December 1997

Science & Technology REVIEW

Lawrence
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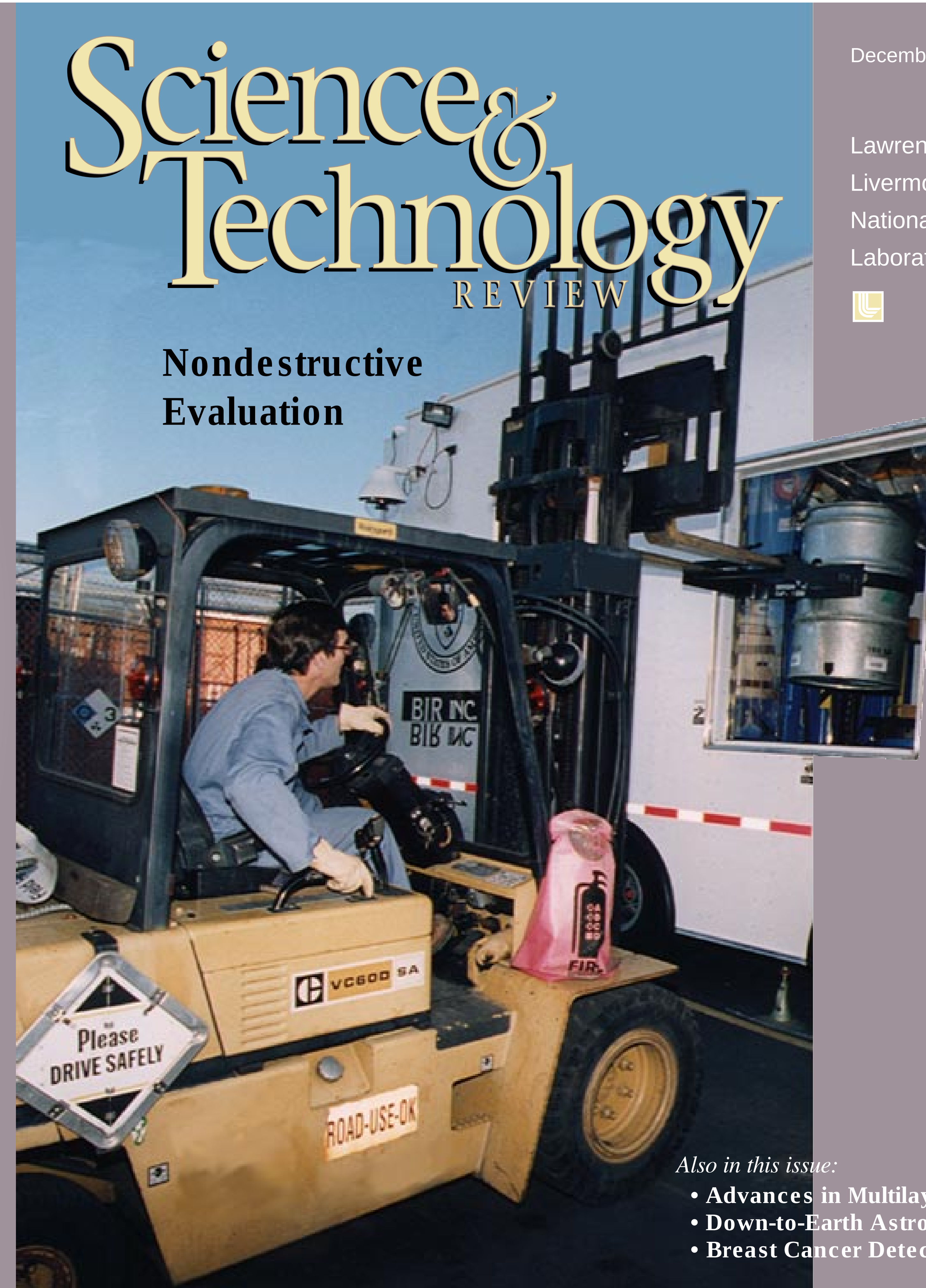
Nondestructive Evaluation



Also in this issue:

- **Advances in Multilayers**
- **Down-to-Earth Astrophysics**
- **Breast Cancer Detection**

University of California
Lawrence Livermore National Laboratory
Science & Technology Review
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

A recent collaboration brought BIR Inc. of Lincolnshire, Illinois, to work with Livermore researchers in nondestructive evaluation (NDE). Here, BIR's trailer was the site of an experiment using active and passive computed tomography to identify and quantify materials inside nuclear waste drums. The feature article, beginning on p. 4, describes this technique as well as other methods in the Laboratory's NDE repertoire—optical, radiographic, thermal, x-ray, and gamma-ray imaging.

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About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy. 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 ten 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 (510) 422-8961. Our electronic mail address is *hunter6@llnl.gov*.

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

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

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-52000-97-12
Distribution Category UC-700
December 1997

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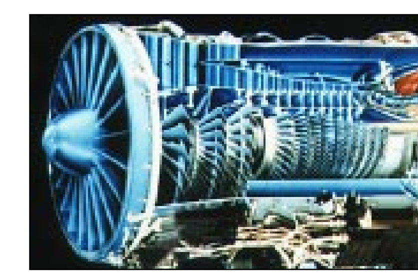

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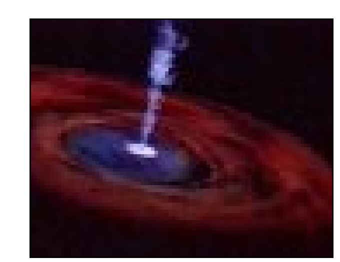

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Firms team with DOE labs to develop superchip

Three of the largest computer-chip makers joined with DOE laboratories to squeeze far more brain power into microprocessors. The unusual partnership aims to make computers a hundred times faster and bring features such as three-dimensional graphics to affordable machines. In addition to boosting computer speed, the memory chips will be able to store a thousand times more information than they currently can.

In the biggest-ever corporate investment with the Department of Energy, the three firms—Intel Corp., Advanced Micro Devices Inc., and Motorola Corp.—are spending $250 million over five years with three laboratories—Lawrence Livermore, Sandia National Laboratories, and E. O. Lawrence Berkeley National Laboratory.

The partnership plans to design a new technique using ultraviolet light to etch ultrathin patterns (less than one-thousandth the width of a human hair) in silicon chips. These patterns will be 60% smaller than the patterns in the most sophisticated chips now available. Another partnership aim is to cram one billion transistors onto each thumbnail-size chip. Currently, Intel's most powerful processor contains 7.5 million transistors.

Contact: Rick Freeman (510) 422-3653 (freeman10@llnl.gov).

Zinc–air technology moves toward commercialization

Zinc–air fuel-cell technology, long a promising source of clean energy and stored-energy recovery, begins a move toward commercialization with the recent signing of a Memorandum of Agreement between Lawrence Livermore and Power Air Tech, USA, a consortium of Australian companies. Discussions are under way to bring other U.S. companies into the consortium.

The next step is a Cooperative Research and Development Agreement between the Laboratory and private industry, which could mean about $100 million of industry funding—$30 million for further research and development on a zinc–air fuel cell and its zinc recovery unit at Lawrence Livermore over the next four to five years and an estimated $70 million for commercialization and manufacturing applications of the refuelable zinc–air technology and recovery unit.

Zinc–air fuel cells mix zinc pellets and electrolyte with air to create electricity. They create five times as much power as lead–acid batteries of the same weight. The Livermore design is unique because it is refuelable, and the spent zinc can be recycled into zinc pellets.

The agreement initially is intended to commercialize several kinds of units: large units for utilities to meet peak power demand, small units as an alternative to gasoline and diesel generators for uninterruptable power supplies, units for heavy and lightweight vehicles, and large uninterrupted power supplies for hospitals and airline reservation systems.

John Landerer, on behalf of Power Air Tech, USA, noted, "We will make every effort to have this technology on display in Sydney by the time of the 2000 Olympic Games."

Contact: John Cooper (510) 423-6649 (cooper3@llnl.gov).

NIF construction contracts awarded

Nielsen Dillingham Builders, Inc., of Pleasanton, California, has been awarded an $11.35-million contract to construct the structural steel shell of the building that will house Lawrence Livermore's National Ignition Facility (NIF), the world's largest laser. Walsh Pacific Construction, based in Monterey, California, has won a separate $4.7-million award for foundation work.

NIF is a stadium-sized, $1.2-billion, 192-beam laser complex now under construction. The NIF design requires that its high-tech laser components be tightly encapsulated in the surrounding building. Slated for completion in 2003, the facility will create—for the first time in a laboratory—brief bursts of self-sustaining fusion reactions similar to those occurring in the sun and stars. The resulting data will help the Department of Energy maintain the safety and reliability of the nation's nuclear stockpile without underground testing while providing benefits in basic science, astrophysics, and commercial fusion power production.

Contact: LLNL Media Relations (510) 422-4599 (garberson1@llnl.gov).

FAA looks to Lawrence Livermore for flight safety

Researchers from Lawrence Livermore and three companies have been awarded $1.5 million to develop a new standard tool to assist the U.S. aviation industry in studying ways to protect against uncontained jet engine debris.

As envisioned, a Livermore computer code written to model weapons systems would be adapted to examine how to mitigate engine fragments and reduce aircraft hazards from any escaped debris. The unclassified code, DYNA3D, models collisions lasting thousandths of a second by simulating how stress moves through structures.

The two-year Federal Aviation Administration agreement teams Lawrence Livermore with two engine manufacturers—AlliedSignal Engines and Pratt & Whitney—and the Boeing Commercial Aircraft Group.

Contact: Rich Couch (510) 422-1655 (couch1@llnl.gov).

Flexibility for Future Technical Successes

WHILE research and development budgets have recently declined, the nation's and the world's economies continue to grow, to a large extent fueled by scientific and technological innovations. The growing economic importance of innovation creates opportunities upon which the Laboratory can capitalize, especially as private long-term R&D investment continues to decrease. The flexibility of people and the breadth and depth of core technologies in Livermore's Engineering Directorate together enable Laboratory programs to make the most of these opportunities.

One example of the strength within Engineering is nondestructive evaluation (NDE), a capability like many in Engineering that contribute to most Laboratory program missions and enable successful outcomes of Laboratory technology. The following article, "Advancing Technologies and Applications in Nondestructive Evaluation," reports on the kinds of specially tailored engineering approaches for which Livermore is particularly known. And with collaborations outside the Laboratory, the NDE capability also broadens Livermore's influence among the technical disciplines of measurement, monitoring, and controls.

In meeting the increasingly faster-paced cycles of innovation and change, Engineering's role is to foster unique, science-based technologies that will substantially enhance the Laboratory's ability to initiate and execute programs. For example, NDE's unique facilities, a variety of energy sources (such as x-ray and gamma-ray instrumentation), and the ability to digitally acquire, process, and image data place the Laboratory at the forefront of inspection, characterization, and certification techniques. Other examples of Engineering's contributions to applied science programs include microtechnologies (see *S&TR*, July/August 1997), regenerative fuel cells (*S&TR*, May 1997), and computational electromagnetics (*S&TR*, March 1997).

Engineering also works to enhance the Laboratory's external visibility by supporting external collaborations. For many years, we facilitated productive interaction between the scientific community and the marketplace, providing insight from industry to Laboratory programs while gaining greater external recognition for our capabilities and achievements in the process. The following article, for example, illustrates how the NDE staff couples the Laboratory to other external collaborators, especially the Department of Energy, with its noninvasive assays of waste drums.

In Engineering, as in other Laboratory directorates and programs, we routinely must sort through our toolbox of intellectual and physical resources to provide what's needed today and what scientists and conceptual engineers will need tomorrow. We find that one key to the next success is the flexibility of the tools that are chosen. For example, most of us discarded the analog world of pocket protectors and slide rules for the digital realm of computers some years ago. Today Engineering's tools include:

- A staff having diverse and specialized skills.
- Operational ability to move people rapidly from program to program as needs change.
- A technology base that is robust and diverse, backed with Laboratory institutional support for continuing technology development.
- Access to and experience with world-class and unique facilities on site, in industry, and at leading academic centers.
- Participation in multiple programs and scientific disciplines.
- Ability to successfully collaborate with various partners.

In fact, these tools look surprisingly like tools elsewhere around our Laboratory and in successful companies. Our biggest ongoing challenge in Engineering is developing the next generation of tools to enable programmatic success while sustaining the most appropriate level and breadth of our expertise with these tools.

■ Spiros Dimolitsas, Associate Director, Engineering.

Technological advances in materials and products pose great challenges for inspection methods used to evaluate their quality, efficacy, and safety. Livermore's nondestructive evaluation techniques provide fast, accurate, quantitative analyses of exotic devices and solve complex evaluation problems.

Advancing Technologies and Applications in Nondestructive Evaluation

WHEN a shopper uses smell to assess the ripeness of a peach and when a homeowner taps on a wall to figure out where the studs are, they are practicing everyday varieties of nondestructive evaluation—the technique of inspecting something without destroying or damaging it.

The most common nondestructive evaluation (NDE) methods used to characterize materials and inspect products are visual, operator-dependent, subjective, and qualitative. Those methods can be slow, imprecise, and inconsistent—and quite unsuited for inspections required during the course of Lawrence Livermore's scientific projects. That's why researchers in the Laboratory's Nondestructive and Materials Evaluation Section develop specially tailored evaluation methods that deliver exact, quantitative results. The methods use automated, digital, breakthrough technologies implemented through such techniques as computed tomography, digital radiography, ultrasonics, machine vision, and infrared thermography. Because the data are digital, the information can be processed and reconstructed into images that are amenable to computational analysis. These NDE methods are more quantitative and sensitive than human sensory perception; they provide researchers a precise look inside the object of interest.

Digital NDE systems have these components in common: an energy source used to probe an object; a receiver or detector that measures how the energy has been changed by the object; and a way to record, process, and interpret the measurement data. To configure this basic system for specific applications, system designers must solve a plethora of problems. Among them are how to deal with interfering noise and nonlinear effects when energy is being delivered and detected; how to acquire data for the best spatial and contrast resolution (that is, how small and how clearly resulting images can be seen); how to mathematically describe features and objects for detection as well as how to distinguish among variations in their size, shape, and intensity; and how to reconstruct digital data into images that can be easily understood and used.

NDE developers benefit from Lawrence Livermore's expertise in engineering, materials science, and computations. In return, NDE technologies support Laboratory science, first, by providing the specialized inspections required of unique projects and, second, by developing new technologies that expand NDE concepts and uses.

Looking into Laser Slabs

Looking at the preparations under way for the construction of the National Ignition Facility, to be the world's largest laser, one can easily see that the project is complex, having a multitude of components that must be carefully inspected before they can be used. Among those parts are 3,100 laser amplification slabs, 0.8- by 0.4-meter, 42-kilogram pieces of glass used to amplify the light and achieve energy gain.

The perimeters of these slabs are bonded with epoxy to cladding glass to absorb any stray light that could reduce amplification efficiency. In the delicate workings of lasers, however, the cladding-glass bond presents problems if it is imperfect and contains bubbles or voids. Those imperfections can reflect stray light right back into the slab and diminish amplification. Furthermore, bonding defects located on opposite sides of the slab could work together to create a conflicting pattern of back-and-forth light reflection that also disrupts amplification and ultimately can damage the slab itself.

Laser researchers have specifications for slabs that define the sizes, volumes, and patterns of bond imperfections that can have adverse effects during laser operation. In the past, the size of a defect was determined by "eyeballing" it against a sizing chart. Clearly, a better inspection method for these slabs was needed, so Skip Perkins and Diane Chinn designed one: an automated, optical inspection system consisting of a staging platform to hold the slab, a CCD (charge-coupled device) camera, light sources, and a computer to store digital image data (Figure 1). They experimented with different optical configurations of camera and light sources before finding the best one for recording epoxy bond images.

A more crucial part of their project has been to develop software algorithms for processing the acquired digital data. The algorithms must accurately distinguish flaws from other optical irregularities, for example, to locate scratches in the bond, categorize the flaws by size and other attributes, and finally, classify the amplifier slab as acceptable for use or not.

According to the researchers, once software algorithms have been completely developed, the automated inspection system will provide standardized, repeatable inspections that assure a consistent level of laser slab quality. Perkins says that because system data can be archived, there will be a record of bond conditions that can be used to identify and assess flaws that are made by laser operation.

Improving the Total Process

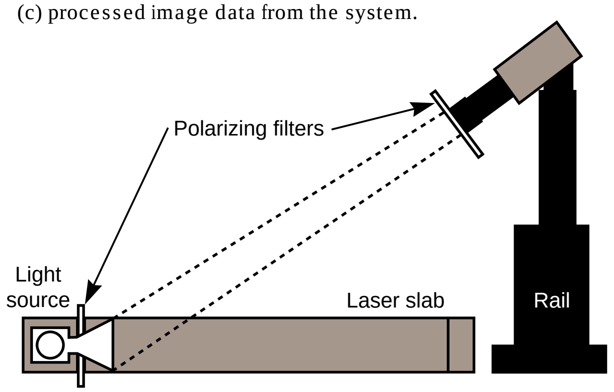
Graham Thomas, group leader for ultrasonics and surface techniques, has also instituted an automated inspection method, using ultrasonic technology, to replace "eyeball" inspections. He did this as part of a collaboration with private industry in work that also included product development monitoring, raw material evaluation, and investigations of manufacturability issues. Interestingly, the ultrasonic technology developed during this project is now being applied to other Laboratory programs.

Thomas was working with an engine piston that had been designed for better fuel efficiency to meet increasingly stringent federal pollution guidelines. It is made by a metal–matrix composite casting process: molten aluminum is force-injected into a refractory metal mold that contains reinforcing ceramic fibers (called a preform). The performance of the finished pistons depends on the quality of the preform. During fabrication of the pistons, uneven fiber concentrations can cause density variations in the casting, and cracks, voids, or other surface abnormalities can appear.

Thomas and his colleagues' first task was to select an inspection technique to assure the quality of the preforms. They tried five techniques (x-ray computed tomography, digital radiography, optical imaging, ultrasonic testing, and infrared imaging), discovering that while all can effectively detect flaws, each one has different strengths and weaknesses. For example, computed tomography provides the best characterization of internal features. Digital radiography is the fastest and has the highest resolution, but it is less sensitive to voids and cracks. They selected digital radiography to screen the preforms during the project's development and demonstration phase.

For the production phase, a different inspection technology was needed, one that is fast, inexpensive to implement, and requires no shielding to protect workers (as the radiographic technique does). Thomas is adapting ultrasonic sources to send out pulses of high-frequency sound waves, which then radiate into the material of interest. Detectors measure how much sound attenuates using specially designed transducers, devices that convert sound pulses into electrical signals. The resulting pulses—the detected electrical signals—are processed and interpreted.

Figure 1. (a) Photo and schematic of an automated, optical inspection system developed by nondestructive evaluation researchers Skip Perkins and Diane Chinn. (b) Raw and (c) processed image data from the system.



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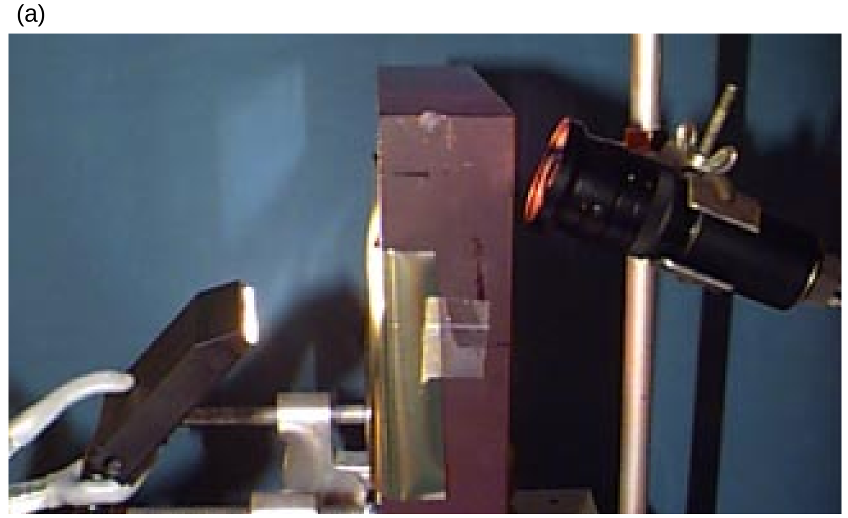

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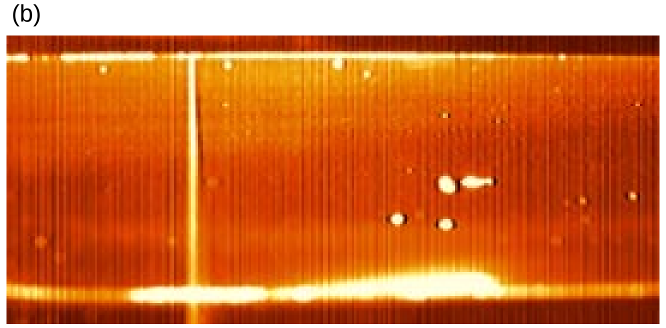

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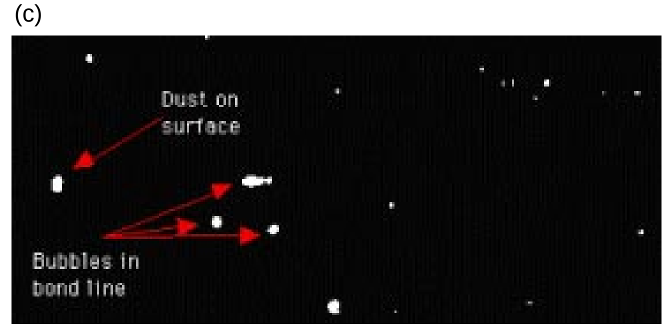


One manufacturing-line inspection study, still under way, will determine how to implement an ultrasonic system to detect porosity defects in pistons. Such defects cause piston surfaces to deteriorate during finish machining. If defective pistons could be culled before the machining process, production costs would be reduced.

Another inspection occurs after machining. Especially critical are the grooves in the piston walls, into which metal piston rings must fit snugly for efficient operation. Grooves containing pits or other low-density spots provide a pathway for combustion gases to leak around the rings.

NDE researchers experimented with a prototype ultrasonic scanning system (Figure 2) for this inspection. The ultrasonic evaluation of metal–matrix castings presents many technical challenges. Very small defects must be detected reliably and, once detected, must be characterized to distinguish benign or noncritical attributes (such as reflections of solid masses) from critical defects (such as air-filled bubbles). Development is under way for advanced signal-processing algorithms and a transducer design that will provide the required spatial and depth resolutions. The NDE researchers have, in the meantime, used the prototype system to demonstrate the feasibility of a computer-controlled, automated inspection on the manufacturing floor. Thomas will work with his private-industry collaborators and a private ultrasonic system manufacturing company to design and build the production version of the Lawrence Livermore prototype system.

This technical know-how is also used for other Laboratory projects. For example, the NDE researchers are now applying ultrasonic evaluation to inspect and characterize castings of special nuclear materials.

Assaying Waste Containers

At Department of Energy facilities around the U.S., radioactive and hazardous wastes generated during scientific experimentation have been packed into waste drums and await treatment, storage, or disposal. Waste regulations are stricter and disposition more costly for wastes that have higher levels of radioactivity.

Opening the sealed drums for an assay is a risky, time-consuming, and expensive proposition. Traditionally, the drums are inspected by real-time radiography, a technique in which an x ray is viewed on a monitor during x-ray exposure of the waste drums. This method allows a partial identification of drum contents. It is limited in that it provides only two-dimensional information; it misses overlapping features, does not "see" depth, and cannot count radioactive quantities. Without an accurate quantification of the radioisotopes, waste regulators must err on the side of safety and designate waste disposal based on higher-end estimates of radioactivity.

Nuclear physicist/chemist Harry Martz and his NDE colleagues have developed hardware and software technology to perform quantitative, noninvasive assays of waste drums. They use a two-step approach called gamma-ray active and passive computed tomography, or A&PCT.

Like radiographic techniques, which produce the familiar medical x rays, computed tomography measures radiation energy that travels from a source through an object to a detector and records the intensities that result from the interaction of the energy with the object. But unlike radiography, tomographic measurements require the acquisition of many different images of an object. In medical tomography (i.e., CAT scans), the source and the detector move around the patient; in industrial tomography, the object is usually rotated, elevated, and translated (moved in parallel motion).

Martz's A&PCT system takes two different tomographic measurements. For the first, called the active measurement, an external radiation source emits gamma rays (instead of x rays), and a gamma-ray spectrometer system measures the gamma radiation that passes through and outside the object being measured. Gamma-ray

Figure 2. Prototype ultrasonic scanning system (with sample pistons atop the monitor) that will be used for detecting very small casting defects.

spectroscopy offers several advantages for waste characterization, one being that gamma rays are emitted at discrete energies, making it possible to determine the attenuated gamma-ray energy for each volume element in the three-dimensional space of the object. This information is vital for an accurate waste assay (Figure 3).

The second measurement is a passive measurement. The gamma-ray source is shuttered, and the waste container is moved through the same positions used to collect the active measurements. This time, the detector records gamma-ray emissions from the radioactive material inside the waste container. The passive measurement localizes the radioactivity distribution in the container.

By combining active and passive measurements, corrections can be made to account for the effect that the waste contents have on the internal radioactive emissions. The corrected gamma-ray spectra can be used to identify, localize, and assay all measured radioisotopes present in the container, and the wastes can thus be categorized and certified for disposition.

This waste assay system is mobile as well as accurate. The technology has now been adapted for a commercial mobile waste inspection system developed by BIR Inc. of Lincolnshire, Illinois, that is providing services at waste sites throughout the U.S.

Measuring Transport

Because high spatial resolution imaging capabilities are now available with x-ray computed tomographic systems, the technique is being viewed as an attractive tool for obtaining rock and soil property measurements. Investigators from the Environmental Programs Directorate at Lawrence Livermore—aided by Pat Roberson, Dan Schnebert, and other NDE researchers—have used x-ray tomography to measure water content in rocks from The Geysers geothermal reservoir in northern California. Concurrently, NDE x-ray computed tomography specialists began planning work with researchers from the University of California at Davis to study contaminant transport mechanisms in soil. The goals are to design a viable method for estimating groundwater contamination risks and to plan remediation.

Early x-ray tomographic studies of Geysers rock were conducted in a laboratory. Lawrence Livermore scientists took a variety of x-ray tomographic scans of preserved core samples.

Pairs of cylindrical core samples, each with different water content, were measured for the extent of their fluid saturation, how fast they dried, and how fractures influenced both saturation and drying. The experiments demonstrated that tomographic scans could be used to monitor moisture distribution and movement in rocks having at least 8% porosity. Scanning was less definitive for measuring rock with lower porosity, such as graywacke, a typical Geysers rock.

With a higher-energy x-ray imaging system that provided better spatial and contrast resolution than medical scanners and also included specialized image reconstruction software, the scientists went on to scan rock samples. At the site of a completed drilling operation, they sealed off sections of core with an aluminum cylinder to preserve and protect each one from further disturbance. Multiple views of the samples were radiographed and three-dimensional tomographs were then reconstructed (Figure 4). The tomographs clearly show changes at different depths in the reservoir and major structural features useful for deducing reservoir processes. The experimenters conclude that, with further refinements to this spatial and contrast resolution, quantitative measurements of mineralogy, porosity, water content, and distribution may be possible.

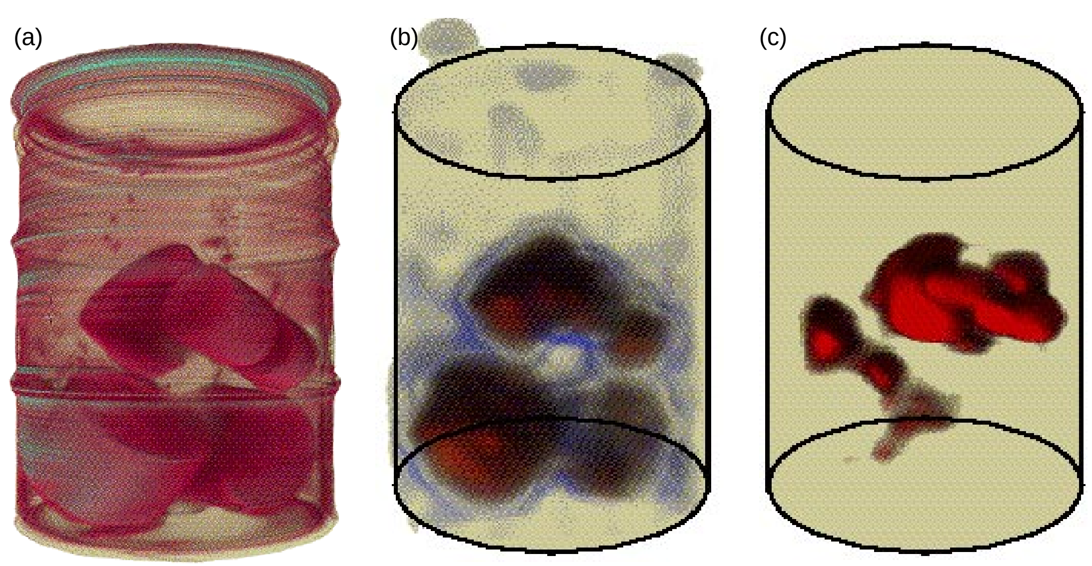


Figure 3. Assaying a container such as this transuranic waste drum is made easier with LLNL's active and passive computed tomography (A&PCT). Here, data are shown in rendered views of (a) a typical industrial transmission tomograph at high spatial and energy resolution, (b) the active data set, and (c) the passive data set, which gives the distribution of plutonium-239 in the drum. When the measurements are combined, radioisotopes can be identified, located, accurately measured, categorized, and certified for disposition.

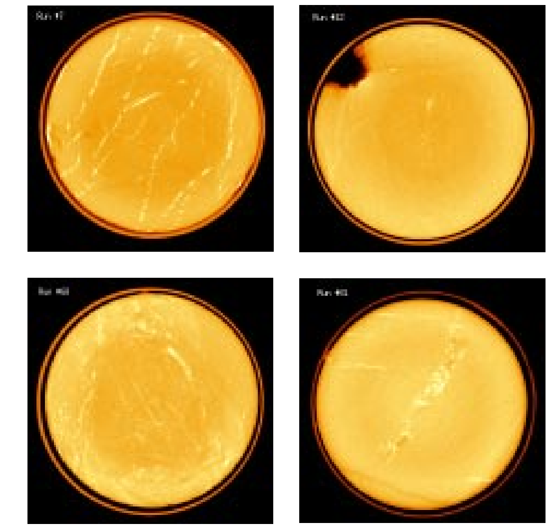


Figure 4. Radiographs of 1.5-meter cores of Geysers rock within sealed aluminum coring tubes show differing degrees of mineralization, texture, and fracturing.

Although only a small part of the reservoir can be studied through core sampling, data from these studies may be useful for extrapolating information to a scale as large as several square kilometers. Geophysical properties, such as seismic velocity and electrical conductivity, depend on water saturation; if these properties could be calibrated to water content, they could be used to provide measures of water saturation.

The soil studies, in collaboration with UC Davis, require microscale x-ray computed tomography with a spatial resolution of 15 to 30 micrometers. The objective is to use the microscale data to better understand transport mechanisms associated with the migration of contamination. This information will be used to verify and improve pore-scale models that predict migration. For dynamic cases, researchers obtain a sequence of highly detailed radiographs of water and contaminates flowing through the soil and observe the changes. For static cases, two three-dimensional computed tomography images are acquired, one from a reference sample that is not contaminated and one from a contaminated sample. By subtracting the reference image, they obtain a three-dimensional, pore-scale distribution of the contaminant. Getting the high-resolution data requires a new, microfocus, in-line CT scanning system that is being developed by NDE.

First, however, the investigators must simulate porous-media (i.e., soil) flow systems by taking computed tomography scans of spherical glass beads in different combinations of fluids. The well-defined shapes of the beads make it easy to quantitate the images. Results from scanning the simulated samples will identify the optimum scanning conditions and parameters for the real samples.

Lawrence Livermore and UC Davis researchers will also compare and refine the three-dimensional visualization techniques that both groups have developed. They are planning a major software improvement—providing dynamic visualization—to show the microscale soil transport changes in time.

Dual Bands More Precise

Another method that is pushing the envelope of NDE technology is dual-band infrared (DBIR) thermography. This method measures apparent surface temperature patterns to detect subsurface flaws, based on the fact that flawed materials or structures heat and cool differently than those without flaws. Normally, heat measurements are taken in one range of infrared wavelengths, but those measurements do not distinguish between real structural defects and "clutter," surface-reflected infrared noise.

Nancy Del Grande has developed a dual-band measurement technique that simultaneously uses short wavelengths (4.5 to 5.5 micrometers) and long wavelengths (8.5 to 11.5 micrometers) to create three-dimensional thermal images of materials for NDE projects. Del Grande knew that hotter defect spots show the same patterns at different wavelengths, whereas clutter shows very different patterns (emitted light and reflected light obey different physical laws). She thus surmised that by comparing the two image data sets, she would be able to analyze heat flow patterns precisely and separate structural flaws from surface emissivity variations. Del Grande has already applied the dual-band technology to detect flaws such as aircraft skin corrosion and bridge deck delamination (see *S&TR*, May 1996).

The very high precision of DBIR temperature measurements can be applied to uses other than detection of material weaknesses and flaws. For Lawrence Livermore's National Ignition Facility (NIF), DBIR technology is supporting efforts to determine what thermal controls and recovery times will be needed to avoid damaging potassium dihydrogen phosphate (KDP) laser crystals that will be used to boost laser energy. Scientists need to know how long the pulsed crystals will take to return to ambient temperature so they can be safely pulsed again. Because the crystal temperature changes in question are

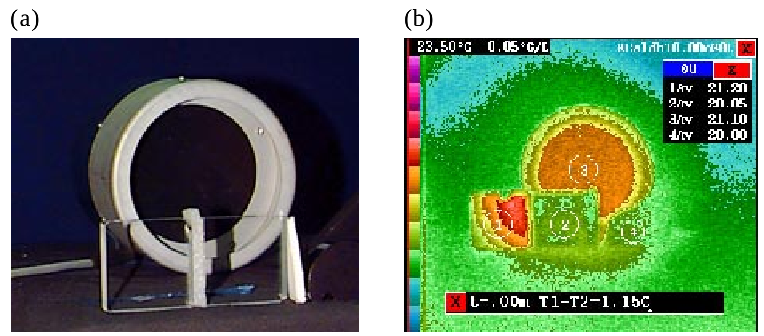


Figure 5. A dual-band infrared (DBIR) experiment measured KDP crystals. (a) The photo shows the setup, and (b) an image demonstrates the different temperatures of the experiment elements. Inset numbers denote (1) an oven-heated crystal, (2) an unheated crystal, (3) a heated blackbody calibration plate, and (4) a calibrated resistance thermometer.

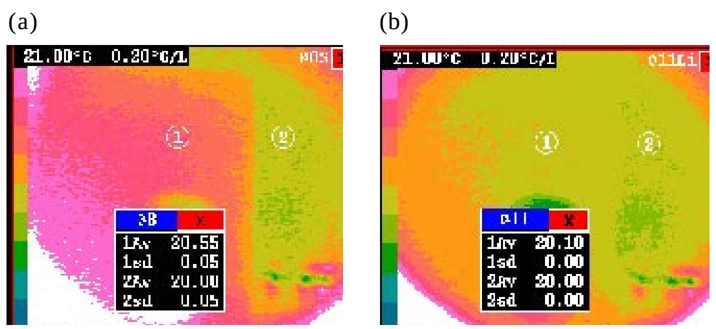


Figure 6. Temperature images of the Beamlet vacuum chamber experiment at (a) 2 minutes and (b) 200 minutes after the heater was turned off. Insert number (1) denotes a fused-silica window, and (2) denotes an aluminum wall.

minute and the measurement environment (a hard-to-access vacuum chamber) is both complex and delicate, tracking crystal cool-down is not easy. DBIR offers a feasible means for taking the necessary measurements.

To demonstrate the capability of the technique to measure temperatures near room temperature to a precision within 0.07°C, Del Grande first acquired dual-band measurements of two KDP crystals (Figure 5), one heated in an oven and one kept at room temperature. Then she heat-imaged KDP crystals through a zinc–selenide vacuum window. The goals were to reproduce the effect of the actual vacuum environment in which crystals will be pulsed and measured, to demonstrate that heat images can be taken through the window, and to determine the corrective calibration measurements for the DBIR system before its use in the actual NIF prototype laser, the Beamlet.

In the next part of the study, heat images were taken of an actual fused-silica Beamlet window, without the crystals. The window was externally heated and allowed to cool down. Cool-down was very slow, indicating that temperatures in the vacuum chamber environment were well controlled and not susceptible to external influences (Figure 6). The comparison of emissivity differences between fused silica and aluminum at 20°C indicated that differences were slight, and window temperatures were unaffected by vacuum chamber walls and aluminum structures.

With these assurances that heat-image measurements are possible and accurate, Del Grande expects to measure two KDP crystals inside the Beamlet (once its full capability is online), one pulsed and one not, to determine the initial temperature rise and required recovery time for the pulsed crystal.

In yet another Laboratory project, the DBIR technique helped the Heavy Ion Fusion Group to determine the extent of temperature uniformity of high-temperature zeolite (aluminum silicate), a material used as a source of ions for a prototype induction accelerator (Figure 7). The image data indicated that high-temperature and temperature-gradient measurements may also provide useful information about zeolite aging so scientists will know when the zeolite source should be replaced, thereby assuring continued accelerator performance.

Aging zeolite can be identified by the uneven distribution of silicate, one of its components, on the zeolite surface. Because silicate ions have a broad infrared resonance (from 9 to 11 micrometers), they cause the zeolite temperature to appear much lower in the long band than in the short band. Nevertheless, making the dual-band zeolite heat measurements was challenging: most of the target is relatively unaffected by the silicate buildup, so measurements had to be very precise to "see" the uneven distributions. In addition, the measurements were made in a vacuum environment, and they were detected

indirectly. That is, the coffin-like chamber of the ion beamline meant that the zeolite infrared signals had to be reflected at right angles off a silver mirror and then transmitted through the vacuum window to reach one detector camera and then the other. Therefore, corrections had to be made for the effect of the silver mirror and for the transmissions of the reflected infrared signals through the window, in addition to corrections for the dual-band, wavelength-dependent emissivity variations. Despite the difficulties, the results demonstrate that such measurements are feasible and, in fact, show uncertainties as small as 3°C at temperatures as high as 915°C.

Technology for the Future

To follow the course of NDE developments is to anticipate ever more innovative and far-reaching uses for its technologies. The NDE researchers' work already demonstrates diverse new areas of NDE applicability. For example, it can be used as an environmental tool (as seen in the work on tomographic waste assays and tomographic contaminant studies) and in unique scientific applications (as in the work for the KDP laser crystals and for zeolite ion sources). With continuing advances in radiation physics, computer algorithm development, and computer visualization, NDE technologies will undoubtedly provide still other uses and applications.

— Gloria Wilt

Key Words: computed tomography, contaminant transport, digital radiography, dual-band thermography, gamma-ray spectroscopy, infrared computed thermography, inspection, nondestructive evaluation (NDE), nondestructive waste assay (NDA), optical inspection, ultrasonics.

For further information contact Clint Logan (510) 422-1888 (logan2@llnl.gov).

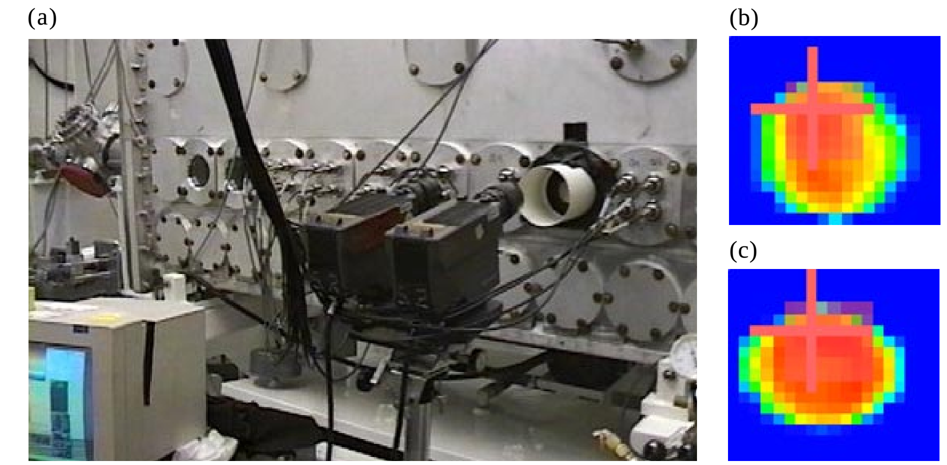
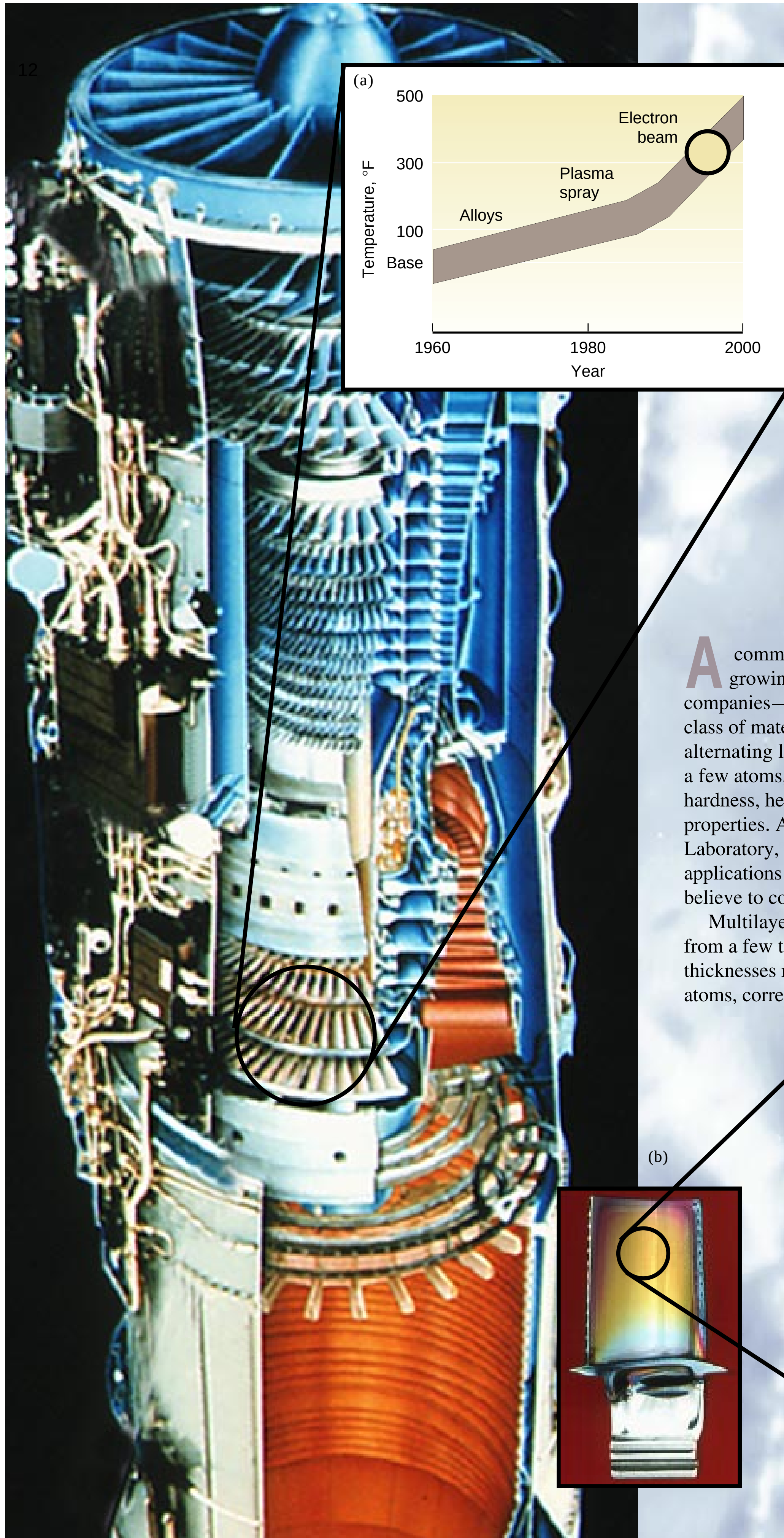


Figure 7. (a) DBIR cameras face the vacuum-chamber port of the Livermore prototype recirculating induction accelerator. Red cursor marks show measurements of the aged 2-centimeter-diameter zeolite heavy-ion sources at (b) a long wavelength band (8.5 to 11.5 micrometers) at 911±3°C and (c) a short wavelength band (4.5 to 5.5 micrometers) at 915±3°C.

About the Engineer

CLINT LOGAN joined Lawrence Livermore National Laboratory in 1963 after receiving a B.S. in mechanical engineering from Montana State University that year. He received an M.S. in materials from the University of California at Davis in 1972. Logan's first job assignment at the Laboratory was in the Mechanical Engineering Department's Apparatus Division. Since that time, he has had experience in the fields of weapons testing, experimental physics, magnetic fusion, x-ray lasers, and digital mammography (also see the article on mammography, pp. 23–25 of this issue). Logan is currently the section leader for nondestructive and materials evaluation.



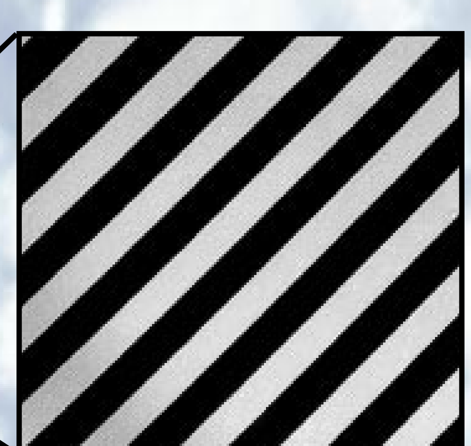


Figure 1. (a) Multilayer materials in aircraft engines withstand greater temperatures, which allow engines to develop greater thrust. (b) A turbine's airfoil thermal barrier coating prolongs engine lifetime.

Atomic Engineering with Multilayers

The future looks bright for multilayers, exceedingly thin alternating layers of materials that often demonstrate remarkable—and unpredictable—properties for a host of applications.

A common adage goes, "thin is beautiful." To a growing number of researchers—and intrigued companies—the saying is especially true for a unique class of materials called multilayers. Composed of alternating layers of two different materials as thin as a few atoms, multilayers offer extraordinary strength, hardness, heat-resistance, and unexpected new properties. At Lawrence Livermore National Laboratory, researchers are pioneering entirely new applications for these materials, which many now believe to constitute an essentially new state of matter.

Multilayers' alternating layers can vary in number from a few to more than 200,000. Individual layer thicknesses range from a few atoms to a few thousand atoms, corresponding to a maximum structure thickness of about 10 millionths of an inch. The repeat distances in the multilayers, that is, the thickness of two adjacent layers, can be purposely selected to be identical to the interaction lengths characteristic of important physical properties (e.g., magnetic interaction lengths) to yield new properties. In this context, says Laboratory material scientist Troy Barbee, Jr., one of the pioneers of modern multilayer technology, "it is generally accepted that one should expect the unexpected when multilayers are fabricated and experimentally characterized."

Multilayers are part of a larger, established scientific field of so-called designer or "nanostructured" (from nanometer, a billionth of a meter) materials that represent the current limits of materials engineering and that are currently impacting numerous Laboratory research programs. Indeed, multilayers are among the first materials to be designed and fabricated at the atomic level, a capacity termed "atomic engineering" by Barbee. "We're building multilayer materials atom by atom and molecule by molecule," he says. The result is tremendous potential for improving the performance of large numbers of products through either new or enhanced mechanical, optical, magnetic, thermal, and other physical properties.

To date, Barbee's team of material scientists, engineers, and technicians has synthesized multilayers from 75 of the 92 naturally occurring elements in elemental form or as alloys or compounds. With that wealth of experience, the team has emerged as one of the world leaders in multilayer science and its applications. The team has also forged partnerships with other national laboratories, U.S. industries, universities, federal agencies such as the Department of Defense and NASA, and researchers worldwide.

The first applications of multilayer structures were demonstrated more than 50 years ago for such uses as optical interference filters and reflection coatings. During the 1970s, "macro" multilayer films became essential to the semiconductor industry for making everything from computer chips to hard disk drives. In the late 1970s, Barbee pioneered significant advances in fabrication technology in the development of multilayers for a wide variety of applications in the x-ray, soft (lower energy) x-ray, and extreme ultraviolet (EUV) regions of the electromagnetic spectrum. For example, high-reflectivity multilayer mirrors have made possible a new class of telescopes for solar physics and astronomical research. Multilayer optics also have found applications in electron microprobes, scanning electron microscopes, x-ray lasers (especially in laser-fusion diagnostic systems), and particle beamlines in accelerators.

To Save Airlines Millions

Livermore researchers are currently pioneering new kinds of multilayers—beyond optical uses—that take advantage of their extraordinary properties. These applications include high-performance capacitors, ultrahigh-strength materials, thermo-electric devices, and coatings for gears and bearings, aircraft and automobile engines, and cutting and machine tools.

Products incorporating multilayers promise higher strength-to-weight ratios, less friction and wear, higher temperature operation, corrosion resistance, fracture toughness, and low electrical resistivity. Multilayer technologies can also have a profound impact on manufacturing processes by decreasing the amount of

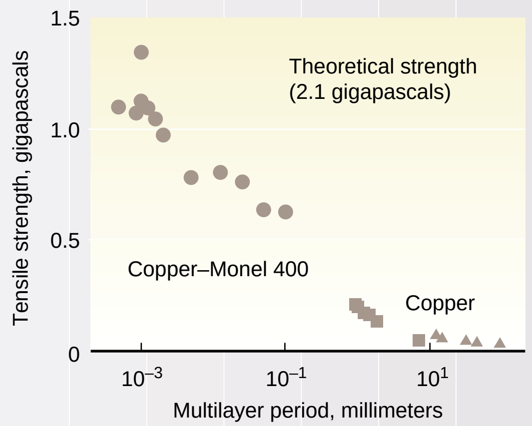


Figure 2. Strength tests show the difference between commercial copper and the copper–Monel multilayer material.

machining necessary between raw material and finished product.

The enormous commercial potential of multilayers has not gone unnoticed by U.S. industry. A recently completed three-year Cooperative Research and Development Agreement (CRADA) joined scientists from Lawrence Livermore, Pratt & Whitney, and Rohr Inc. to develop high-performance multilayer coatings for aircraft engine blades and high-strength engine parts (Figure 1). Such advances could safely increase the operating temperatures of gas turbine engines by 10 to 38°C, thereby permitting the engines to develop greater thrust. The coatings would also prolong the life of many parts throughout the engine, conceivably saving commercial airlines and the Department of Defense tens of millions of dollars annually.

Such coatings work because extremely thin slices of matter exhibit new and sometimes unanticipated properties. Scientists believe the reason is their extensive “boundary structure.” In a multilayer with layers only four atoms thick, half of the atoms lie at an interface between the layers. They do not develop the conventional molecular structure and bonding found in pieces of matter greater than 100 nanometers in diameter. As a result, the layers are stronger and less likely to fail under stress. Multilayers made of metals get stronger and harder, while multilayer ceramics become less brittle. The strongest materials are those with the thinnest layers because they have the most uniform structure.

Barbee says it is a complex task to choose materials to make up a multilayer because a researcher must understand metallurgy as well as the physics of the intended application. Indeed, combinations of two materials sometimes result in surprising new properties. A multilayer fabricated by Livermore scientists and composed of copper and Monel (copper–nickel alloy) (Figure 2) has more than 10 times the strength of copper alone and is highly resistant to chemical corrosion. Sometimes materials with different properties can be combined in multilayers to eliminate or mitigate some of their individual drawbacks. For instance, very hard materials can be combined with those that are very tough to produce something, such as copper–Monel, that is both hard and resistant to cracking.

One multilayer designed by Barbee illustrates the advantages gained by adding even a small quantity of a different material. This multilayer is composed of 7,100 individual layers of materials—3,550 layers of copper (each layer is 325 angstroms, or 156 atoms, thick) and 3,550 layers of a copper–zirconium mix (each layer is 100 angstroms, or 38 atoms, thick). All told, the multilayer measures about 142 micrometers thick, equivalent to the thickness of about two human hairs. Although only about three atoms in every hundred are zirconium, the material has a tensile strength of about a billion pascals (160,000 pounds) per square inch, more than six times the strength of commercial copper. With their high strength, nonmagnetic nature, and more environmentally friendly materials, copper–zirconium multilayers could be used to replace beryllium– copper alloys commonly used in springs and tools.

Seeing the Sun in New Ways

One of the most important applications of multilayers is astronomical imaging. High-performance multilayers have been used as mirrors to focus light in the x-ray, soft x-ray, and EUV regions. Images taken by telescopes using multilayer mirrors reveal important features that cannot be captured by standard imaging instruments operating at longer wavelengths. Furthermore, because multilayer mirror surfaces are reflective only within a certain wavelength range, they can be used to isolate a particular region of the spectrum of interest to astronomers (Figure 3).

Barbee notes that standard optical techniques cannot be used in x-ray imaging devices because x rays are substantially absorbed by the materials. As a result, reflective optics based on collective scattering of the individual layers in a multilayer solid are used to collect and image the x rays. X rays are reflected only if they hit a metal surface at a very shallow, or grazing, angle. However, natural crystals have spacing between their planes on the order of a few angstroms, which limits the

reflection angles and x-ray wavelengths for which they can be used. To retain this range of reflected light, one can use a series of multilayers to replace the natural crystals. An added advantage of multilayers is that they can be smoothly deposited on curved substrates, a requirement for high-performance optical systems.

Barbee’s work on multilayer optics began in the 1970s at Stanford University, where he was laboratory director of the Center for Materials Research. He led development of multilayers using a technique called magnetron sputter deposition, now the most common technique for depositing multilayers on substrates (see box, p. 18). In 1976, the technique was reported to Congress by the National Science Foundation as a major breakthrough in material science.

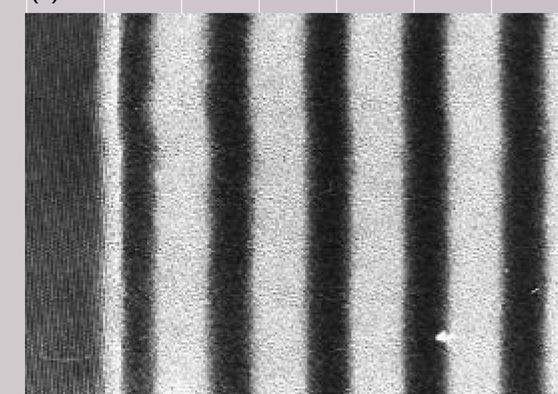
Barbee and his staff at Stanford designed a set of magnetron sputtering sources to produce multilayers based on copper layered with the transition metals niobium, tantalum, molybdenum, and tungsten. From analyzing these early multilayers, they found that the structures might be of x-ray optical quality.

An effort was begun to explore this opportunity with the material pair tungsten and carbon. These elements were selected because only a minimum number of layers were required to achieve significant reflectivity, minimizing the demands on the stability of the maturing sputtering process. These materials proved to be very effective and have been a staple of the international multilayer x-ray optics field ever since. In addition, the development effort was aided by the appearance of new tools, namely the scanning transmission electron microscope (STEM) for characterizing multilayer structures and synchrotron x rays for characterizing mirror performance.

When Barbee came to Livermore in 1985, he set out to advance the sputtering process, develop more advanced multilayer optics, and explore a wider range of multilayer applications. Today, Livermore is known internationally for the design and manufacture of optics for obtaining high-resolution images of the Sun and astronomical objects in the x-ray to EUV spectrum. The Livermore team made the multilayer optics for a Cassegrain telescope on the Stanford University/Marshall Space Flight Center sounding rocket launched on October 23, 1987. The images (Figure 4) clearly resolved features, such as loops and plumes, of the Sun’s corona for the first time in this region of the electromagnetic spectrum. One of the photos appeared on the September 20, 1988, cover of *Science* magazine.

Since then, Livermore researchers have manufactured multilayer optics used in several satellites by the U.S., the U.K, and France. Livermore multilayer optics for an x-ray telescope will be onboard a new NASA research

(a)



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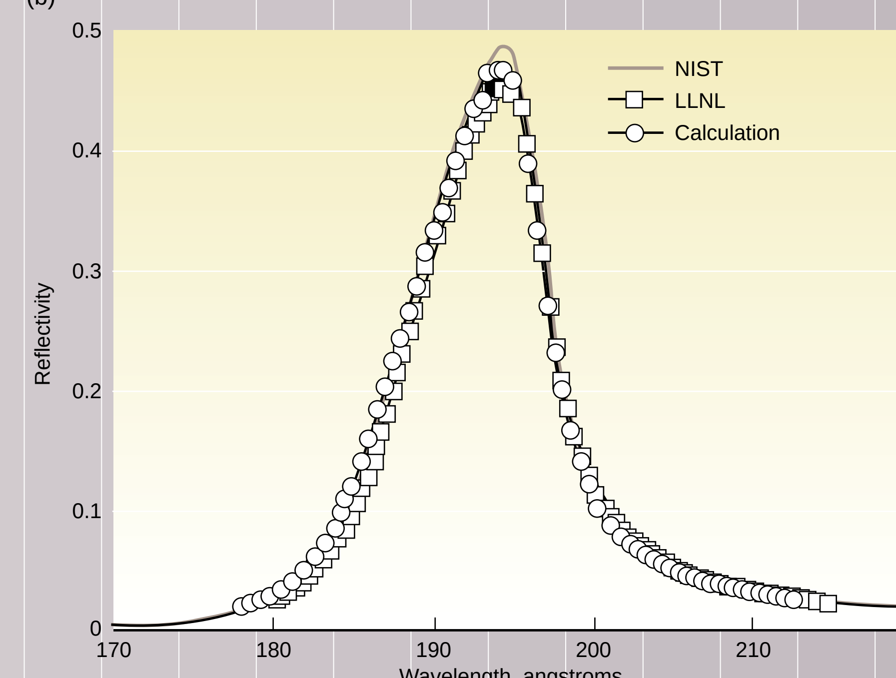


Figure 3. (a) Multilayers of molybdenum carbide and amorphous silicon (Mo_2C/Si) are shown in a transmission electron microscopy image at 4 million magnification after annealing at 500°C. (b) Reflectivity measurements of Mo_2C/Si, taken by Lawrence Livermore and the National Institute of Standards and Technology (NIST), are extremely close to the theoretical calculation of a perfect structure at the wavelengths shown.

Figure 4. Early advances in multilayer technologies brought images of the Sun with higher resolution than previous grazing incidence telescope images. The reason: multilayer laminates in the x-ray optics allow the use of a normal incidence optics system for which aberrations can be minimized.

satellite scheduled to be launched by a Pegasus spacecraft in December 1997. The x-ray telescope is designed to have the highest spatial resolution of any such instrument ever flown. Livermore multilayer optics are also being considered for two other U.S. space missions and for satellites for the Japanese and European space programs. The popularity of the multilayer optics is a significant factor in the growing interest in x-ray imaging of astrophysical phenomena from stellar sources.

The outstanding properties of Livermore's x-ray optics can be seen in STEM images of multilayers containing alternating layers of molybdenum carbide (Mo_2C) and amorphous silicon (Si). The image (Figure 3a) shows that the interfaces between the multilayers are very smooth and abrupt in contrast, with no intermediate chemical reaction layer at the interfaces of the two layers. Figure 3b shows that the measured reflectivity of the multilayer is essentially equal to that predicted for a perfect structure.

Extensive Effort Under Way

The Laboratory-wide multilayer development effort consists of more than 15 senior researchers and 25 technicians at work in five laboratories. The results of their work can be seen across Lawrence Livermore's directorates—Chemistry and Materials Science, Engineering, Defense and Nuclear Technologies—and especially in the Laboratory's Laser Programs. Barbee's team produced more than 250 multilayer optics last year for laser applications, particularly for laser-fusion research.

"Using multilayer technology, we've been imaging high-energy-density plasma of the Sun and then turning around and imaging the same kinds of phenomena in laser fusion," Barbee explains.

Multilayer optics make possible x-ray interferometry for characterizing plasmas created by high-power lasers. The technique provides the only workable diagnostic tool to directly look at extremely hot, high-electron-density plasmas of matter produced in inertial confinement fusion experiments (Figure 5).

Researchers in Lasers' Advanced X-Ray Optics Group are using multilayer mirrors in recently developed soft x-ray lasers. One potential use of a laboratory x-ray laser is in imaging biological samples. A spherical multilayer mirror is used to condense x-ray laser light onto living organisms to obtain a high- resolution (greater than 800 angstroms) image.

Barbee's team is also collaborating with researchers in Lasers' Advanced Microtechnology Program to make possible computer chips with 10 times the performance yet one-tenth the size of today's devices. Achieving these breakthroughs will be possible only with lithography using EUV light. The new EUV technology is the focus of a major CRADA announced in September 1997 by Department of Energy Secretary Federico Peña. As with today's deep-ultraviolet-light-based technology, EUV lithography will employ multilayers in creating computer chips and their master patterns, called masks.

Capacitors around a Corner

One research avenue of significant potential is using multilayers as ultra-compact, high-energy storage, and extremely cost-effective capacitors made up of alternating metal (conductor) interdigitized with dielectric (insulator) layers. Power electronic "snubber" capacitors, normally made of ceramic or polymer dielectrics, and similar in size to a C battery, are usually connected to much smaller solid-state switching devices. These capacitors typically store 0.1 to 0.2 joules per cubic centimeter capacitor volume and are widely considered the limiting factor in many applications. In contrast, multilayer capacitors the size of a postage stamp would store 10 joules per cubic centimeter while costing perhaps one-twentieth that of their ceramic forebears.

Project leader Gary Johnson, an electronics engineer, says that the first commercial multilayer capacitors will likely be targeted at power electronics, computers, and communication devices. Compact multilayer capacitors, for example, would be highly useful in power conditioners that convert dc to ac (or vice versa) and for adjustable-speed motor drives.

Johnson says longer-term multilayer capacitor applications include temporary energy storage for physics experiments such as high-energy lasers. Other potential applications include electric motor controls and energy ballasts for batteries in electric vehicles. Multilayer capacitors could deliver at least 100 times more power per unit of volume than anything available today for electric vehicles. Multilayer capacitors have the potential to be especially useful in regenerative braking, in which the considerable energy dissipated in braking is converted by a generator back into electricity to recharge capacitors (see *S&TR*, October 1995, p. 12). Realizing the potential of these large storage applications, however, is dependent upon substantial advances in multilayer capacitor fabrication processing, the next major research and development thrust of this work.

The present multilayer capacitor effort focuses on honing the manufacturing process, in particular, eliminating sources of contamination. When a layer is only a few atoms thick, even the tiniest dust particle can severely compromise capacitor performance, Johnson notes. The Livermore team is in early discussions with capacitor manufacturers and tooling companies to license this technology. Johnson says capacitor companies are particularly enthusiastic about the high energy density offered by multilayer capacitors because they could create entirely new markets.

Another application that may soon see commercial use is a multilayer foil made of reactive materials such as aluminum and nickel that would act as a highly portable welding tool. A piece of the multilayer could be slipped into a break or crack of metal, for example, and the foil would be lit with a match. The multilayer would quickly reach a temperature of up to 2,000°C to repair the crack. The multilayer materials would be chosen to produce different temperatures and rates of heat release to correspond to the material being welded.

Replacing Loud Compressor

Further away from commercial realization than multilayer capacitors or welding materials, yet with as many potential applications, are multilayer thermo-electrics. The thermo-electric effect uses heat transported by electrons to produce cooling with electrical current. Conversely, thermo-electric materials can also take advantage of diffusion of electrons in a thermal gradient to produce a current. Thermo-electric materials have no moving parts, so they can be miniaturized and may be very reliable. Current applications include temperature-sensing thermocouples, electric power generators for spacecraft, and portable food and beverage coolers.

The application of thermo-electric devices for cooling or heating large equipment is primarily limited by their efficiency, which is lower than that of conventional gas cycle refrigeration. However, the development of multilayers has sparked interest that multilayer thermo-electric materials may be the key to taking these devices into the commercial mainstream.

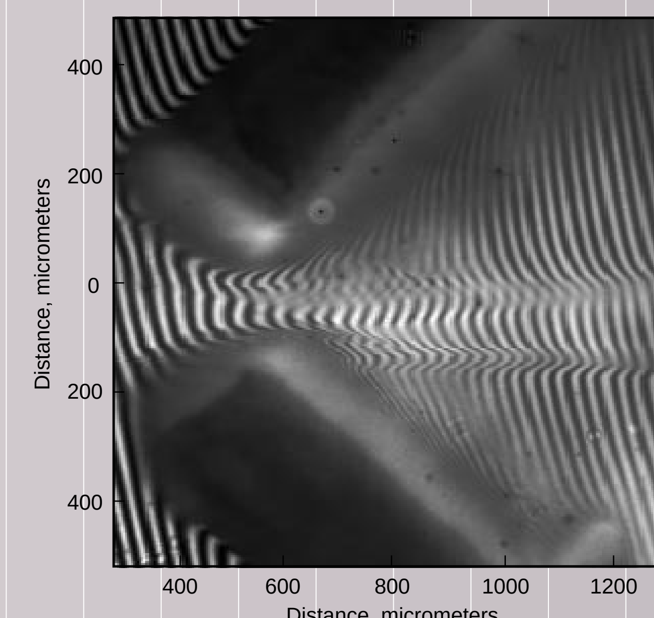
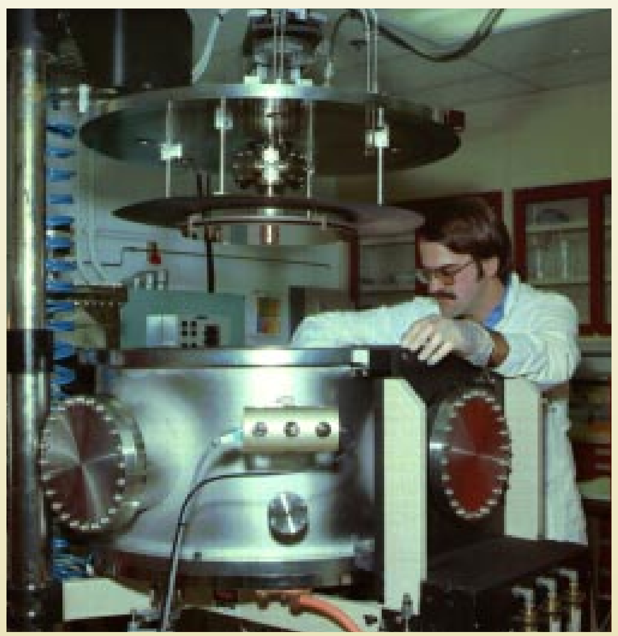


Figure 5. Where no other systems have worked, multilayered optics allow an x-ray interferometry measurement of electron-density, colliding-plasma experiments relevant to inertial confinement fusion.

Making Multilayers by Sputtering

In manufacturing multilayer materials, the Livermore team uses a process called sputtering, a technique created more than a century ago. Livermore materials scientist Troy W. Barbee, Jr., applied an advanced form of sputtering, called magnetron sputtering, to fabricating multilayers in the 1970s. Today, the semiconductor industry, for example, uses magnetron sputtering to deposit thin films on computer parts, and the machine tool industry uses the technique to apply hard coatings to cutting tools. It is even used to tint windows by forming thin, optically active interference coatings of metal upon glass and to coat jewelry with gold-appearing coatings.



Dan Noecker of Livermore's vapor-phase deposition laboratory adjusts atom-by-atom fabrication of a new class of materials for high-strength and high-temperature applications.

Most of the sputtering work at Livermore takes place at the vapor-phase deposition laboratory. Here, technicians secure a substrate to a table that rotates over two magnetron sputter sources of material for the multilayer. The table rotates at a predetermined speed, and the alternating layers are quickly built up as the substrate passes over first one material source and then the other. The sputter sources operate by bombarding plates of the material to be deposited with high-energy argon gas ions. The impact of these ions blasts atoms from the surface of the sources into the vapor and onto the substrate. As the multilayers revolve from magnetron source to magnetron source, the alternating layers, ranging from a few to many thousand, are sequentially formed.

Sputtering gives a constant deposition rate in which the thickness of each layer is precisely determined by the distance of the substrate from the sources and the time the substrate spends over each source. The technique enables layer thickness control of one-hundredth of an atomic diameter for up to one thousand layers. This process can also achieve a layer thickness uniformity of better than 0.7% (approximately one-thirtieth of an atomic diameter) over a 10-centimeter-diameter substrate (see photo at left).

To help evaluate the performance of multilayers, researchers use a soft x-ray diffractometer that was designed and built at Livermore. It is contained in a vacuum chamber and scans the surface of a sample under computer control to provide a map of reflectivity uniformity. In addition, samples are sectioned and thinned for electron microscope analysis to inspect interface sharpness, layer-to-layer uniformity, and layer smoothness.

"Multilayers may have the potential to increase the efficiency of thermo-electric materials by a factor of three or four," says Livermore material scientist Andrew Wagner. He notes that an efficient multilayer thermo-electric cooling system could replace the conventional large, heavy, and noisy refrigerator compressor that often cycles on and off. A multilayer thermo-electric device would be silent, operate continually, and not require environmentally unacceptable hydrofluorocarbon gases.

Wagner, together with researcher Joseph Farmer and technicians Ronald Foreman and Leslie Summers, has conducted basic research on the feasibility of producing multilayer thermo-electric materials, which, in that application, would require millions of alternating layers of conducting and insulating materials.

Another area of active development is using multilayers as optics for imaging sources of neutrons. This application has important implications for the Department of Energy's Stockpile Stewardship and Management Program because high-energy neutron radiography can be used to image low-density materials for surveillance of stockpile nuclear assemblies. For physics research applications, the Livermore team is collaborating with the University of Illinois on a new neutron beamline that makes use of multilayers as optics for neutrons from a variety of sources.

The neutron work is another application for multilayers. But multilayers have that way about them: they force new thoughts about making materials—this time on the atomic scale—and finding applications that will benefit society.

—*Arnie Heller*

Key Words: multilayers, nanostructured materials, sputtering, thermo-electrics, x-ray optics, x-ray lasers.

For further information contact Troy W. Barbee, Jr. (510) 423-7796 (barbee2@llnl.gov).

About the Scientist

TROY W. BARBEE, JR., is a materials scientist at the Laboratory, focusing on the science, technology, and application of multilayers. Before arriving at Livermore in 1985, Barbee was at Stanford University, where he was a senior research associate in the Department of Materials Science and Engineering and laboratory director at the Center for Materials Research. Barbee also was a visiting professor in San Jose State University's Materials Science Department and at the Stanford Research Institute. Barbee received his B.S. in metallurgical engineering and his M.S. and Ph.D. in materials science engineering from Stanford.

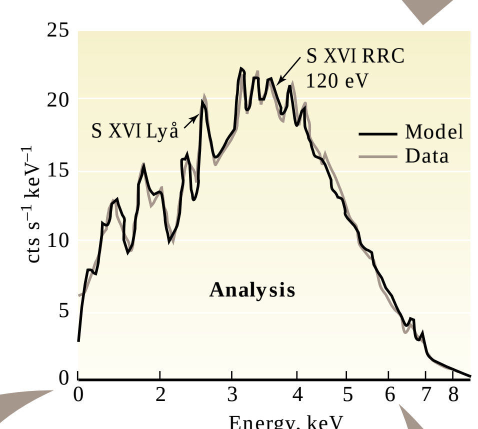
Marrying Astrophysics with the Earth

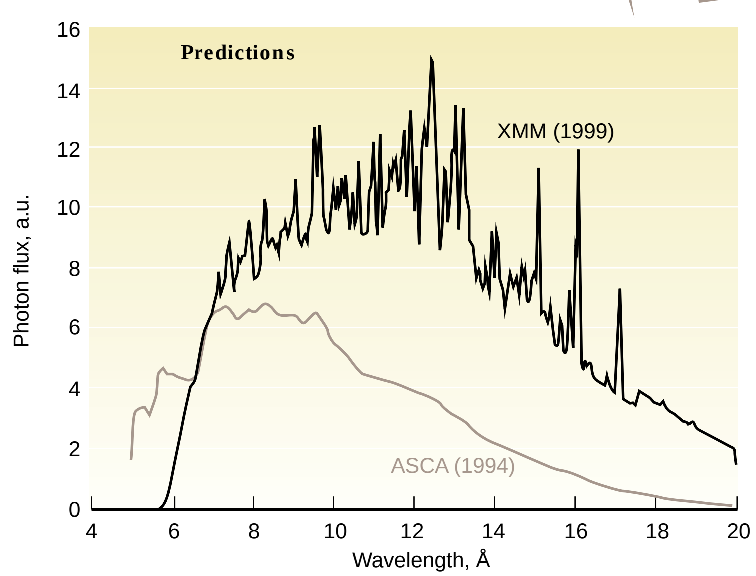
ASTROPHYSICISTS, it could be said, have the universe for a laboratory. And what a laboratory it is, with conditions that cannot be duplicated in an earthly setting—nearly perfect vacuum, extraordinary temperatures and pressures, and enormous distances. But the very vastness that provides these conditions makes study of astrophysical phenomena difficult.

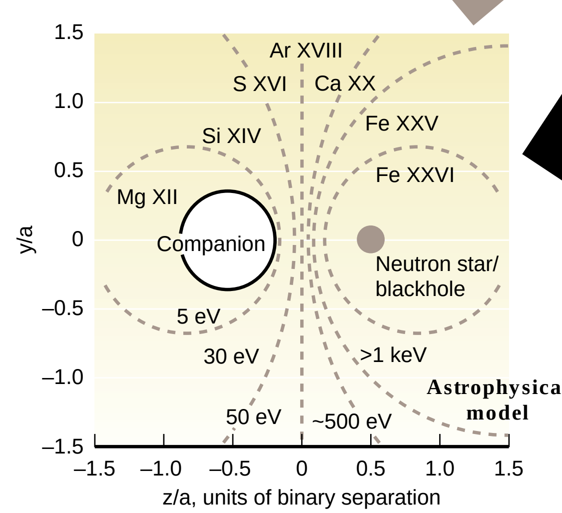
The observable phenomena in the universe often are the result of complex interplay between several physical processes, each of which operates over a scale that cannot be controlled or modified by the experimenter. Obviously, a researcher cannot perform any type of controlled experiment on objects outside the solar system. Theory and computer simulations must be called upon to fill the void left by the absence of controlled experiments.

To complement their observations, astrophysicists must leave their laboratory of the universe and return to the more modest facilities on Earth. Lawrence Livermore, with its advanced computational resources and laser plasma research capabilities, is a natural place to conduct this research.

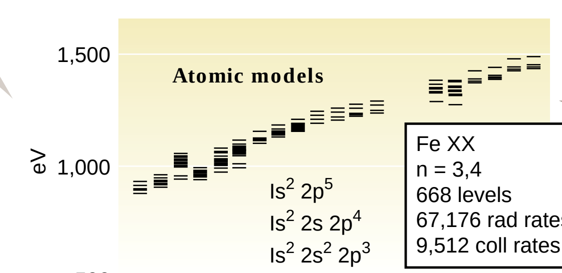
Occupying that particular spot on Earth is astrophysicist Duane Liedahl. Along with astrophysicist Christopher Mauche, Liedahl is working to shed some light on the properties of cosmic x-ray sources while also using the data from space-borne experiments to refine and improve the accuracy of computer simulations of these phenomena.

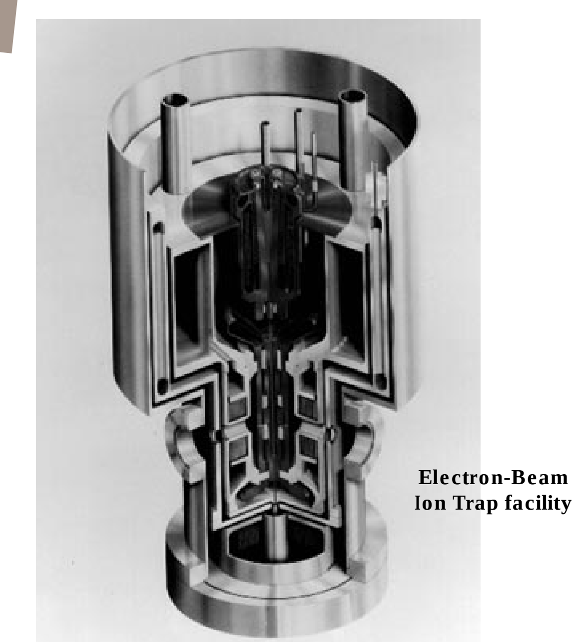






The interplay of astrophysical research at Lawrence Livermore benefits from unique facilities and capabilities.





Works in Both Directions

The goal of Liedahl's project is to improve and experimentally benchmark a sophisticated suite of computational tools for modeling the radiative properties of astrophysical plasmas. Liedahl and his colleagues are approaching solutions to problems in astrophysics along four avenues: astronomical observations, laboratory experiments, computer simulations, and theory (see figures for the interplay of these approaches). Historically, laboratory experiments have been performed to identify elements by measuring wavelengths that can be matched to stellar spectra. But the interaction of computer simulations and laboratory experiments works in both directions. Data from experiments are used to refine the computer models, and the computer models help scientists understand the problem and develop theories.

Especially now, in the Department of Energy's nuclear-test-free Stockpile Stewardship and Management Program (SSMP), x-ray astrophysical observations and related modeling will play an essential role in benchmarking our ability to understand the physics of thermonuclear weapons because much of the physics is common to both fields. For example, high-quality x-ray observations from satellites may well be the source of future data supporting the SSMP. Lawrence Livermore's current leadership position in modeling x-ray sources is a result of its work to understand high-energy-density physics, which is required to predict the behavior of weapons.

"In short, theory draws from computer simulation, and computer simulation draws from experiment," Liedahl says. "Livermore's computational modeling for the SSMP will benefit from the improved atomic models that allow us to verify the accuracy of our computational models."

Liedahl also works closely with Peter Beiersdorfer of Lawrence Livermore's Electron-Beam Ion Trap (EBIT) facility. At EBIT, measurements of electron-impact ionization, excitation, and recombination can be made that are crucial to understanding high-temperature plasmas. These experiments yield data that can be used to verify the completeness and accuracy of atomic models of the emission properties of various elements involved in astrophysical processes. Liedahl and his colleagues use these improved atomic models, along with data from space-borne experiments, to calibrate astrophysical models. In turn, these improved models allow scientists to refine theories about the behavior of plasmas and highly charged ions—essentially, our basic understanding of matter in extreme environments.

Science Born by Chance

"The science of x-ray astronomy was born in 1962 during a rocket-based experiment to detect x-ray-induced fluorescence on the lunar surface," Liedahl says. "By chance, the Moon's orbit passed close to the position of the star Scorpius X-1, and a dramatic increase in flux—changes in the radiation emitted—was detected. This discovery indicated that x-ray observations could reveal new and exotic cosmic phenomena that are largely invisible to conventional optical and radiotelescope techniques."

Our solar system is inside a million-degree ball of gas—purportedly carved out by an ancient supernova—that is radiating x rays. The Sun, because of its proximity to Earth, is our brightest source of x rays. However, most objects in the universe—stars, supernova remnants, galaxies, and black holes—also produce x rays. Scorpius X-1 is a much brighter source of cosmic x rays, 100 billion times stronger than our Sun. But it is also 100 million times more distant than our Sun, and the apparent brightness decreases with the distance squared.

"We've found that x-ray spectroscopy is a very useful measuring tool for cosmic plasmas," Liedahl continues. "However, its real usefulness in astrophysics depends on significant improvements in its sensitivity and capabilities. This usefulness will be realized only after we can make significant improvements in our spectroscopic modeling tools. Some of the unique characteristics of cosmic plasmas include ultralow density (down to 10^{-3} atoms per cubic centimeter, roughly a million times better than the best vacuum achievable on Earth), high radiation-energy density, ultrahigh magnetic fields, relativistic gas flows, and very-high-temperature shock waves."

Traditionally, spectroscopy has been used to identify elements. As data quality improves, the demands placed on spectroscopic models will become much more stringent because astrophysicists will want to know the physical conditions of the plasmas in which the elements exist. Liedahl's approach seeks to identify the detailed behavior of atoms in a wide range of physical environments. His team uses these data to build atomic models to hypothesize about the composition and physical conditions of cosmic plasmas. Then the team uses these atomic models to refine the astrophysical models and improve accuracy.

"Atomic physics operates the same way on Earth as it does in space," Liedahl says. "By improving our atomic models under conditions we can control, we develop the confidence to apply them to more complex astrophysical environments, which we can't control."

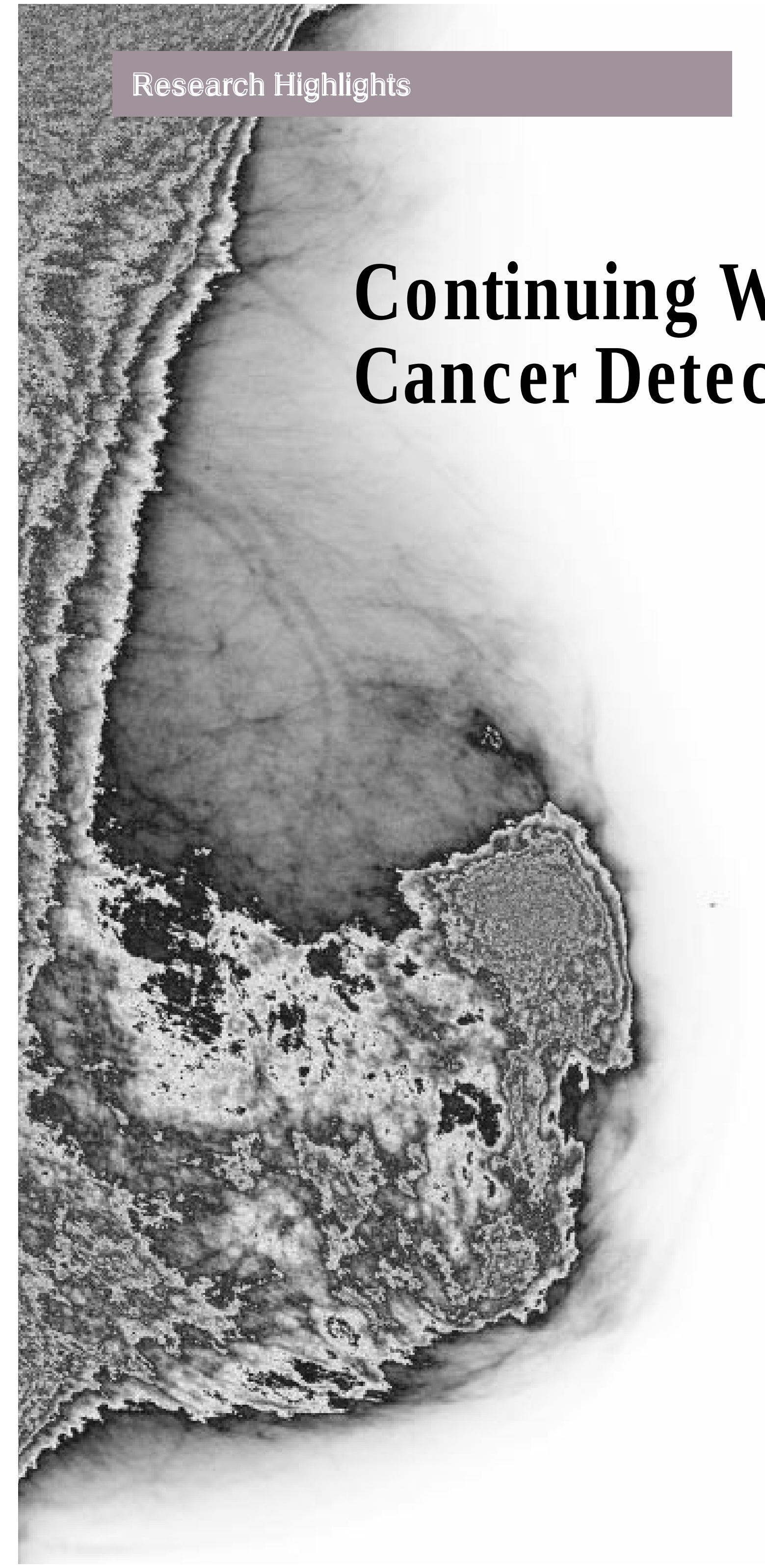
Liedahl's work helps further our understanding of both the relevant atomic physics and the astrophysics of the sources themselves. Unfortunately, acquiring high-quality x-ray spectra of cosmic sources poses experimental challenges because the sources are extremely faint, and observations must be conducted from space. Although the interstellar medium is an extremely good vacuum, it is not perfect and thus is not entirely transparent to x rays. However, our ability to collect high-quality data will be dramatically improved in the near future when new satellites are launched. The U.S. project AXAF; the European XMM, for which Lawrence Livermore collaborated with the University of California at Berkeley to construct the grating arrays in the spectrometers; and Japan's Astro-E will provide more than order-of-magnitude improvements in sensitivity and resolution. "We also are expecting to achieve great improvements in the versatility of x-ray spectroscopy analysis tools," Liedahl adds.

The tremendous quantity of data expected from the new satellites launched by the U.S., Europe, and Japan will provide a basis for significant advances in our understanding of a wide range of phenomena. Lawrence Livermore's ability to coordinate large-scale technology, formidable computational power, and an experienced team of researchers can have a major impact on the astrophysics community by helping to maximize the scientific yield from major space missions.

—Sam Hunter

Key Words: astrophysics, astrophysical plasmas, atomic physics.

For further information contact Duane Liedahl (510) 423-9647 (duane@serpens.llnl.gov).



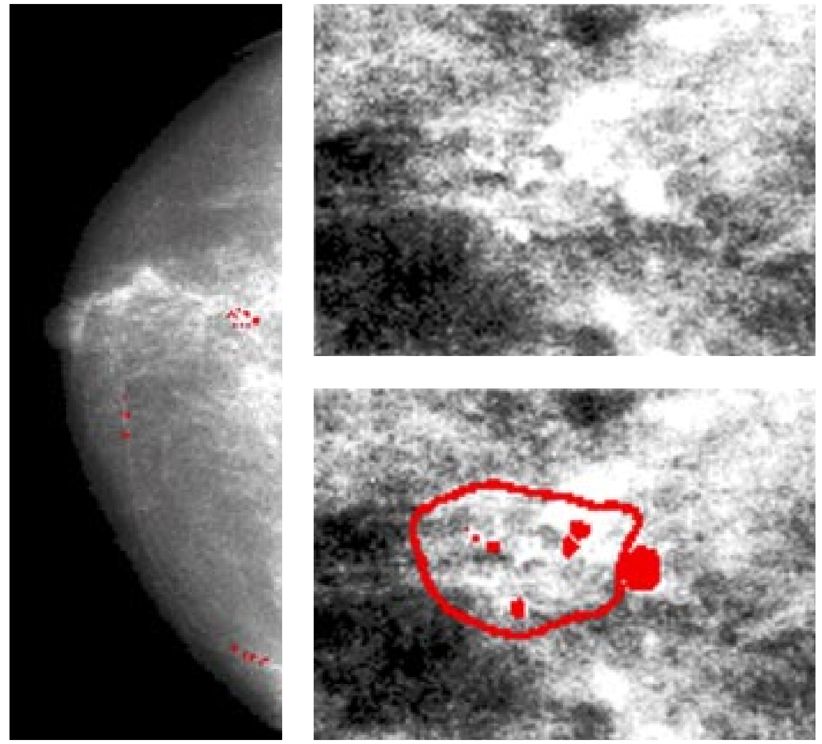
Continuing Work in Breast Cancer Detection Technologies

NEITHER cause nor cure is known for breast cancer, a serious disease that may affect one out of every nine women in the United States. Early detection is the only known means for increasing a victim's chances for survival; mammography is currently the best means of cancer detection in women showing no symptoms.

The power of mammography is proven. Yet, some breast cancers are missed, usually because the cancer is not imaged or because its indications in the image are too subtle to be recognized. The difficulty of visually detecting the cancer's subtle warning signs (in particular, sorting out significant microcalcifications—the calcium-rich deposits that are clues to malignant breast cancers) point to the need to improve image quality and the means of interpreting mammograms.

In 1991, help for improved breast cancer detection came from an unexpected source—Lawrence Livermore scientists and engineers working on national defense projects. They began to recognize that their technologies had important medical applications. Clint Logan, an engineer with expertise in materials imaging, an important aspect of nondestructive evaluations (see article on p. 4 of this issue), proposed using digital computer analysis on film mammograms. His proposal was carried out in a three-part project, first described in *Energy and Technology Review*, Nov.–Dec. 1992, pp. 27–36. The first part was to digitize mammograms, that is, to convert the data on the film record into numbers, applying a high spatial and contrast resolution to the entire mammogram. When digitized, data could be displayed with a variety of contrast settings, which allow clearer viewing than film studied over a light box.

The second part of this work was to develop computer algorithms to automatically detect microcalcifications in the digitized mammograms. The objective was to provide a "mammographer's assistant" that would quickly and objectively detect and flag microcalcifications for radiologists and doctors. The algorithm, developed by biomedical image processing specialist Laura Mascio, first performs two types



The panel on the left is a mammogram with calcifications. The area containing calcifications is magnified in the two panels on the right, (top) without annotation marks and (bottom) with the overlying annotation marks.

of high-frequency analysis on a digitized image. One procedure extracts contrast (intensity difference) information, saving structures that have abrupt changes in brightness (from edges, for example) and are larger than several pixels in size. The other procedure extracts spatial, or size, information and thus saves small, textured structures.

Adding together what has been preserved by the two high-frequency analyses produces an image that is brightest where it contains detail common to both. When a selective erosion or enhancement (SEE) filter is applied over this image, it further reinforces image pixels that show strong evidence of belonging to a microcalcification and erodes pixels that show otherwise. The method developed by Mascio forms the basis of a computer algorithm that distinguishes between microcalcifications and mimicking spots, such as specks and flecks on the film. It was the first microcalcification-detection algorithm to use a gray-scale morphology for extracting frequency and texture information. It served as a model for further development of mammography screening algorithms.

The third part of the project was the design of a filmless, directly digital mammography system. Such a system would provide information and detection superior to the conventional film-based system, yet it would require a lesser x-ray dose to the patient. In collaboration with Fischer Imaging Corp., Logan and Jose M. Hernandez, another Livermore engineer, developed a digital screening unit with a novel x-ray source that can be adjusted for each patient's body size and an image detector that uses a charge-coupled device camera. Early trials indicate that this system yields images with better signal-to-noise ratios than conventional x rays. And because the images are digital, they can be manipulated in terms of contrast, magnification, and area of interest for the best view.

Improving Detection Algorithms

Algorithms having better sensitivity lead to earlier diagnosis of breast cancer and improved long-term survival. Algorithms having improved specificity (that is, they can separate suspicious spots that turn out to be benign from those that are malignant) mean fewer unnecessary biopsies and thereby less cost and less patient anxiety. However, sensitivity must be retained when improving specificity; otherwise, early, curable cancers could be missed.

In recent years, several other institutions have developed algorithms for computer detection of breast cancer. Until recently, however, there has been no way to compare the different algorithms because each research group has tested its own algorithms on different sets of film images that have varying degrees of diagnostic difficulty. Comparison of their relative performance is important because, in many cases, only partial records have been digitized.

To provide a standardized algorithm evaluation tool, Mascio and other Lawrence Livermore scientists began collaborating in 1995 with researchers from the University of California at San Francisco (UCSF) to compile a library of mammograms that could be used to test detection sensitivities and specificities. They used UCSF screening data of patients whose identities had been obscured. A total of 50 patient cases were selected to represent different categories: 5 normal, average, healthy cases; 5 normal but difficult cases (e.g., with implants, asymmetric tissue); 20 cases with obviously benign microcalcifications; 12 cases of suspicious but benign microcalcifications; and 8 cases of a biopsy-proven, malignant cluster of microcalcification. A radiologist then worked with the Livermore team, using all available clinical information, to annotate the mammograms.

The library is a first step toward a meaningful comparison of microcalcification-detection algorithms. The completely digitized mammograms have been put onto a CD/ROM in binary data format (see photos, p. 24) to make them available for other researchers. Images will be available soon on Lawrence Livermore's Web site (http://www.llnl.gov/).

Another problem with digital mammography is that its very large data files can present storage and processing problems, especially for small clinics with limited computer resources. Digital mammography usually records four views per patient, each taking up 200 megabytes of computer memory. To make this technology more efficient and practical, Mascio has proposed a way to compress mammogram files by factors of 10 to 30 without sacrificing image detail or diagnostic accuracy. Furthermore, it requires no decompression time when data are retrieved for viewing or analysis.

Generally, the more data are compressed, the more the data values differ from their original form once they are decompressed. Mascio's approach, called dynamically lossless compression, avoids wholesale data compression and instead selectively assigns the most data space (i.e., provides the highest spatial resolution) to the features that must be depicted in the most detail, such as detected microcalcifications. Less important features—such as background, healthy, nonglandular tissue—are given coarser resolutions. Thus, an image may contain many different spatial resolutions, each appropriate to the significance of the particular feature, and all based on mammogram-specific knowledge. This compression approach parallels human visual inspections of mammogram film—radiologists use a magnifying glass to get a higher-resolution view for studying microcalcifications, but they inspect larger abnormalities without the magnifier and by standing at a distance from the mammogram.

For the Next-Generation System

As a result of this collaboration, four direct-digital screening systems produced by Fischer Imaging Corp. have been installed at sites around the U.S. Even as they are being introduced to the general population, Jeff Kallman, a Lawrence Livermore engineer, is starting research on the sensors for a new generation of mammography screening. He proposes to generate three-dimensional images of soft breast tissue speedily and painlessly with linear ultrasonic diffraction tomography. Because breast tissue has neither large sonic variations nor appreciable multiple scattering, linear imaging techniques can be used. There is some evidence that cancerous tissue has sound speed and attenuation properties different from normal tissue; the hope is that such an imaging system will be able to distinguish between them.

Data collection would be done while the breast is immersed in water or gel, bypassing the breast compression that makes conventional mammography uncomfortable and even painful for some women. Furthermore, it would involve no ionizing radiation, thus eliminating concerns about x-ray exposure. With appropriate data-acquisition technology, which Kallman is investigating, breast cancer screening in the future would be done quickly as well as safely.

— Gloria Wilt

Key Words: breast cancer, data compression, detection algorithms, digital mammography, linear ultrasonic diffraction tomography, mammogram library, microcalcifications.

For further information contact J. Patrick Fitch (510) 422-3276 (jpfitch@llnl.gov).

Patents

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

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Anthony F. Bernhardt Robert J. Contolini Vincent Malba Robert A. Riddle	**Repairable Chip Bonding/Interconnect Process** U.S. Patent 5,653,019 August 5, 1997	A chip-on-sacrificial-substrate technique, using laser processing, for mounting and interconnecting chips. Transmission lines or leads are formed on the top or horizontal surface and the sides or vertical surfaces of a chip, ending in a gull wing configuration interconnect at the bottom of the chip for subsequent solder or compression bonding to a substrate or board. The leads or lines may be coplanar transmission lines. The chip or die attachment and lead bonding are repairable so that chips can be removed without damage to any component.
Abraham P. Lee M. Allen Northrup Paul E. Ahre Peter C. Dupuy	**Polymer Micromold and Fabrication Process** U.S. Patent 5,658,515 August 19, 1997	An extrusion micromold, i.e., a singular, hollow device that can be tailored to be thermally uniform and has micrometer-sized features. The mold is a metal shell with a passageway having an inner contour profile with diameters on the order of tens to hundreds of micrometers, and an outside diameter of 1 to 8 millimeters. The features of this mold are made by using a sacrificial mandrel that is machined to define the desired contour profile of the mold, coated to form an outer shell or mold body, and then selectively etched away, leaving a mold in the form of a hollow tube with the desired inner contour profile.
Anthony F. Bernhardt Robert J. Contolini	**Method of Forming a Spacer for Field Emission Flat Panel Displays** U.S. Patent 5,658,832 August 19, 1997	A method for forming spacers that uses a dielectric mold formed on a substrate and mold release agent. The spacers are formed of dielectric-containing aerogels or xerogels. A gel precursor is applied to the mold, filling holes that expose the substrate. A release agent is applied to the mold prior to precursor application, to ease removal of the mold after formation of the dielectric spacer. The shrinkage of the gel during solvent extraction also improves mold removal. The final spacer material is a good dielectric, such as silica, secured to the substrate. The resulting spacers have the capability to withstand atmospheric pressure, which tends to collapse the space between the phosphor faceplate and the field emitter cathode or baseplate in a flat panel display, provide standoff against high voltage imposed between the two plates, and are inexpensive to fabricate.
Jerald A. Britten	**Moving Zone Marangoni Drying of Wet Objects Using Naturally Evaporated Solvent Vapor** U.S. Patent 5,660,642 August 26, 1997	A contactless drying process whereby a surface tension gradient driven flow (a Marangoni flow) is used to remove the thin film of water remaining on the surface of an object following rinsing. The process passively introduces minute amounts of alcohol (or other suitable material) vapor in the immediate vicinity of a continuously refreshed meniscus of deionized water or another aqueous-based, nonsurfactant rinsing agent. Used in conjunction with cleaning, developing, or wet etching applications, the rinsing coupled with Marangoni drying provides a single-step process for cleaning, developing or etching, rinsing, and drying objects such as flat substrates or coatings on flat substrates without using heat, forced air flow, contact wiping, centrifugation, or large amounts of flammable solvents.
Thomas E. McEwan	**Window-Closing Safety System** U.S. Patent 5,661,385 August 26, 1997	A safety device with a wire loop embedded in the glass of a passenger car window and routed near the closing leading edge of the window. The wire loop carries microwave pulses around the loop to and from a transceiver with separate output and input ports. An evanescent field, an inch or two in radius, is created along the wire loop by the pulses. Just about any object coming within the evanescent field will dramatically reduce the energy of the microwave pulses received by the transceiver. Such a loss in energy will cause electrical interlocks to halt or reverse a power window motor that is actively trying to close the window.

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Abstracts

Advancing Technologies and Applications in Nondestructive Evaluation

The methods used to inspect and evaluate materials, devices, and products are now based on imaging systems that collect digital data and process and interpret them through specially developed computer algorithms. Lawrence Livermore's Nondestructive and Materials Evaluation Section has been developing a wide range of imaging systems, implementing them through a range of technologies, including digital radiography, computed tomography, machine vision, ultrasonics, and infrared computed thermography. Applications of these various technologies are described in the article. They demonstrate the range and increasing flexibility of the concept of nondestructive evaluation.

Contact:
Clint Logan (510) 422-1888 (logan2@llnl.gov).

Atomic Engineering with Multilayers

Composed of alternating layers of two different materials as thin as a few atoms, multilayers offer extraordinary strength, hardness, heat resistance, and unexpected new properties. At Lawrence Livermore National Laboratory, researchers are pioneering new applications for these materials. They have synthesized multilayers from 75 of the 92 naturally occurring elements in elemental form or as alloys or compounds. The team has emerged as one of the world leaders in multilayer science and its application and has forged partnerships in government and industry to develop and apply multilayer materials. The article describes current and future applications of multilayers, including high-strength aircraft engine parts, mirrors for astronomical imaging, high-energy capacitors, and thermo-electric devices.

Contact:
Troy Barbee, Jr. (510) 423-7796 (barbee2@llnl.gov).

U.S. Government Printing Office: 1997/683-051-60036