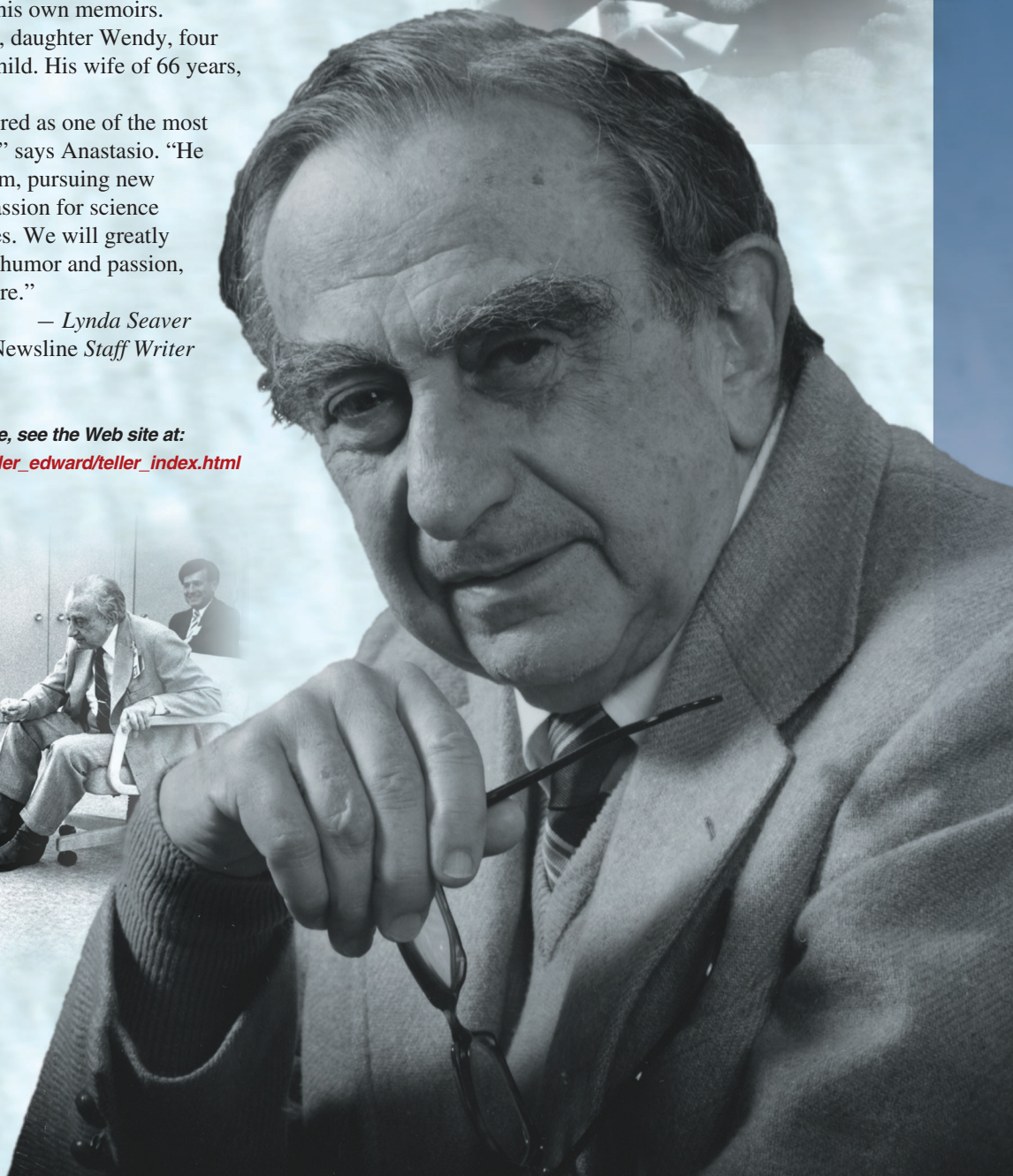
Teller received numerous awards for his contributions to physics, his dedication to education, and his public life. He published more than a dozen books on subjects ranging from energy policy and defense issues to his own memoirs.

Teller is survived by his son Paul, daughter Wendy, four grandchildren, and one great grandchild. His wife of 66 years, Mici, died three years ago.

"Dr. Teller will long be remembered as one of the most distinguished individuals in science," says Anastasio. "He devoted his life to preserving freedom, pursuing new knowledge, and passing along his passion for science and technology to students of all ages. We will greatly miss his enthusiasm and insight, his humor and passion, and the optimism he had for the future."

— *Lynda Seaver*
Newsline *Staff Writer*

For further information on Dr. Teller's life, see the Web site at:
www.llnl.gov/llnl/06news/NewsMedia/teller_edward/teller_index.html



Lab's aerogel sets world record

An aerogel developed by researchers in Livermore's Chemistry and Materials Science (CMS) Directorate has taken the record for the world's least dense solid. The Laboratory's aerogel, which is listed in *Guinness World Records 2004*, has a density of only 1.9 milligrams per cubic centimeter. It replaces the 2003 record holder—an aerogel developed by Jet Propulsion Laboratory having a density of 3 milligrams per cubic centimeter.

Discovered in 1931, aerogel is a translucent solid that looks much heavier than it is. Early scientific application of aerogels was limited by the high densities of the samples and the small amount of materials available for production. Today, less dense samples are used in electronics, acoustics, thermal insulation, and optical devices as well as for physics experiments.

Livermore scientists have been working with aerogels for more than two decades. Not only have they reduced the density of aerogel, but they also have improved material composition and clarity.

According to chemist John Poco, the Laboratory is a leader in aerogel technology. "We use more materials to create it and more innovative procedures than most anyone else." But he adds, "Setting a world record was never on our radar screen." When CMS researchers determined that others had claimed the lowest density, they wanted to set the record straight. They contacted Guinness World Records, sent documentation and samples, and received confirmation that they now hold the world record.

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Cargo industry briefed on threats

At this summer's International Cargo Security Summit in Chicago, Livermore's Executive Officer Ron Cochran described some of the technology solutions being developed at the Laboratory to address the threats that confront the freight transportation industry. He noted that, in addition to the Laboratory's unique capabilities in assessing nuclear threats, it also has developed breakthrough technologies in radiation and biological detection, information analysis, and infrastructure protection systems.

Topics at the summit included regulatory requirements, how the transportation industry can prepare for and respond to terrorist attacks, and some of the technologies now available to improve security. Participants also discussed the practicality of managing security risks throughout the supply chain and how counterterrorism measures can be implemented by all cargo transporters and related third parties.

"Cargo container security is one of the nation's most difficult technical and practical challenges in preparing for and countering terrorist threats," says Cochran. "This [summit] was an opportunity for the top experts in this area to get together to discuss the issues and priorities as well as identify better ways to keep their industry safe."

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Study confirms human effects on tropopause

A collaborative study including Livermore scientists has shown that human-induced changes in ozone and well-mixed greenhouse gases are the primary drivers of recent changes in the height of the tropopause. The team—which included scientists from Lawrence Livermore and Lawrence Berkeley national laboratories, the National Center for Atmospheric Research, the Institut für Physik der Atmosphäre in Germany, and the University of Birmingham in the United Kingdom—focused its research on understanding how different mechanisms affect atmospheric temperatures and, hence, tropopause height.

The tropopause is the boundary between the lowest layer of the atmosphere—the turbulently mixed troposphere—and the more stable stratosphere. It lies about 16 kilometers above the Earth's surface at the equator and 8 kilometers above it at the poles. Its altitude is sensitive to changes in vertical profiles of atmospheric temperature.

This collaborative study is the first to show that a model-predicted "fingerprint" of tropopause height changes can be identified in observations. Earlier research showed that increases in the height of the tropopause over the past two decades are directly linked to stratospheric ozone depletion and increased greenhouse gases.

The research team used climate models to provide quantitative estimates of the relative contributions of natural and human influences to overall tropopause height changes. From 1979 to 1999, tropopause height increased about 200 meters, and according to the model calculations, 80 percent of that increase is directly linked to human activities. In the first half of the 20th century, tropopause height increases were smaller and were caused primarily by natural variations in volcanic aerosols and solar irradiance.

A paper describing this work appeared in the July 25, 2003, issue of *Science*. Output from the climate models is available at www.nersc.gov/projects/gcm_data/.

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Award-Winning Technologies from Collaborative Efforts

PARTNERSHIPS and collaborations are important to the success of research and development organizations. Through them, one person's idea can be developed from a new concept to a revolution in technology. In fact, most technological innovations made today advanced to that point through collaboration.

Researchers at the national laboratories play a key role in building the connections that turn ideas into the tools and technologies needed to accomplish the laboratories' missions. At Livermore, our collaborations with universities often bring valuable breakthroughs that lead to a program's success. With private industry partnerships, Livermore researchers have been developing and improving technologies and processes for more than 50 years. These partnerships are also a rich source for ideas and inventions that can lead to unanticipated products.

This year, when *R&D Magazine* included six Livermore developments in its annual list of the 100 best new products and processes, the awards also confirmed our important, tangible results from recent collaborations with other organizations. Highlights of the award winners begin on p. 6.

The R&D 100 Award for BASIS, the Biological Aerosol Sentry and Information System, exemplifies a collaboration between two national security laboratories. BASIS is a detect-to-treat technology for countering an airborne terrorist attack. Submitted to the competition by Los Alamos National Laboratory, it is a joint accomplishment of Los Alamos and Lawrence Livermore. This award-winning technology is now an active element in the arsenal of defenses advanced by the Department of Homeland Security.

One of Livermore's missions is to develop the computational capabilities needed to maintain the nation's nuclear weapons stockpile. Success in this mission means continually pushing the limits of high-performance computing, and that requires steadily improving computer-chip technology. Two of the Laboratory's R&D 100 awards are related to this challenge: the extreme ultraviolet lithography (EUVL) full-field step-and-scan system and the ion-beam thin-film planarization process.

The EUVL full-field step-and-scan system was developed as part of the largest Cooperative Research and Development Agreement between national laboratories and private industry. This computer-chip lithography system writes and prints features one-half the size of those made by other systems, leading to microprocessors tens of times faster than today's most powerful chips and to similar increases in computer memory capacity.

A key challenge in developing EUVL technology is to manufacture reticle blanks that are virtually defect-free. Ion-beam thin-film planarization is a deposition and etching process that smooths the reticle surfaces as thin-film coatings are applied. Contaminated surfaces with particles up to 70 nanometers high can be smoothed until the coating is less than 1 nanometer high. As a result, much finer features can be written on chips.

A different type of collaboration is responsible for a new tool to measure eyesight aberrations. The microelectromechanical systems–based adaptive optics phoropter (MAOP) was developed in a collaboration among universities, national laboratories, and private industry—including optical component manufacturers and a leading provider of custom contact lenses. MAOP is an eye-correction system that significantly improves the diagnosis and treatment of eyesight aberrations. It also has the potential for use in treating ophthalmic and retinal disease.

The Laboratory has been a long-time leader in high-average-power lasers, and today, lasers are increasingly used in industrial applications. Our final two R&D 100 awards stem from Livermore's expertise in laser technology.

The first is a thermally compensated Q-switch, which maintains the quality of a laser beam. The Q-switch produces a system that's more compact and efficient than previous models. In addition, it is expected to allow laser systems to generate 5 kilowatts of average power—well beyond the capabilities of current switches.

Lasershot^{SM} Precision Metal Forming, which Livermore developed in collaboration with Metal Improvements Company, allows manufacturers to use lasers to precisely shape large metal sections. Because the shaped components retain the material's strength, this metal-forming process is an important new tool for manufacturing stronger large shaped metal products, such as those used for aircraft components or nuclear waste canisters.

These six R&D 100 awards demonstrate the fruition of science and technology collaborations—with other national laboratories, universities, and private industries. Through such partnerships, Livermore researchers are better able to deliver the technological advances needed to strengthen the nation's security. These endeavors also produce innovative products and capabilities—both the expected and the unexpected—that can benefit society.

■ Hal Graboske is acting deputy director for Science and Technology.

BASIS Counters Airborne Bioterrorism

ONE of the most frightening weapons in a terrorist's potential arsenal is the airborne release of deadly microbes such as those that cause anthrax or smallpox. In most cases, the prognosis for victims from such an attack depends on how quickly antibiotics, vaccines, or other medical treatment can be administered. And treatment options can't be determined until the pathogen has been accurately identified. A quick turnaround time can thus save lives.

The job of countering bioterrorism now has a potent weapon in BASIS, the Biological Aerosol Sentry and Information System, which won a 2003 R&D 100 Award. Designed by a team of researchers from Lawrence Livermore and Los Alamos national laboratories, BASIS is a detect-to-treat technology. That is, it's designed to detect and locate an aerosol release of a biothreat organism quickly and accurately enough for an effective response. For example, the survival rate from exposure to the anthrax bacterium is high when antibiotic therapy can be administered before symptoms appear, but after symptoms manifest, the survival rate diminishes significantly.

BASIS collects air samples at well-defined locations and at specified time intervals to help determine both the time and place of the release. Its mobile field laboratory rapidly tests samples for evidence of potentially lethal bacteria and viruses. Safeguards built into the system ensure a sample's integrity.

Aerosol releases of bacteria or viruses tend to quickly become diluted as their distance from the release site increases. BASIS is designed with extremely high sensitivity for detecting the most likely threat pathogens. By identifying a pathogen within hours, BASIS allows medical response units to mobilize while law-enforcement agencies begin the search for terrorists.

Key Goal Is No False Alarms

According to Dennis Imbro, the principal investigator for Livermore's BASIS effort, false alarms have the potential to cause immense disruptions and panic among civilians. Therefore, a primary goal in developing BASIS was to achieve a virtually zero rate of false-positive detections. To date, no false-positive events have been generated by deployed systems.

Livermore's BASIS team (left to right): Mark Wagner, Evan Skowronski, Cheryl Strout, Paula McCready, Julie Avila, Kris Montgomery, Linda Danganan, Linda Ott, Jackie Cofield, Patsy Gilbert, Paul Sargis, Virginia Montgomery, Tom Slezak, Dennis Imbro, Robert Johnson, Rich Parker, and Bruce Henderer.

BASIS is designed for indoor or outdoor use at high-visibility events or around likely terrorist targets. In 2001, the technology was successfully tested with live microbes inside a sealed chamber at the U.S. Army's Dugway Proving Ground. BASIS was first deployed in the month following the September 11 terrorist attacks. It was also deployed in Salt Lake City, Utah, for the 2002 Winter Olympic Games. During the Olympics, BASIS operated for 35 days at sports venues, urban areas, and transportation hubs. In all, 2,200 air samples were analyzed.

BASIS was later deployed in Albuquerque during the summer of 2002 and in New York City for the first anniversary of 9/11. BioWatch, a derivative of BASIS, is now deployed in major cities nationwide under the auspices of the U.S. Department of Homeland Security. BioWatch features elements of the BASIS technology but, instead of a mobile laboratory, uses laboratories that are part of the federal Laboratory Response Network operated by the Centers for Disease Control and Prevention (CDC).

Field Lab Tests for Pathogens

BASIS includes three major components. Aerosol collection hardware continually collects, time-stamps, and stores samples. A mobile field laboratory analyzes DNA from the samples and can identify and characterize a threat organism in less than half a day with a virtually zero false-alarm rate. Software designed by the BASIS team controls and integrates the operations.

The air samplers, called distributed sampling units (DSUs), suction air through filters that have microscopic-size pores and collect any regional microbes onto the filters' surface. DSUs can be deployed indoors, for example, at sports arenas or airline terminals or within heating and air-conditioning systems, and outdoors at airport drop-off areas, urban commercial centers, bridges, tunnels—any area with a significant threat of bioterrorism. DSUs are locked and password-protected to prevent unauthorized access and to guarantee the integrity of filters.

A semi-automated mobile field laboratory analyzes each filter, searching for DNA from target pathogens—those organisms identified by the CDC as high-priority threat agents. Inside the field lab, DNA is amplified via the polymerase chain reaction (PCR), a quick, reliable method for detecting DNA of specific microbes. Should a target pathogen be present, PCR amplifies its DNA while ignoring DNA from other microbes.

To confirm a positive finding and identification of the organism, the laboratory analyzes the target sample a second time. The characterization is so precise that a microbe can often be identified down to the strain level. The suspect DNA can then be sequenced to determine if genetic engineering has, for example, increased a microbe's virulence or has in any way engendered drug resistance.

When a positive identification has been confirmed, the field lab immediately notifies the appropriate response agencies. The entire process—from collecting samples to identifying a threat organism—typically requires only 8 to 10 hours.

BASIS features air samplers that suction air through filters and collect any airborne microbes onto a filter's surface. Above, the bar code of a single filter is scanned.

The BASIS software package runs on a standard laptop computer. The software is divided into two modules: the BASIS Operations Center (BOC) control package and the Sample Management System (SMS) filter-tracking package. The SMS uses bar codes to track filters at every point of the operation—from preparing a filter to processing the final results in the field laboratory. Each DSU can receive operational parameters via shielded cable, radio frequency, or cellular modem and can transmit them in real time to a BOC laptop.

BASIS is just one of a host of counterterrorism technologies and systems being developed at the national laboratories. Its success demonstrates that Livermore researchers are on the right track in the fight against terrorism.

—Arnie Heller

Key Words: BASIS (Biological Aerosol Sentry and Information System), BioWatch, bioterrorism, homeland security, polymerase chain reaction (PCR), R&D 100 Award.

For further information contact Dennis Imbro (925) 423-0220 (imbro1@llnl.gov).

In the Chips for the Coming Decade

MICROELECTRONICS permeate our lives. They are in our cars, our kitchen appliances, our computers, and thousands of other products that drive our modern-day existence. Now, researchers at Lawrence Livermore, Sandia, and Lawrence Berkeley national laboratories have developed a system that will keep microchips rolling off the line with ever-smaller features.

The extreme ultraviolet lithography (EUVL) full-field step-and-scan system is the first tool that demonstrates all of the key technologies needed for production of next-generation microprocessors. This fully integrated system prints 50-nanometer features—less than half the size of those made by current production tools—and it writes the full field size of the chip—24 by 32 millimeters. The projection optical system, which was developed at Livermore, is the first large-field diffraction-limited camera for extreme ultraviolet (EUV) wavelengths and may rank as the most accurate imaging system ever constructed.

Because it prints smaller features, the system produces chips that are higher in density. That is, they can "do more" in less space, which will dramatically improve the speed and memory capacity of computer systems. Microchips with features smaller than 50 nanometers may well lead to systems for facile speech recognition, improved weather prediction, enhanced medical diagnostics, three-dimensional image processing, microcontrollers for "intelligent" machinery, and more powerful supercomputers for scientific and defense research.

Physicist Regina Soufli, one of Livermore's principal investigators on the multilaboratory team, says such applications will be possible because the system embodies a set of groundbreaking technologies. In fact, until a few years ago, the science and technology community considered many of them impossible to develop.

Making the Jump for Moore's Law

For several decades, integrated circuits have steadily gotten faster, smaller, and cheaper. Circuit performance has basically doubled every two years—a pace of development referred to as Moore's Law. This rapid development rate is primarily responsible for the remarkable advances in computer technology that have occurred over the past few decades.

Unfortunately, fundamental physics laws on the diffraction of light are threatening to put the brakes on this progress. Photolithography uses light to print features onto a circuit substrate, which is usually silicon. The wavelike nature of light makes it extremely difficult to print images whose features have

Livermore team members (standing, from left): Eberhard Spiller, Russ Hudyma, Rick Levesque, Chris Walton, Regina Soufli, John Taylor, Sherry Baker, Mark Schmidt, Franklyn Snell, Layton Hale, Michael Johnson, Nhan Nguyen, Don Phillion, Henry Chapman, Butch Bradsher; (kneeling): Gary Sommargren, Ken Blaedel, Jim Folta, and Don Sweeney.

a resolution less than the wavelength of the light being used. To print 100-nanometer features—the current size for computer chips—manufacturers have had to add expensive enhancements to lithographic systems. The enhanced systems use light in the deep ultraviolet part of the spectrum with wavelengths of 193 to 248 nanometers.

The EUVL full-field step-and-scan system goes beyond deep ultraviolet into the EUV part of the spectrum, using light with wavelengths of about 13 nanometers—more than a factor of 10 shorter than the wavelength of even the most aggressive deep ultraviolet system. The current resolution for the EUVL system is 50 nanometers, but Soufli says that a resolution of 20 nanometers will ultimately be possible. She adds that such a fine resolution is not likely to be attained with other semiconductor technologies for high-volume manufacturing.

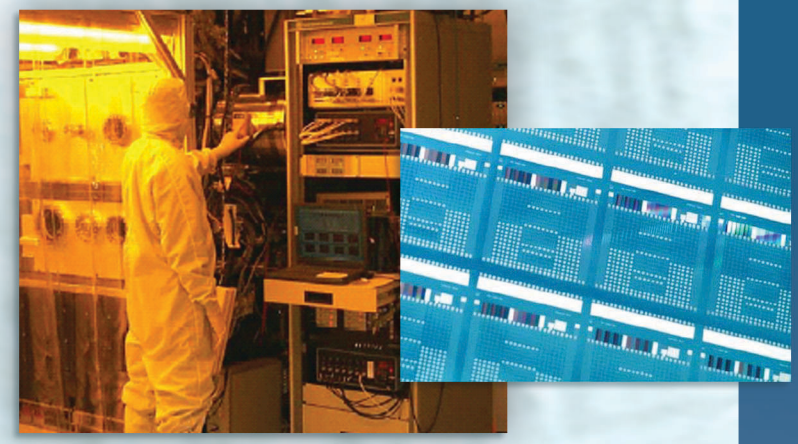
Because it uses EUV light, the new system will also have a greater depth of focus than systems using longer wavelengths, which will guarantee more robust processing capabilities. In addition, the mask patterns for imaging onto the silicon wafers can be relatively simple, which eliminates the complex and expensive pattern modifications that non-EUV systems use to enhance the resolution of the printing process.

Bringing the EUVL full-field step-and-scan system into reality for the next Moore's Law jump required the multilaboratory team to rapidly develop several technologies. Many of these technologies were thought to be too difficult or even impossible to develop in time for EUVL to play a role in manufacturing.

For example, the team developed highly accurate metrologies to fabricate and align the system's mirrors (see *S&TR*, October 1997, pp. 6–7) because no existing method came even close to measuring figure and smoothness with the accuracy required. With the new metrologies, these measurements are accurate down to atomic dimensions. The team also developed the world's most precise multilayer reflective coatings, which are necessary for EUVL optics (see *S&TR*, October 2002, pp. 10–11; October 1999, pp. 12–13), as well as a clean, 13-nanometer light source with a high-power laser-produced plasma. The source provides enough light for rapid scanning without creating contaminants that would damage the system.

Since EUV radiation is absorbed by gases, new controls were needed to ensure a suitable, ultrahigh-vacuum environment in which to operate the system. The team developed magnetically levitated precision stages compatible with the vacuum environment. Custom sensors were also created that could operate in the EUV environment, and control hardware and software were designed to provide full step-and-scan capabilities.

The EUVL full-field step-and-scan system is the central element of the largest Cooperative Research and Development Agreement (CRADA) between the U.S. national laboratories and private industry. This unprecedented CRADA is a 6-year, $250-million program, funded by the EUV LLC, a consortium of six semiconductor manufacturers. The system's development was key in convincing the microelectronics industry that EUV systems could follow deep ultraviolet systems as the next-generation lithography technology for producing microelectronics. In fact, Charles W. Gwyn, general manager of EUV LLC and a program director at Intel, noted that the success of this system led EUVL to be selected by international semiconductor organizations as the best candidate technology for use with circuit features below 50 nanometers.



Front view of the extreme ultraviolet lithography full-field step-and-scan system. Inset shows a close-up of the 24- by 32-millimeter fields that this technology can print on a silicon wafer.

The EUVL system also has potential applications outside the semiconductor manufacturing industry. Various nanotechnologies could benefit from the large surface area that can be imaged with features smaller than 50 nanometers. Possibilities include photonic crystals, surface-acoustic-wave detectors, and molecular electronic devices.

Set for the Future

With the success and acceptance of the system, EUVL now appears on the road maps of all the major semiconductor manufacturers. Soufli notes that subsequent versions of this system most likely will be used to fabricate microelectronics that are 100 times faster than those currently available. With Moore's Law now in good shape for well into the next decade, microelectronics will continue to advance at the pace we have all come to take for granted for nearly half a century.

—Ann Parker

Key Words: Cooperative Research and Development Agreement (CRADA), extreme ultraviolet lithography (EUVL) full-field step-and-scan system, EUV LLC, R&D 100 Award, semiconductor computer chips.

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Smoothing the Way to Print the Next Generation of Computer Chips

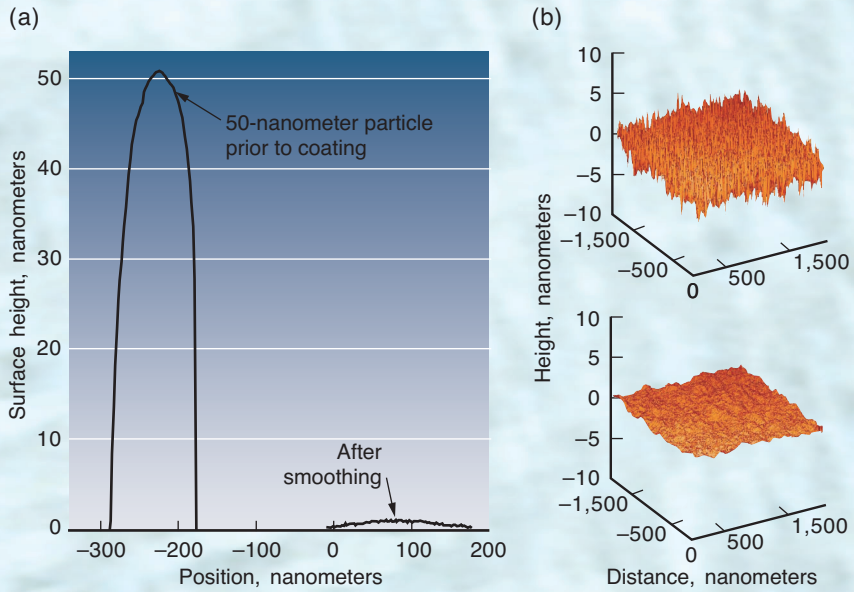
A frantic race is under way in the microelectronics industry to integrate more and more capability onto computer chips. Yet conventional optical lithography—the current practice of directing light through a mask, or reticle, to print integrated circuits on chips—is being pushed to its limits. When beams of light cannot be made thinner, the number of circuits that can be written on a given chip can go no higher. Extreme ultraviolet lithography (EUVL), which has emerged as the lithographic method of the future, is expected to be capable of reducing the feature size from 130 nanometers to less than 50 nanometers.

"One of the highest risk areas for EUVL technology was the development of the reflective reticle," says materials scientist Paul Mirkarimi. Mirkarimi's team has not only overcome that concern but also won an R&D 100 Award for the ion-beam thin-film planarization process, which generates nearly perfect surfaces for reticles and other critical components for EUVL. With this novel deposition and etching process, surfaces that have been contaminated with particles piled up to 70 nanometers high can be made almost perfectly smooth. The resulting profile of the thin-film coating is less than 1 nanometer high. Imagine "smoothing" a 70-story skyscraper to the height of a single-story house.

Almost Perfect Surfaces

An EUVL reticle blank consists of a substrate coated with a molybdenum–silicon (Mo/Si) multilayer film designed to have optimal reflectivity at extreme ultraviolet (EUV) wavelengths of 13 to 14 nanometers. Reflectivity is critical because EUVL uses strongly attenuated EUV light directed at reflective optical components to create minute features. The film is coated with a buffer layer and an absorber layer and is processed with an electron-beam lithographic tool to form a patterned EUVL reticle. The finished reticle absorbs EUV light at specific locations and reflects it everywhere else.

Development team for the ion-beam thin-film planarization process (left to right): Dan Stearns, Victor Sperry, Sherry Baker, Eberhard Spiller, and Paul Mirkarimi.



Ion-beam thin-film planarization can be used to fabricate nearly defect-free reticles and projection optics for extreme ultraviolet lithography. (a) With the deposition and etching process, a 50-nanometer particle is smoothed until it is less than 1 nanometer high, or about the height of a single atom. (b) Overall surface roughness is dramatically reduced as well.

The key challenge in developing this reticle technology is to manufacture reticle blanks that are virtually defect-free. The allowable defect density is about 0.0025 defects per square centimeter for defects of approximately 50 nanometers and larger. This density corresponds to just one defect for every two 15-centimeter-square reticle blanks—or a single defect the size of a basketball on a flat surface slightly larger than the states of Oklahoma and Texas combined. Says Mirkarimi, "To our knowledge, these are the most stringent defect specifications ever required for a coating process."

The Livermore team's technology smooths, or "planarizes," substrate particles during the multilayer coating process. A primary ion source sputters material off a target onto the substrate, and a second ion beam etches, assisting in the formation of a smooth, uniform film with remaining defects less than 1 nanometer high. Defects that small—just a few atomic layers thick—are considered to be benign according to EUVL printability modeling.

Two other deposition processes—magnetron sputtering and ion-assisted electron-beam evaporation—can also be used to print computer chips. But magnetron sputter deposition results in larger substrate particles. And at least for Mo/Si coatings, there are no data to suggest that ion-assisted electron-beam evaporation smooths out defects.

Mirkarimi's team also demonstrated that their planarization process smooths rough substrates, making it applicable to projection optics, another critical EUVL component. The figure and finish specifications of these optics are about 0.1 nanometer, which are extremely challenging and expensive to achieve simultaneously. "There is the risk that sufficient quantities of these optics won't be produced because of the difficulty in fabricating them," says Mirkarimi.

With the planarization process, coatings with EUV reflectivities of about 67 percent can be obtained on substrates with roughness of approximately 0.4 nanometer, which is sufficient for projection optics. Thus, finish specification for the optics could be relaxed, significantly reducing the production costs and increasing the availability of these optics. Livermore's process is equally effective for smoothing homogeneous films. By successively depositing and etching thin silicon layers, the team achieved a level of particle smoothing with homogeneous silicon films similar to the level accomplished with Mo/Si multilayer films.

Putting EUVL to Use

With the smaller feature size that's possible with EUVL, many more transistors can be placed on an integrated circuit. Desktop computer microprocessor chips will operate at more than 10 gigahertz, and random access memory chips can have gigabyte capacities. Such powerful, affordable computers are expected to make a variety of computationally intensive applications practical. Real-time, multilanguage voice recognition and translation are just two examples.

In 2001, the Semiconductor Industry Association reported that the industry was annually manufacturing about 60 million transistors for every man, woman, and child on earth. By 2010, this number is expected to be 1 billion transistors, as integrated circuits make their way into even more devices used in our daily lives. If we think our lives are computerized now, we obviously haven't seen anything yet.

—Katie Walter

Key Words: extreme ultraviolet lithography (EUVL), ion-beam thin-film planarization, R&D 100 Award, reticle.

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Eyes Can See Clearly Now

MILLIONS of people use eyeglasses or contact lenses to correct their vision, and many are opting for laser eye surgery. But determining the needed correction is not an exact process. When we have our eyes checked, we sit in a darkened room, peer through a device called a phoropter, and look at a focusing target, often an eye chart, projected in front of us. As we read the chart, an optometrist or ophthalmologist changes the lenses we're looking through while we repeatedly answer the doctor's only question: "Which one looks better—number one … or number two?"

A new optical device, called the microelectromechanical systems– (MEMS-) based adaptive optics phoropter (MAOP), will greatly improve this process. It allows clinicians to integrate a computer-calculated measurement of eyesight with a patient's response to the target image. Patients can immediately see how objects will look—and the clinician can adjust the prescription—before they are fitted for contacts or undergo surgery. As a result, patients will experience better vision correction outcomes, especially with custom contact lenses or laser refractive surgery.

MAOP was developed in a collaboration among universities, national laboratories, and industry, including a team of researchers from Lawrence Livermore. Funded by the Department of Energy and the Center for Adaptive Optics—a National Science Foundation Science and Technology Center—the project brings together optical component manufacturers and one of the world's leading providers of custom contact lenses and refractive eye surgery equipment. The MAOP team received an R&D 100 Award for developing an eye-correction system that combines technologies to improve the diagnosis and treatment of eyesight aberrations and ophthalmic and retinal disease.

Livermore members of the MAOP team (left to right): Scot Olivier, Steve Jones, Kevin O'Brien, Don Gavel, Abdul Awwal, and Brian Bauman.

An Objective Measure of Eyesight

The current phoropter used to measure vision addresses only the lower-order aberrations, such as defocusing and astigmatism. MAOP is designed to help patients with higher-order problems, such as coma, spherical aberration, trefoil, and quadrifoil. Scot Olivier, who led Livermore's MAOP effort, says future versions of the system will incorporate retinal imaging, so clinicians can more successfully diagnose and treat retinal diseases—such as retinitis pigmentosa, glaucoma, diabetic retinopathy, and macular degeneration—that cause blindness.

MAOP combines adaptive optics technology—a technology used on the world's largest telescopes for high-resolution imaging of astronomical objects—with MEMS deformable mirror technology. By using the MEMS deformable mirror, says Olivier, the team significantly reduced the size of the phoropter and could build it with commercial components, thus making MAOP compact and affordable.

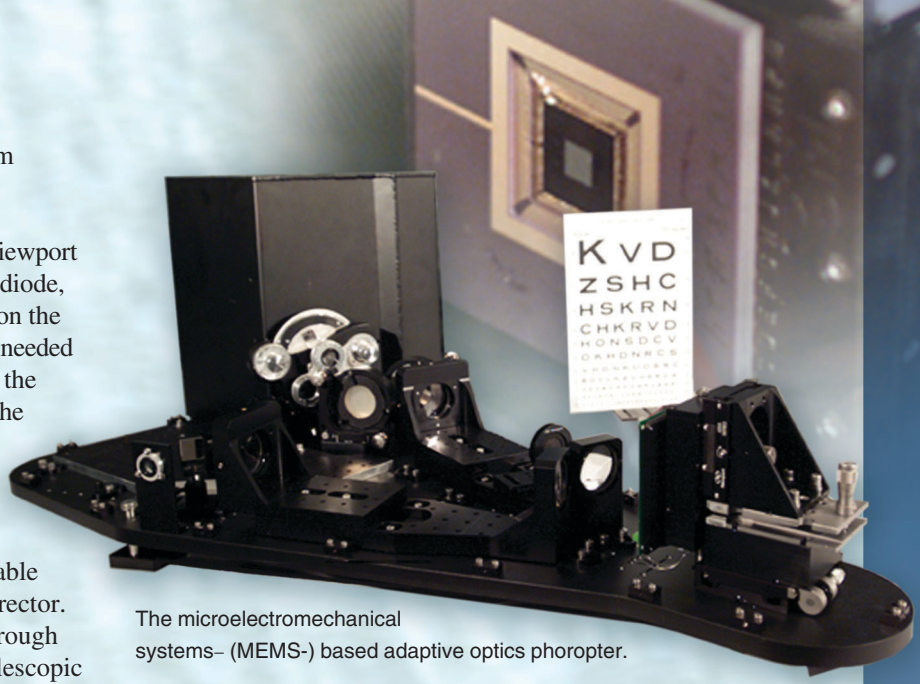
Adaptive optics compensates for optical aberrations by controlling the phase of the light waves, or wavefronts, as they hit the retina—much like waves breaking on a shoreline. The optical structures in the eye, particularly the cornea and lens, can distort

these wavefronts and thus produce the aberrations we encounter in our natural vision. An adaptive optics system measures aberrations with a wavefront sensor and uses a wavefront corrector to compensate for the distortion.

With MAOP, a patient looks through the phoropter viewport at a focusing target. A light source, a superluminescent diode, is projected into the patient's eye and creates an image on the retina. A flip-in mirror allows a computer to calculate the needed correction. By pushing a button, the clinician can apply the computer-calculated prescription and ask the patient if the image is clear.

A beam splitter can be incorporated with the system to combine these two steps. Then the patient can simultaneously view the focusing target while the computer corrects the aberrations. The MEMS deformable mirror uses a standard Shack–Hartmann wavefront corrector. Light from a laser or superluminescent diode passes through the beam splitter, flip-in mirror, adjustable lens, and telescopic lenses and is then reflected off the corrector. Another set of telescopic lenses directs the light through the eye and creates an image on the retina. The wavefront sensor sends information to the computer interface, telling the computer how to adjust the corrector.

MAOP is the first system to use the much smaller and less expensive MEMS deformable mirror for adaptive optics and ophthalmic applications. The wavefront sensor determines how much the wavefront is distorted as it passes through the eye's cornea and lens. A computer uses this information to create an internal, three-dimensional (3D) representation of the distorted wave. That 3D shape is then used to instruct the 144 MEMS actuators to move to positions that will minimize the distortion and "flatten" the wavefront.



The microelectromechanical systems– (MEMS-) based adaptive optics phoropter.

Hope for Fighting Retinal Disease

Because MAOP features a modular design, it can be adapted for other applications. Modules under construction will enable the system to also perform retinal imaging. Traditional retinal imaging systems cannot apply wavefront corrections and thus produce images with a limited resolution, which hinders a doctor's ability to diagnose early-stage retinal disease. Adaptive optics systems, which can correct wavefronts, produce far superior retinal images.

Higher-order aberrations, such as distorted vision from halos or glare, increase with an individual's age. Previous computer-calculated methods do not correct for these problems and have not produced acceptable results. MAOP not only measures and corrects these aberrations, but it also can be used to evaluate eyesight under conditions that limit vision, such as while driving at night.

Clinical studies at the University of Rochester, which were conducted with earlier versions of MAOP, showed the benefits of correcting higher-order aberrations. Patients with extremely poor vision—say 20:400, which is far below the normal 20:20 eyesight—reported significant improvement when these aberrations were corrected. One patient's vision became 24 times better.

With MAOP, clinicians can train their staffs to operate a single instrument with multiple functions and applications. The system can also collect and store patient information—before and after the correction is applied and the patient's input is received—to provide an eyesight history for help with later diagnosis. A MAOP system outfitted with retinal imaging could be used to test new therapeutics in clinical trials and provide objective measurements of a therapy's effectiveness.

MAOP is the first system to measure higher-order aberrations in the human eye, apply corrections, and immediately allow the patient to see the results. It's an innovative technology for early detection and treatment of retinal diseases that cause vision loss and blindness. And it will improve optical treatment for the millions of people who depend on vision correction just to make it through the day.

—Sharon Emery

Key Words: eyesight correction, microelectromechanical systems–(MEMS-) based adaptive optics phoropter (MAOP), R&D 100 Award, retinal disease.

Acknowledgments. In addition to the Livermore team, collaborators included Ian Cox: Bausch & Lomb; Paul A. Bierden: Boston Micromachines Corp.; Stephen Eisenbies, Steven Haney: Sandia National Laboratories; David Williams: University of Rochester; and Dan Neal: Wavefront Sciences.

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This Switch Takes the Heat

A powerful laser pulse generates plenty of heat. Some lasers, like Livermore's National Ignition Facility or the older Nova laser, produce a highly intense burst of light and then must cool for hours before another shot can be fired. Other laser systems are designed to operate almost continuously. The challenge in designing this latter variety, known as average-power lasers, is to maintain the beam quality in the presence of heat. Heat can cause aberrations to the laser beam, degrading its quality.

Livermore physicist Chris Ebbers and technician Keith Kanz, working with visiting scientist Hitoshi Nakana from Japan's Kinki University, have helped to solve this problem by developing a Q-switch that compensates internally for the heat from the laser beam. They received an R&D 100 Award for their innovation.

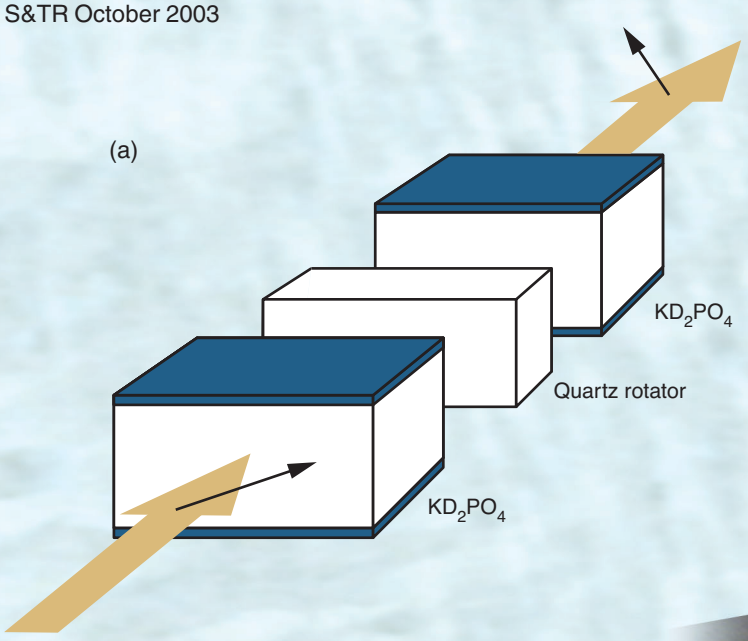
Q-switches, which maintain the quality, or "Q," of the beam, stop unwanted laser oscillations—laser pulses before and after the main laser pulse. An efficient Q-switch is essential for a high-energy, multipass laser to function at all. In fact, the thermally compensated Q-switch enables an entirely new type of laser architecture—a higher-average-power system that is more compact and more efficient than was previously possible. The team designed the award-winning switch for Livermore's Mercury laser, which has an unusually large beam size, but the switch can be used for any high-average-power laser.

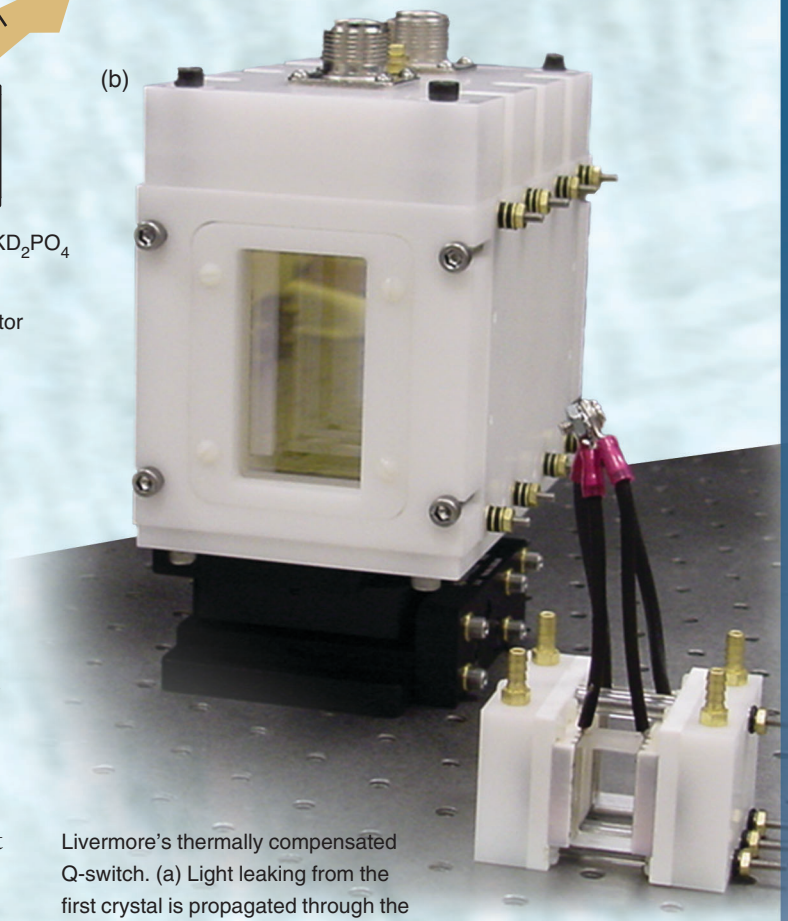
An electronically controlled shutter is required to stop unwanted laser oscillations, and it must respond in a time frame as short as the desired laser pulse. A Q-switch—also known as a Pockels cell or an electro-optic switch—uses a crystal whose refractive index is dependent on the voltage applied to it. It is one of the few electrically driven devices that can respond in a nanosecond. Because light travels approximately 1 foot (or 0.3 meter) in 1 nanosecond, a light switch must change the propagation direction of the laser light on this nanosecond time scale.

The problem with existing electro-optic cells is that heat absorbed from the laser beam prevents the cell from functioning. At average powers above 30 watts, the cell's crystal heats up. The switch then allows light to "leak" because the laser beam is depolarized. That leaked light can be amplified as well, creating spurious parasitic laser beams, degrading the quality of the initial beam, reducing the average power output, and possibly damaging the laser's optics.

Traditional electro-optic Q-switches use a single electro-optic crystal made of potassium di-deuterium phosphate, also known as deuterated KDP or KD_2PO_4. All single-crystal Q-switches exhibit a temperature-dependent loss of power above 15 to 30 watts, which allows light to leak. Livermore's thermally compensated Q-switch is made of the same material, but it incorporates a quartz rotator and a second, identical crystal, as shown in the figure on the next page. The leakage, or depolarization loss, exhibited by the first crystal is canceled because the leaked light is propagated through the polarization rotator and the second crystal.

Chris Ebbers (left) and Keith Kanz show the high-average-power electro-optic Q-switch.





Livermore's thermally compensated Q-switch. (a) Light leaking from the first crystal is propagated through the polarization rotator and the second crystal. (b) Livermore's Q-switches for large aperture (3.25-by 6-centimeter) and smaller aperture (1.5- by 3-centimeter) high-average-power laser systems. The switches are made of carefully machined and aligned potassium di-deuterium phosphate (KD_2PO_4).

Also critical to the device's success is the care with which it is fabricated. "The precision with which the parts have been machined and aligned and the process of binding the crystal to ceramic are unequaled," says Ebbers.

The new Q-switch shows less than a 1-percent loss up to 100 watts of laser light, which was the testing limit in the laboratory. "Extrapolating from these measurements, we expect the device to operate up to and even beyond 300 watts," says Ebbers. That range is 10 times higher than any equivalent commercially available electro-optic Q-switch. A laser system using Livermore's new switch could thus generate an unprecedented 5 kilowatts of average power or more without significant light leakage.

Putting the Q-Switch to Work

Livermore's Q-switch is one of several devices and systems developed in recent years to enable the construction of the Mercury laser, a large-aperture (large-beam-size), high-average-power laser with a high repetition rate. The Mercury laser is a smaller version of a potential prototype for an inertial fusion energy driver. As such, it will be used to study how high-intensity light interacts with matter. It will produce 100-joule pulses at a repetition rate of 10 hertz, for an average power of 1 kilowatt. Funding from the Laboratory Directed Research and Development Program has been key to developing the Mercury laser and components such as the Q-switch that make this unique laser possible.

Similar high-average-power lasers are also being considered for defense and civilian applications. For example, a compact laser in a helicopter would function as a very bright flashlight to detect mines, look for bodies in murky water, or search for obstacles on the floor of an ocean bay. The high repetition rate and short pulse width made possible by the Q-switch would give this detection tool excellent time resolution.

Laser peening, a process developed at Livermore several years ago to strengthen metals, also makes use of high-average-power lasers. By inserting the Q-switch into this system, the laser's pulse could be tailored to any desired shape to match the needs of the material being peened.

—Katie Walter

Key Words: high-average-power lasers, laser peening, Mercury laser, R&D 100 Award, thermally compensated Q-switch.

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Laser Process Forms Thick, Curved Metal Parts

MANY industries, most notably the aircraft industry, must precisely shape large metal parts while maintaining the material's structural properties. Shaped parts must also resist cracks from corrosion and fatigue. The traditional techniques manufacturers use to shape metal, such as shot peening, have significant limitations, especially regarding the thickness of pieces that can be formed.

A team of Livermore researchers has developed a new approach that overcomes these problems by using a laser to form parts. Called Lasershot℠ Precision Metal Forming, the technique is especially effective for forming pieces greater than 2 centimeters thick—pieces so thick they are difficult to shape without weakening the material structure. The Livermore team, led by physicist Lloyd Hackel, won an R&D 100 Award for this innovative technology.

Lasershot℠ Precision Metal Forming shapes parts to exact curvature and contour specifications, preserves a smooth surface finish, and leaves the parts resistant to stress corrosion cracking and failure from fatigue. The process can be applied to any metal or alloy and is particularly effective with the aluminum alloys used for structural aircraft components. As the process is introduced commercially, manufacturers can significantly reduce aircraft design weight, thereby increasing payloads and fuel efficiency and making new designs possible.

The process can also be used to precisely form the final shape of nuclear waste canisters.

Because it offers higher precision than current methods and the ability to exactly shape local areas, manufacturers can reduce the number of processing steps and the amount of material needed for machining components.

Lasershot℠ Precision Metal Forming was developed jointly with New Jersey–based Metal Improvement Company, Inc. The technique uses a solid-state laser system that induces a compressive stress to a depth of 1 millimeter or more on the desired surface of a section of metal. The strain from the deep level of compressive stress elongates the treated surface, effectively bending the metal within the processed area. The straining process also confers a beneficial compressive stress on both the treated and untreated surfaces.

By applying a much deeper stress, Lasershot℠ Precision Metal Forming can produce curvatures three to eight times greater and a surface six times smoother than the shot-peening process can produce. Manufactured sections also can be larger, which will reduce the number of welds or joints and, thus, strengthen the structure while reducing its overall weight. In addition, the precision of the process results in fewer manufacturing steps required to form large panels and assemble aircraft.

Members of the Lasershot℠ Precision Metal Forming team (left to right): Hao-Lin Chen, Andre Claudet, Tania Zaleski, C. Brent Dane, Laurie Lane, and Lloyd Hackel. Not pictured: Fritz Harris and John Halpin.

Third R&D 100 Award for Lasershot℠ Technology

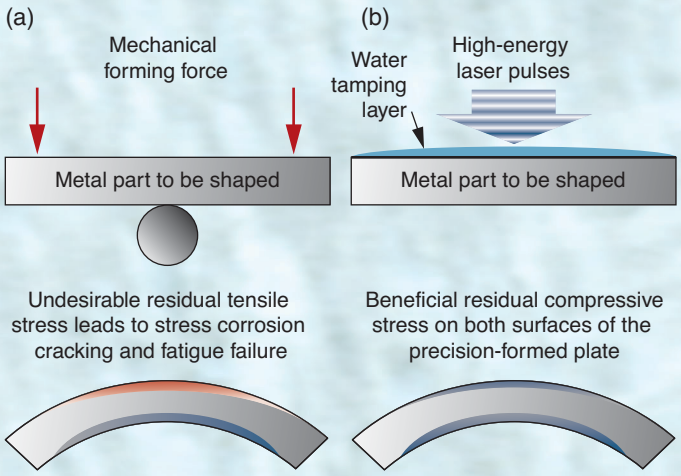
The metal-forming technology builds on Lasershot℠ Peening, a technique that uses lasers to strengthen metal components, which received an R&D 100 Award in 1998 (see *S&TR*, October 1998, pp. 12–13). It is also related to Lasershot℠ Peenmarking, an R&D 100 Award winner in 2001 (see *S&TR*, September 2001, pp. 8–9).

Lasershot℠ Peening has since been deployed commercially to arrest cracking problems in critical components of jet engines. In its first 14 months of commercial production, many aircraft engines have been treated—from large jumbo jets to fast, long-range corporate jets. As a result of these improvements, the jets are now allowed to remain in operation as much as 12 times longer between engine teardown and maintenance. The technique is also being applied to engine components in other commercial aircraft and is slated for use in manufacturing military aircraft. Hackel says, "Those of us on the team expect Lasershot℠ Precision Metal Forming to have an effect on the aviation manufacturing industry equal in significance to Lasershot℠ Peening."

The heart of the metal-forming process is a neodymium-doped glass laser, a type of solid-state laser that Livermore scientists have been using for more than two decades. The laser emits up to 6 pulses per second of 1-micrometer wavelength light with 25 joules of energy. The pulses, each lasting only 20 billionths of a second, pass through a 1-millimeter-thick layer of water that flows over the area to be shaped. This material absorbs the laser light, creating a high-pressure plasma. The water protects the metal from scarring or melting, thereby maintaining a high-quality surface finish.

The laser beam's high irradiance (5 to 10 gigawatts per square centimeter) and short pulse duration cause a rapid ablation of the absorption material and form a high-pressure plasma. The plasma is trapped by the thin film of water and creates an intense pressure wave (nearly 7 gigapascals). The pressure wave travels into the metal, plastically straining it and thereby inducing a residual stress that is 5 to 10 times deeper than the stress achieved by traditional shot peening. The metal responds to this residual stress by elongating at the peened surface and effectively bending the overall shape. In production, the laser beam is scanned across the metal surface with such accuracy that shaping can be precisely controlled. The intensity and depth of compressive stress to be applied to each area is determined by finite-element analysis. The exact desired stress is then created by controlling the laser energy, the pulse duration, and the number of pulses.

Hackel explains that many structural aircraft components, such as wing skins, elevator and rudder panels, and winglets, must be formed to precise complex curvatures so they can carry structural loads, meet aerodynamic requirements, and fit precisely on the airframe. It is undesirable to bend these components using hydraulic or other force-forming techniques because mechanical bending reduces the component's structural strength and lowers its fatigue and corrosion resistance.



Comparison of (a) a conventional metal-forming process and (b) the Lasershot℠ Precision Metal Forming process.

Lasershot℠ Precision Metal Forming also performs better than shot peening in its ability to shape tight curves—curves with a small radius—in metal whose cross section is less than 2 centimeters thick. Of greater importance, similar curves can be formed in metal plates more than 2 centimeters thick—plates that would be too thick for shot peening to effectively curve.

Process Ideal for Aerospace-Grade Aluminum

Hackel foresees two immediate uses for Lasershot℠ Precision Metal Forming. One is shaping structural components for new designs of very large jet aircraft, which will require bending thick material without reducing its mechanical strength. The second is precision final-forming of nuclear waste canisters. The technology can also be applied to the automotive and nuclear industries to make complex parts with fewer or no joints without suffering losses from cracks caused by corrosion or fatigue. Another potential application is to use it to precisely straighten components such as automotive and aerospace drive shafts, struts, and spars.

Lasershot℠ Precision Metal Forming offers many desirable characteristics in shaped metals: high surface finish quality, tight curvature on thick material, excellent control and repeatability, and high resistance to fatigue and corrosion cracking—all of which should make it a valuable technique for producing components for a range of industries.

—Arnie Heller

Key Words: aircraft industry, Lasershot℠ Precision Metal Forming, nuclear waste canisters, R&D 100 Award, shot peening.

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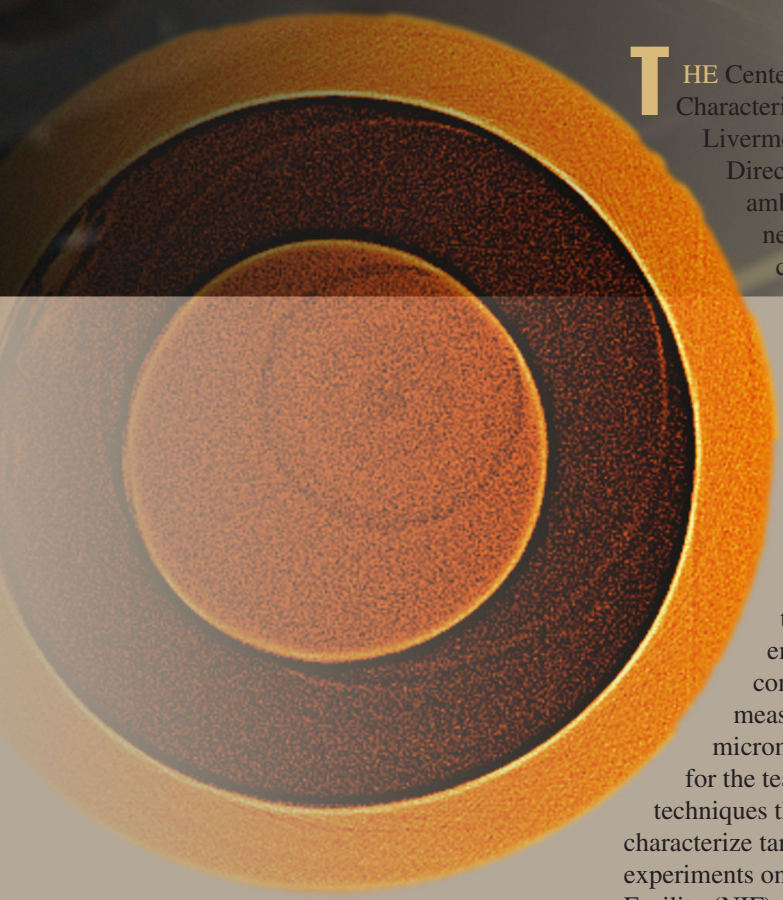
Characterizing Tiny Objects without Damaging Them

Livermore researchers are developing ways to characterize mesoscale objects for stockpile stewardship, medical diagnostics, and fuel cells.



THE Center for Nondestructive Characterization (CNDC) in Livermore's Engineering Directorate has begun an ambitious effort to develop a new capability to characterize materials and objects in the mesoscale—the length scale between macro and nano. New nondestructive characterization (NDC) methods will allow scientists to "see" inside millimeter-size materials, which typically have fragile embedded features or complex structures measuring only a few micrometers. One primary goal for the team is to develop NDC techniques that can be used to characterize target packages for experiments on the National Ignition Facility (NIF). But advances in mesoscience are expected to lead to new materials, parts, and techniques for many other applications, such as medical diagnostics and fuel cells.

"We need to be able to verify nondestructively that mesoscale parts are assembled correctly and are not damaged in any way before they find their way into other components or are the basis of experiments," says principal investigator Harry E. Martz, Jr., the center's director (see the box on pp. 20–21). NDC methods for mesoscale objects must see into or penetrate a few millimeters of material, ranging from low-density (0.03-gram-per-cubic-centimeter), low-opacity foams such as aerogels to high-density (20-gram-per-cubic-centimeter), high-opacity metals such as gold. The methods must also provide a signal-to-noise ratio of 1,000:1 and take images at a resolution of about 1 micrometer over a field of view as large as 3 millimeters. Another focus of the center's research is to acquire data using tabletop instruments and to improve the turnaround time so results are available in tens of minutes.

Martz explains that many established techniques exist to characterize objects

with adequate resolution, but they neither see *inside* nor image *through* mesoscale materials or objects. For example, electron and atomic-force microscopes can evaluate an object's surface and near surface at a resolution of less than 1 nanometer, but they cannot see inside or penetrate the objects. Visible light microscopes do not penetrate opaque materials, and far-infrared (heat) imaging does not have adequate resolution for characterizing mesoscale objects.

To overcome these problems, the Livermore team wants to develop techniques that use x rays, sound waves, light atomic particles, and magnetic resonance imaging (MRI), all of which offer the potential to meet the requirements for characterizing mesoscale objects. Such methods could also be used in standard laboratory settings—not just at large dedicated facilities, which can be expensive to build and operate.

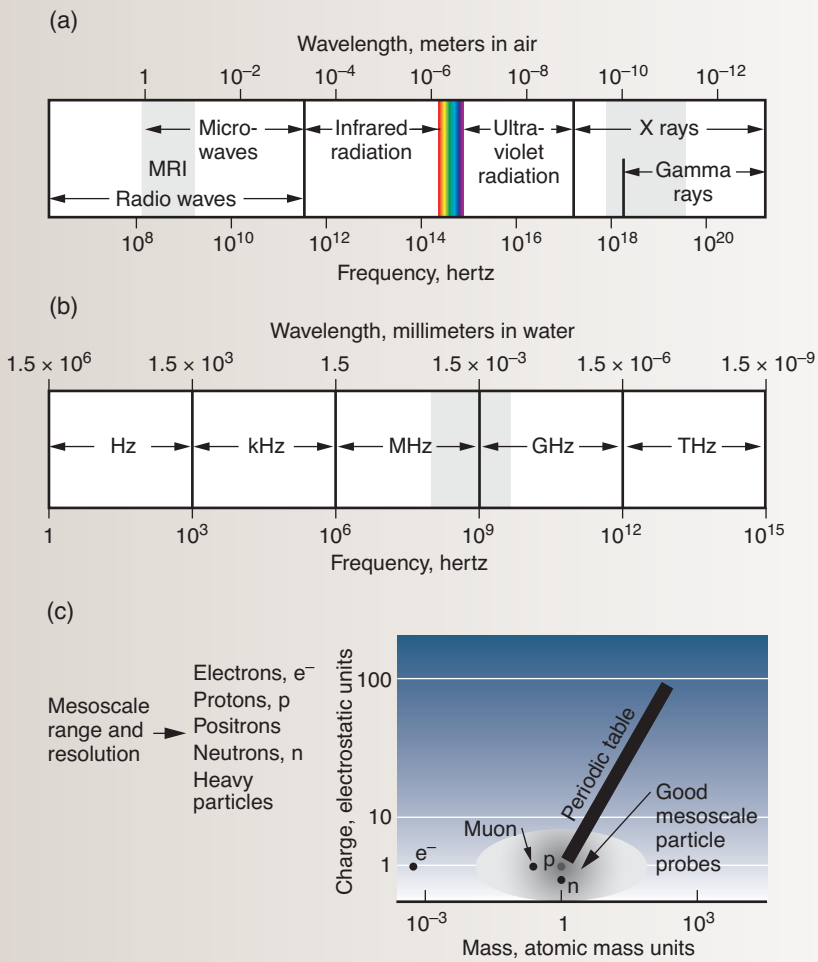
A Comprehensive Capability

"No single characterization method meets every need," says Martz. As a result, he foresees a combination of techniques forming the basis for a comprehensive mesoscale NDC capability (see the box on p. 25). Of all the technologies, x-ray microscopy has the greatest near-term potential for characterizing the internal structure of mesoscale objects with the required resolution, contrast, and efficiency.

CNDC researchers are also studying the feasibility of acoustic techniques at gigahertz frequencies, which may offer the needed spatial resolution and penetration. With current acoustic technology, the objects examined often must be immersed in a fluid such as water. Most mesoscale objects, however, must be characterized using noncontact methods because many of them are porous or hydrophilic; that is, they absorb or dissolve in water. If noncontact gigahertz ultrasound can be applied to a non-immersive characterization method, researchers could use it to identify gaps, bond integrity, and material density variations.

Two other techniques being considered by CNDC are MRI and proton imaging. MRI has already been used to image mesoscale materials, but the image resolution and processing time need to be improved. MRI, which penetrates dielectric materials, is a potential technology for characterizing an object's mechanical strength, homogeneity, and composition. Researchers at the center are evaluating methods to advance these technologies so they can be used to characterize aerogels and low-density foams in three dimensions.

In principle, imaging with energetic particles offers yet another approach. Neutrons do not yet provide the required resolution and can be difficult to image; electrons do not have the penetration depth; and heavy ions can modify the target. However, light ions



Nondestructive characterization (NDC) of mesoscale objects is targeted toward three regions: (a) electromagnetic spectrum, (b) acoustic spectrum, and (c) particles.

such as protons with energies of tens of megaelectronvolts can even penetrate opaque metals, so proton radiography is also a feasible technology for mesoscale characterization.

Benchmarks for New Techniques

To establish benchmarks for the new techniques they develop, CNDC researchers will use standards and reference objects. For example, they will characterize the tiny laser targets for the high-energy-density physics (HEDP) experiments on NIF. HEDP experiments are designed to investigate phenomena relevant to stockpile stewardship, astrophysics, planetary physics, and basic science. Data from those experiments can then be used to validate and improve the high-fidelity codes that simulate these phenomena.

"NIF targets can contain a dozen parts," says Livermore physicist Warren Hsing, who works in the NIF Inertial Confinement Fusion Program. "We can characterize individual pieces, but characterizing the assembled target is more difficult." Inspecting and characterizing materials, machined components, spares, subassemblies, and final assemblies could require 10 to 12 steps per target. Thus, a few thousand NDC measurements may be needed each year to characterize the targets' diverse materials and features.

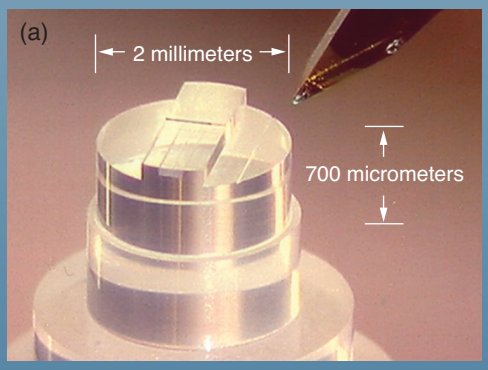
Martz points out that Livermore is not alone in its plans to strengthen mesoscale NDC methods. All three national security laboratories under the National Nuclear Security Administration plan to conduct experiments on NIF. In May, a workshop on HEDP characterization

Livermore Center Develops New Ways to See into Materials

Livermore's development of new ways to image mesoscale objects is led by the Center for Nondestructive Characterization (CNDC). The center was created in 1999 to advance technologies that characterize objects when they are first manufactured and when they must be safely disposed or reused.

Harry E. Martz, Jr., heads the research and development efforts of characterization methods such as x- and gamma radiography, computed tomography, visual and infrared imaging, ultrasonics, micropower impulse radar imaging, and signal and image processing. Martz and his colleagues at the center have inspected automobile and aircraft components, reactor-fuel tubes, high explosives, dinosaur eggs, concrete, and radioactive wastes. A team led by Martz and Livermore engineer Pat Roberson received an R&D 100 Award in 2000 for waste inspection tomography using nondestructive assays.

CNDC assembles multidisciplinary teams to research and develop nondestructive characterization (NDC) techniques for use in various Livermore research programs. The center's current focus is in three areas: nuclear weapon component reuse and certification for stockpile stewardship, laser target characterization and diagnostics for the



and fabrication was held at Livermore. Representatives from Livermore, Los Alamos, and Sandia discussed common issues and ways to collaborate.

Optics Key to X-Ray Microscope

One technique for characterizing the internal structure of a reference object combines x-radiography with computed tomography. With this technique, two-dimensional (2D) images are assembled to produce a three-dimensional (3D) view of the object. Livermore physicist John Kinney demonstrated x-ray tomographic imaging of mesoscale objects by using the synchrotron source at Stanford Synchrotron Radiation Laboratory (SSRL).

In that demonstration, a test object with known surface features was imaged in 0.25-degree rotational increments over 180 degrees using x-ray energy of 12 kiloelectronvolts. The resulting images were then built up into a 3D image. Kinney's experiments with prototype NIF targets achieved about 1-micrometer resolution without the use of x-ray optics.

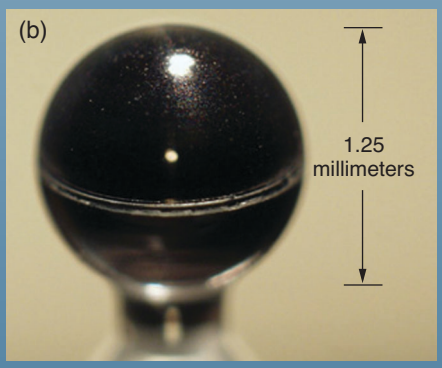
In principle, a large facility such as SSRL could be used to characterize the many laser targets being assembled. In practice, a local, dedicated laboratory for such work would provide more flexibility in schedule. To meet that need, Martz assembled a team to develop a tabletop x-ray microscope. This effort taps Livermore's experience in x-ray design, multilayer-coated x-ray optic fabrication, precision engineering, x-ray optics modeling, signal and image processing, and 3D x-ray image reconstruction.

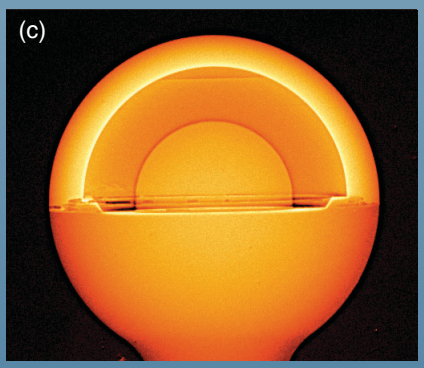
National Ignition Facility, and homeland security and reducing the threat from weapons of mass destruction. For example, the center is developing new methods to detect explosives in luggage for the Transportation Security Administration. In addition, the center's x-ray computed tomography work supports a government–industry effort to demonstrate 30-percent weight savings in automobiles by converting major structural components from cast aluminum to cast magnesium.

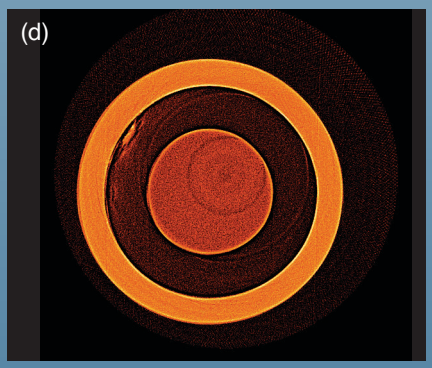
The center is designing and fabricating a series of reference objects with known features and density ranges to evaluate the optics for a prototype x-ray microscope. These reference objects, with precisely machined features milled into them, can be used to set benchmarks for characterization technologies as they are developed. Livermore engineer Robin Hibbard is leading an effort to fabricate parts to extremely high tolerances. Once these parts are measured and assembled, they will become what Martz calls the reference "gold standard" for the characterization techniques being developed not only at the Laboratory but also at universities and in industry.

Nondestructive characterization is not limited to mesoscale objects, and the techniques developed have many potential applications—even in the art world. For example, Martz is collaborating with Franco Casali, a professor in the Physics Department at the University of Bologna. They are using NDC techniques to determine how much deterioration has occurred on the ankle of David—the towering marble figure sculpted by Michelangelo (shown in the background photo on p. 20).

Two examples of the reference objects being used to benchmark Livermore's new nondestructive characterization (NDC) techniques for mesoscale objects: (a) a planar stepped target and (b) a spherical target. Several NDC technologies are needed for a comprehensive capability. Shown are (c) a digital radiograph and (d) a computed tomography (CT) image of target (b). In the CT image, glue (between 10 and 11 o'clock) has wicked or was pushed into the aerogel area.







"To obtain high-resolution x-ray images with single-image exposure times of tens of minutes," says Martz, "we knew we'd need an x-ray imaging optic with a high collection efficiency and a small, bright source of x rays." But because x rays penetrate most optical materials, traditional mirrors cannot focus them. They can, however, be focused to a chosen point when they impinge on a smooth gold surface at a glancing angle of less than 1 degree.

In 1952, the German physicist Hans Wolter invented a nearly cylindrical mirror that increases the collection efficiency and brings the x rays to a common focus. The NDC team decided to use Wolter multilayer imaging optics and a commercially available high-brightness x-ray source to develop an x-ray microscope. (See the top figure on p. 23.)

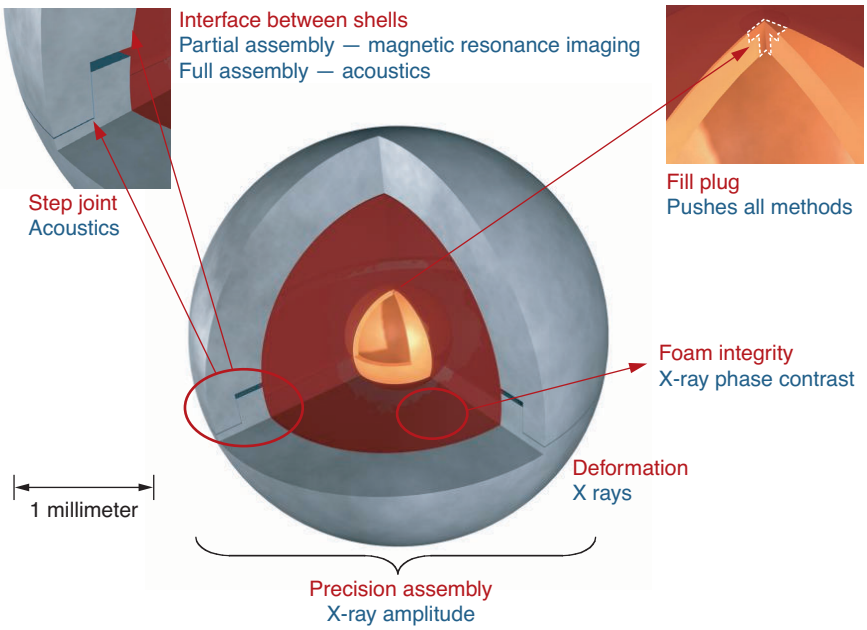
Wolter optics are traditionally coated with gold or iridium. The Livermore team reasoned that replacing the gold with a multilayer coating would improve collection efficiency as much as 100 times. Fabricating the multilayered optic is the key to a successful microscope design.

A team from the Chemistry and Materials Science Directorate, led by materials scientist Troy Barbee, Jr., designed a way to manufacture, for the first time, many multilayered Wolter optics from the same mandrel, or mold. (See the bottom figure on p. 23.) The aluminum mandrel is diamond-turned to a surface roughness of less than 25 nanometers and then is superpolished to a surface roughness of 0.3 nanometer. Multilayers are applied to the mandrel and coated with 1 to 2 millimeters of nickel to provide structural rigidity. The resulting Wolter optic is separated from the mandrel with slight pressure or with liquid nitrogen so the mandrel can be used repeatedly to fabricate identical optics.

The Wolter multilayer x-ray optics system is being integrated with an amplitude x-ray microscope in an effort led by physicist Michael Pivovaroff from the University of California at Berkeley and Livermore engineer Walter Nederbragt. By incorporating the two techniques, the team should be able to achieve about 1-micrometer spatial resolution over a 1-millimeter field of view. The current Wolter optic design will provide 12× magnification to give about 1-micrometer resolution over a 0.25-millimeter field of view. A high-resolution, charge-coupled device camera that is lens-coupled to a scintillator will give 3× optical magnification and will record an image of the focal plane.

In 2002, the mesoscale NDC team designed the optical system for a microscope 5 meters long and simulated the system's x-ray imaging properties. The team then constructed a mandrel for testing and adjusting the multilayer coating process. Several mandrels were fabricated to test the mandrel–optic separation process. This year, the team is completing the mechanical design of the prototype microscope and fabricating several optics using the superpolished mandrel. In 2004, they will construct and test the prototype microscope.

An 8-kiloelectronvolt x-ray source was chosen to demonstrate a proof of principle. Higher-energy (about 60-kiloelectronvolt) x rays, with matched-energy Wolter optics, will be needed to penetrate materials with higher opacities and greater densities.

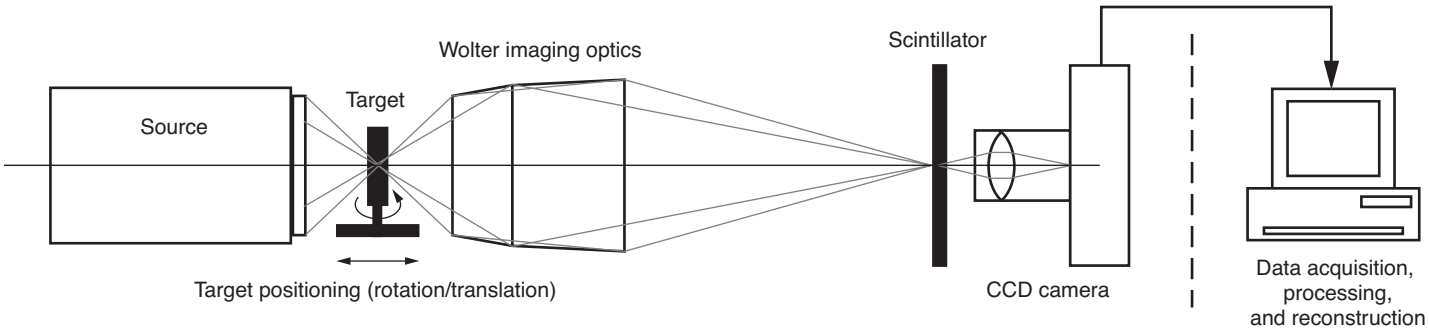


Livermore researchers will establish benchmarks for the nondestructive characterization techniques they develop by characterizing reference objects, such as the double-shell laser targets for experiments at the National Ignition Facility. For example, on this laser target, the technologies listed in blue will provide the measurements in red.

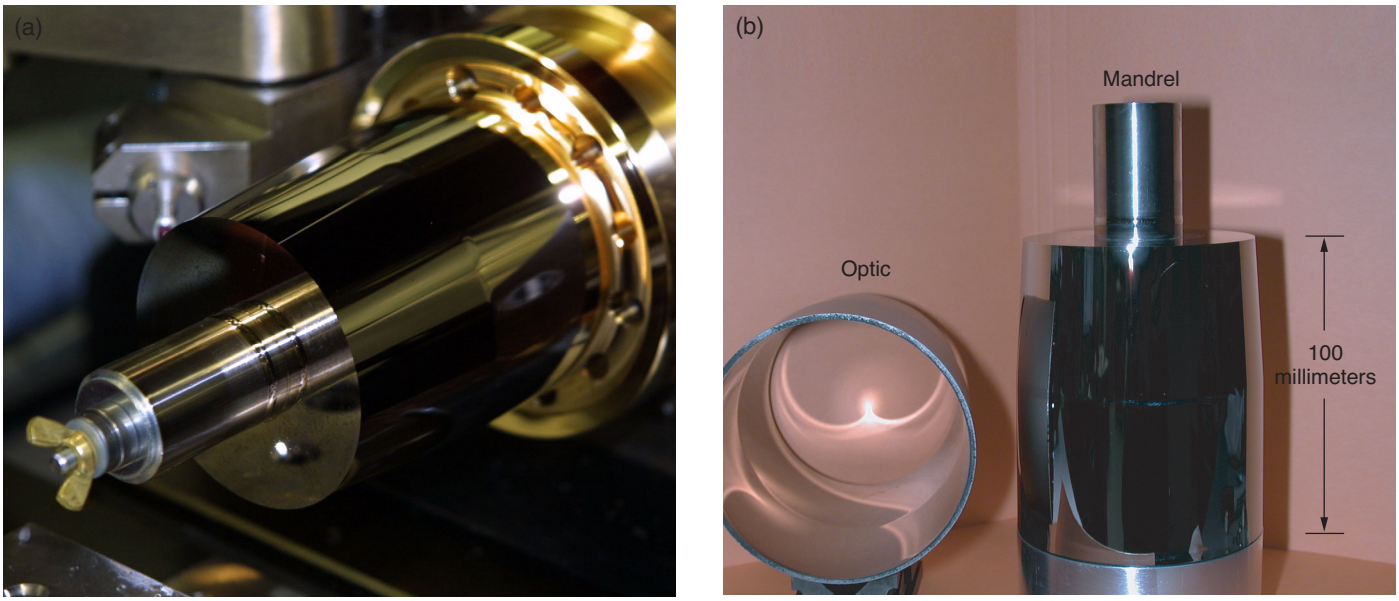
Calculations show that individual images taken with the 8-kiloelectronvolt source can be processed in tens of minutes; with the 60-kiloelectronvolt source, images can be processed in several minutes to hours. In addition, the team is developing an algorithm to reconstruct a 3D image of an object from successive 2D slices through it.

A team led by Livermore physicist Jeff Koch is exploring an alternative x-ray imaging technique called phase contrast. Phase-contrast imaging takes advantage of the diffraction and refraction of x rays off the edges where two materials meet. It can detect irregularities in materials that have small differences in x-ray absorption and is particularly sensitive to gaps or spaces. Phase-contrast imaging will be especially useful for characterizing biological samples and laser targets for inertial confinement fusion research.

A multilayered x-ray condenser optic may be needed to acquire phase-contrast data in the laboratory. Livermore researchers have already developed x-ray condensers—for extreme ultraviolet (EUV) lithography and solar EUV astronomy—but these optics have not been applied to mesoscale imaging. Martz says that, in addition to using Livermore's facilities, CNDC will explore phase-contrast



A tabletop x-ray microscope designed for nondestructive characterization of mesoscale objects. The microscope uses a Wolter multilayer imaging optic, which provides 12× magnification to give about 1-micrometer resolution over a 0.25-millimeter field of view. A high-resolution, charge-coupled device (CCD) camera is lens-coupled to a scintillator to record an image of the focal plane at 3× optical magnification.



For the first time, many multilayered Wolter optics can be manufactured from the same mandrel, or mold. (a) The aluminum mandrel is diamond-turned and then superpolished. Multilayers are applied to the mandrel and coated with 1 to 2 millimeters of nickel for rigidity. (b) The Wolter optic is then separated from the mandrel by applying a slight pressure.

imaging for NIF targets at facilities such as the Advanced Photon Source at Argonne National Laboratory and the Advanced Light Source at Lawrence Berkeley National Laboratory. The center is also consulting with experts at the University of Melbourne in Australia.

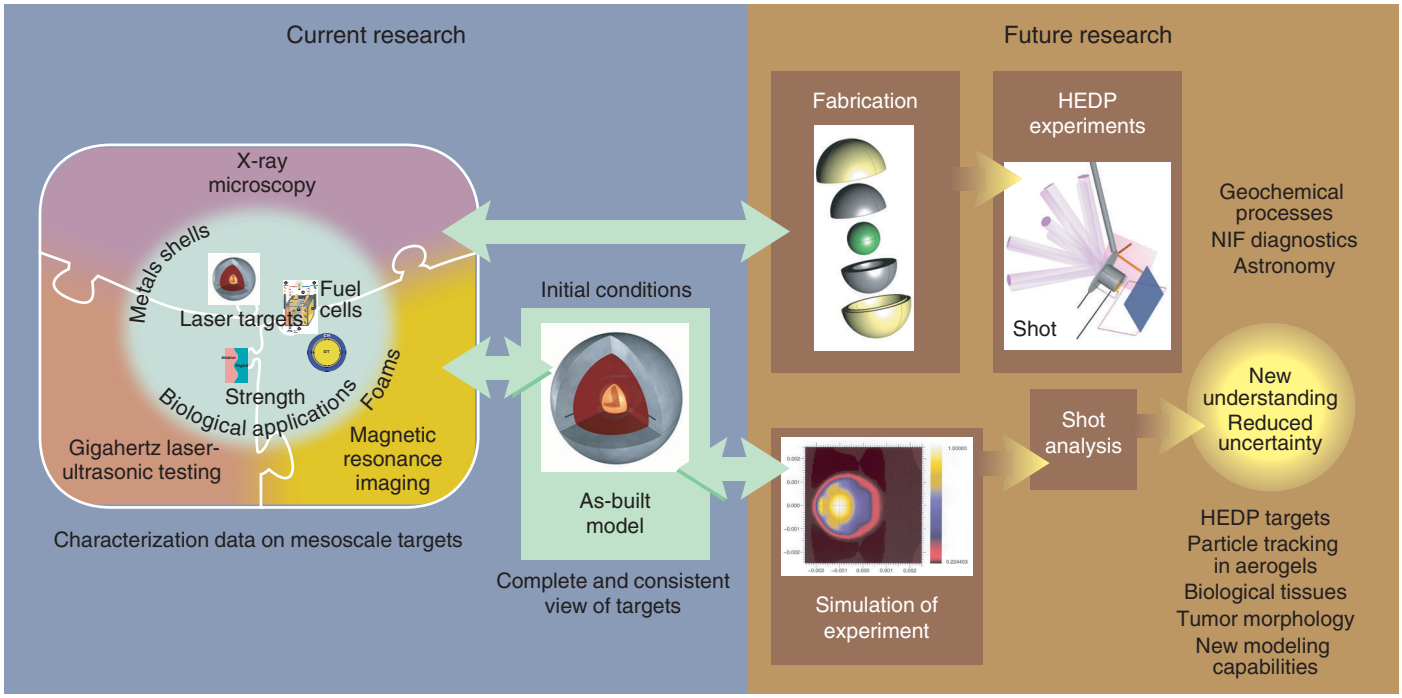
As-Built Computer Modeling

An equally challenging project is to develop the first mesoscale computer models to simulate "as-built" objects. With as-built models, as opposed to idealized or as-designed models, scientists can include accurate initial conditions of an actual object in the simulations. These 2D and 3D models will bridge the gap between predictive simulations and experimental results and, in so doing, fundamentally improve research.

The majority of computational analyses in Livermore's engineering and physics work are finite-element models. In these models, simulated objects are divided into a 2D or 3D mesh of blocks, called elements or cells. General-purpose finite-element codes, such as Livermore's DYNA3D and ALE3D, represent some of the most advanced mechanical engineering simulation programs. However, these codes are optimized for idealized systems. As-built models would, instead, represent actual fabricated objects directly in a simulation.

"Discrepancies between experiment and simulation often arise because the simulations don't accurately represent the actual experimental conditions, especially any defects or irregularities in the test object," says Martz. "We want to create a computer model from how an object was built, not how we wish it had been built. That way, we can begin simulations with the most realistic initial conditions." As-built models would allow scientists to reconcile experimental data with predictive simulation by reducing the uncertainty associated with the actual test objects and experimental conditions.

According to Martz, such models are not specific to research in support of the Laboratory's stockpile stewardship mission. For example, biomedical researchers are developing patient-specific models directly from computed tomography imagery so simulations can be analyzed prior to surgery. These models, however, require much human interaction. Some aerospace firms are



Livermore researchers are developing a range of capabilities for analyzing mesoscale objects because no single technology for nondestructive characterization (NDC) solves every problem. For example, as-built computer models will allow scientists to include accurate initial conditions of manufactured objects, such as the targets designed for high-energy-density physics (HEDP) experiments on the National Ignition Facility (NIF). Such models will help bridge the gap between predictive simulations and experimental results.

also generating models of aircraft components directly from 3D images, but the methods are not automated and require a great deal of skill.

Livermore will address the scales and resolutions needed to model as-built components and assemblies at the mesoscale—an effort that is being led by Robert Sharpe, director of Livermore's Center for Computational Engineering. The goal of this project is to make as-built models a basic capability that would support Laboratory scientists and engineers in many fields. Because the effort has such wide application, the development team includes researchers in materials science, physics, and computation.

Ideally, scientists would be able to automatically extract features of interest directly from NDC data and then use this information either directly in an existing computational mesh or indirectly as the seeds for a new mesh. For example, researchers might examine such features as material interfaces and surface features, gaps and cracks, and bonding layers between materials.

Researchers at CNDC are also learning how to combine information from different characterization technologies into a single integrated model. Another challenge is automating some of the manually intensive steps associated with directly connecting NDC data with simulations.

"Right now, we don't know how to add the detailed features that we've determined nondestructively into a model," Martz says. "For example, our model may not be able to incorporate a crack or a gap. The ability to directly

Wealth of Applications for Characterizing Tiny Objects

A strong mesoscale nondestructive characterization (NDC) capability would help scientists analyze the targets designed for the high-energy-density physics (HEDP) experiments to be conducted on the National Ignition Facility (NIF). New NDC techniques can also be used to characterize biological tissues and materials for fuel cells.

Without characterization of laser target assemblies designed for HEDP experiments, uncertainties may be introduced when the target is assembled. For example, if a target is leaking gas or if the foam has a crack, the experimental results could be affected. Imperfectly manufactured target joints, which may include gaps and warps, can influence the target's behavior, thereby introducing uncertainties in the analysis. Advanced NDC methods could be used to discern assembly features and, thus, reduce these uncertainties.

Inertial confinement fusion (ICF) could be an important future energy source. In one ICF target design, an outer shell containing plastic or beryllium serves as an ablator and pusher, and a metal or plastic inner shell contains a gas of deuterium and tritium at high pressure. These double-shell targets would be only about 1 millimeter in diameter with a low-density aerogel between the two shells. The inner shell is, in essence, a tiny pressure vessel supported by the aerogel. After the shell is filled with the deuterium–tritium gas, it is sealed, and the foam hemisphere and outer shell are constructed around it.

Mesoscale NDC will be of use to Livermore's program to develop miniature fuel cells that can replace batteries in powering unattended sensor systems and, eventually, consumer electronics. A complex set of modules comprise these devices, and the materials used to make them have different porosities and densities, making the characterization problems similar to those of an HEDP target—although in a fuel cell, the density differences are less extreme. For example, mesoscale characterization efforts would provide nondestructive, three-dimensional information about the quality of bonding between various material layers and about the uniformity of these layers. Without such techniques, fuel-cell materials must be cut into sections to be examined.

CNDC is also studying acoustic, magnetic resonance imaging (MRI), and proton radiographic methods for HEDP characterization, which could help locate and quantify defects in fuel cells. The key to an efficient fuel cell is materials with the correct chemical and diffusive properties and reliable bonds between thin laminations of these materials. The bonding between various material layers and the uniformity of these layers must be of high quality because delaminations and density or thickness variations disrupt fuel-cell function. Membrane materials can be similar to the aerogels used in laser targets, so MRI is a potential technology for finding voids and delaminations in the membrane materials proposed for fuel cells.

Another potential application for NDC technologies is in the field of biology. For example, pathologists must visually examine samples of prostate tissue to determine whether a sample is normal or tumor tissue. Recent acoustic imaging research at Livermore has detected subtleties in tissue that cannot be detected visually. Tumor tissue, with slightly higher density, has slower acoustic velocities than normal tissue. Pockets of low-velocity areas in normal tissue indicate that possible tendrils of tumor, not visible optically, have invaded the normal area. High-resolution gigahertz acoustic imaging of prostate tissue may offer a way to detect and image tumor tissue embedded in normal tissue.

feed as-built information into 2D or 3D simulation tools would fundamentally improve the way designers work." To demonstrate as-built modeling capabilities, the NDC researchers will characterize a selected object, add those data to an as-built model, and then compare the simulation results directly with experimental data.

Multiple Program Benefits

New NDC capabilities are of interest to many Laboratory programs. The advanced Wolter optics will benefit research efforts in such diverse programs as NIF diagnostics, medical technologies, astronomy, and biology and biotechnology. The advances in acoustic microscopy and computer modeling, led by engineer Diane Chinn, can be used in health technologies and fuel cell research. Chemist Robert Maxwell is leading a research effort to improve MRI techniques so they can be used to characterize aerogels. The mesoscale as-built model research will be applicable to most, if not all, scale lengths and, thus, will benefit many Laboratory programs.

Martz hopes that, as mesoscale technology evolves, Livermore will be able to work with an industrial partner to transfer these capabilities to applications other than stockpile stewardship. "We have an opportunity to establish Livermore as the premier research institution in mesoscale materials development, fabrication of structures, and nondestructive characterization."

—Arnie Heller

Key Words: acoustics, aerogel, amplitude contrast, as-built modeling, finite-element model, high-energy-density physics (HEDP) laser targets, inertial confinement fusion, magnetic resonance imaging (MRI), mesoscale, National Ignition Facility (NIF), nondestructive characterization (NDC), phase contrast, proton radiography, Wolter optics, x-ray imaging, x-ray microscopy.

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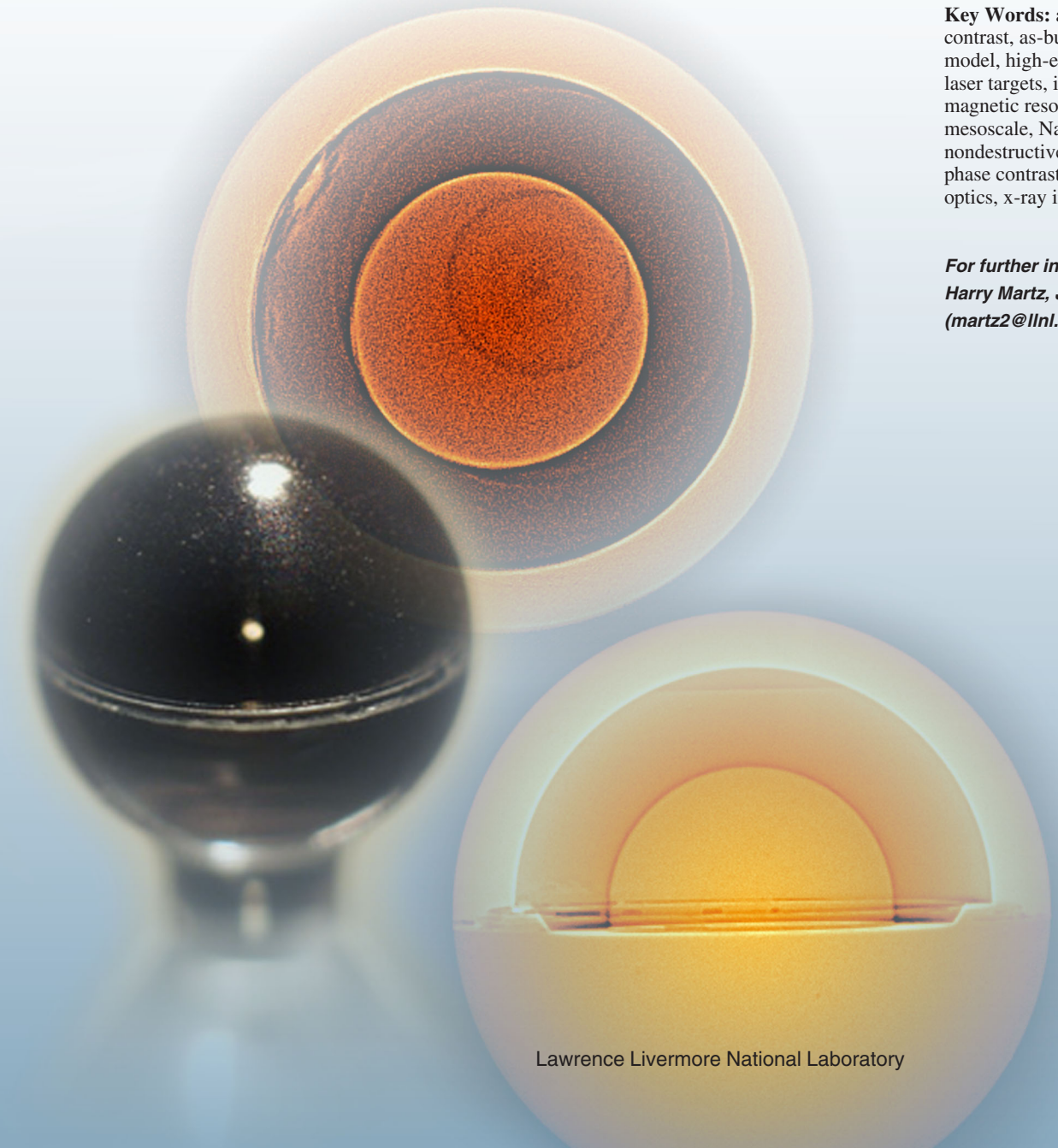

Patents and Awards

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

Convectively Driven PCR Thermal-Cycling

William J. Benett, James B. Richards, Fred P. Milanovich
U.S. Patent 6,586,233 B2
July 1, 2003
A polymerase chain reaction system provides an upper and lower temperature zone in a fluid sample. Channels set up convection cells in the fluid sample and move the fluid sample repeatedly through the upper and lower temperature zones, which creates thermal cycling.

Hyperbaric Hydrothermal Atomic Force Microscope

Kevin G. Knauss, Carl O. Boro, Steven R. Higgins, Carrick M. Eggleston
U.S. Patent 6,586,734 B2
July 1, 2003
A hyperbaric hydrothermal atomic force microscope (AFM) is provided to image solid surfaces in fluids, either liquid or gas, at pressures greater than normal atmospheric pressure. The sample can be heated and its surface imaged in aqueous solution at temperatures greater than 100°C with less than 1 nanometer of vertical resolution. A gas-pressurized microscope base chamber houses the stepper motor and piezoelectric scanner. A chemically inert, flexible membrane separates this base chamber from the sample cell environment and constrains a high-temperature, pressured liquid or gas in the sample cell while allowing movement of the scanner. The sample cell is designed for continuous flow of liquid or gas through the sample environment.

Technique to Quantitatively Measure Magnetic Properties of Thin Structures at <10 nm Spatial Resolution

Sasa Bajt
U.S. Patent 6,590,209 B1
July 8, 2003
A highly sensitive, high-resolution magnetic microscope images magnetic properties quantitatively. Imaging is done with a modified transmission electron microscope that allows imaging of the sample in a zero magnetic field. Two images from closely spaced planes, one in focus and one slightly out of focus, are sufficient to calculate the absolute values of the phase change imparted to the electrons and, hence, to obtain the magnetization vector field distribution.

Low-Cost Fiber Optic Pressure Sensor

Sang K. Sheem
U.S. Patent 6,597,820 B1
July 22, 2003
The size and cost of fabricating fiber-optic pressure sensors is reduced by fabricating the membrane of the sensor in a nonplanar shape. The design of the sensors may be made in such a way that the nonplanar membrane becomes a part of an air-tight cavity. The membrane thus becomes resilient because of the air-cushion effect of the cavity. Such nonplanar membranes are easier to make and attach.

High Average Power Laser Using a Transverse Flowing Liquid Host

Earl R. Ault, Brian J. Comaskey, Thomas C. Kuklo
U.S. Patent 6,600,766 B1
July 29, 2003
A laser includes an optical cavity. A diode laser pumping device is located within the optical cavity. An aprotic lasing liquid containing neodymium rare-earth ions fills the optical cavity. A circulation system that provides a closed loop for circulating the aprotic lasing liquid into and out of the optical cavity includes a pump and a heat exchanger.

Temperature Control Apparatus

M. Allen Northrup
U.S. Patent 6,602,473 B1
August 5, 2003
A silicon-based sleeve-type chemical reaction chamber that combines heaters, such as doped polysilicon for heating and bulk silicon for convection cooling. The reaction chamber combines a critical ratio of silicon- and nonsilicon-based materials to provide the thermal properties desired. For example, the chamber may combine a critical ratio of silicon and silicon nitride to the volume of material to be heated (such as a liquid) to provide uniform heating and yet meet low power requirements. The reaction chamber will also allow a secondary tube (such as plastic) to be introduced into the reaction sleeve that contains the reaction mixture, thereby alleviating any potential material incompatibilities. The reaction chamber may be used in any chemical reaction system to synthesize or process organic, inorganic, or biochemical reactions, such as the polymerase chain reaction, and other DNA reactions, such as the ligase chain reaction. The reaction chamber may also be used in synthesis instruments, particularly those for DNA amplification and synthesis.

Awards

The **American Nuclear Society** has awarded the prestigious **2003 Edward Teller Medal** to veteran Laboratory researcher **Laurance J. Suter**. Suter, who leads the Hohlraum Dynamics Group in Livermore's A-X Division, is an expert in the design and use of hohlraums, the tiny gold containers that hold a laser target as intense x rays heat it during inertial confinement fusion experiments.

In announcing the award, the society recognized Suter "for his seminal work on almost all aspects of laser hohlraum physics. During the past 20 years, he has become widely known as one of the world's leading experts on laser hohlraum physics, with contributions on many topics, including X-ray conversion and drive in hohlraums, symmetry control, the impact of pulse shaping on capsule implosion, and development of a wide variety of experimental techniques to verify and improve the computational models."

John Elmer, who leads the Materials Joining Group in Livermore's Chemistry and Materials Science Directorate, has been named a **2003 American Society for Metals (ASM) Fellow** in recognition of his innovative contributions to the use of synchrotron radiation to welding science. Elmer was cited "for development and application of synchrotron-based, in situ, spatially resolved X-ray diffraction techniques to permit quantitative understanding of phase transformation kinetics during fusion welding."

ASM International is the society for materials engineers and scientists worldwide who are dedicated to advancing industry, technology, and applications of metals and materials. In 1969, ASM established the honor of Fellow to recognize members for distinguished contributions in the field of materials science and engineering, and to develop a broadly based forum for technical and professional leaders to serve as advisors to the society. The Fellows provide the board of trustees with guidance that enhances the capability of ASM as a technical and professional society to serve the technical community in the field of materials science and engineering.

Abstract

Characterizing Tiny Objects without Damaging Them

Livermore researchers are developing new nondestructive methods to characterize materials and objects in the mesoscale—where millimeter-size objects are measured to micrometer accuracy. Nondestructive characterization (NDC) methods for mesoscale objects must see inside or penetrate a few millimeters of material ranging from low-density (0.03-gram-per-cubic-centimeter), low-opacity foams such as aerogels to high-density (20-gram-per-cubic-centimeter), high-opacity metals such as gold. Techniques that use x rays, sound waves, light atomic particles, and magnetic resonance imaging all offer the potential to meet the characterization requirements without requiring large dedicated facilities. X-ray microscopy has the most immediate potential. A team has designed a tabletop x-ray microscope that uses a Wolter multilayer imaging optic, a nearly cylindrical mirror that increases the collection efficiency and brings the x rays to a common focus. In addition, researchers are developing as-built models so computer simulations will more accurately reflect the attributes of a test object. Benchmarks for the new NDC techniques are being established by characterizing various reference objects, such as the targets designed for high-energy-density physics experiments to be conducted on the National Ignition Facility.

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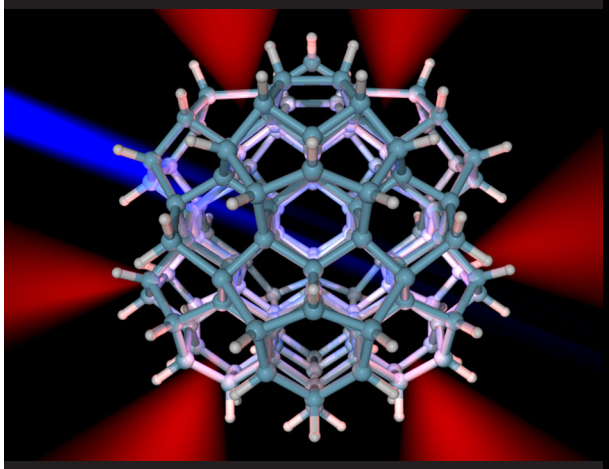
U.S. Government Printing Office: 2003/583-060-70050

When Semiconductors Go Nano



Researchers found some surprising behavior when they studied the nanostructure of semiconductors used in biodetectors. A miniscule bit of diamond, just a few hundred atoms, takes on the unexpected shape of a soccer ball.

Also in November

- *The Inductrack magnetic levitation (maglev) system for urban and high-speed trains moves down the development track on the way to a full-scale demonstration.*

- *Livermore joins a national effort to develop a retinal prosthesis for restoring sight to people who have lost the photoreceptor function.*

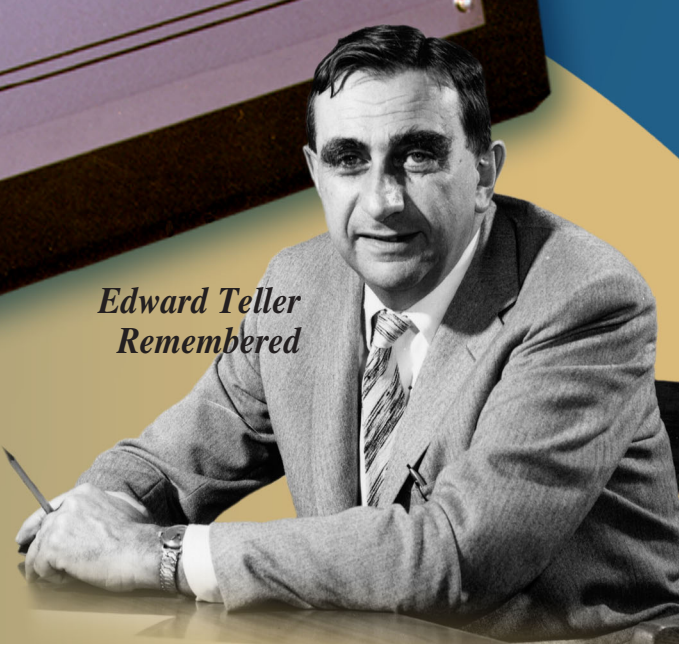
- *A dime-size processor, developed to feed a miniature fuel cell, provides a longer lasting power source for unattended sensor systems and consumer electronics.*

Coming Next Month

Science & Technology Review

October 2003

National Nuclear Security Administration's
Lawrence Livermore National Laboratory



Edward Teller Remembered