Nondestructive Evaluation

Also in this issue:
- Advances in Multilayers
- Down-to-Earth Astrophysics
- Breast Cancer Detection
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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Advancing Technologies and Applications in Nondestructive Evaluation

Lawrence Livermore’s Nondestructive and Materials Evaluation Section has been developing breakthrough technologies that serve specialized scientific inspection needs and stretch the concept of nondestructive evaluation.

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Livermore researchers have developed multilayers with more than 75 different elements to improve the performance of precision materials. So close to perfection, multilayers from Livermore are in great demand.

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.

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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.
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 L. 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.

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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 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, the next four to five years and an estimated $70 million for commercialization and manufacturing applications of the refillable zinc-air—technology and recovery unit.

Zinc-air fuel-cell modules—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 refillable, and the spent zinc can be recycled into zinc powder.

The agreement 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 uninterruptable power supplies for hospitals and airport rescue vehicles.

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

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NIF construction contracts awarded

Nielson Dillingham Builders, Inc., of Pleasanton, California, has been awarded a $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 54-meter, $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. Scaled 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.

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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.

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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.

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 called 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 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.

Figure 2. Prototype ultrasonic scanning system (with sample pistons atop the monitor) that will be used for detecting very small casting defects.
Dual-band measurement technique that simultaneously uses short wavelengths has 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 tomography 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. Lawrence Livermore and 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, high-resolution, x-ray imaging 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 quantify 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.

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Figure 3. Assaying a container such as this transuranic waste drum is made easier with LIL-100 active and passive computed tomography (APCT). 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, radiographs 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.
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. Insert 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.

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.

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

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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...
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 thrust output of gas turbines 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), 3,550 layers of a copper–zirconium mix (each layer is 100 angstroms, or 18 atoms, thick), and 375 layers of layers of a copper–zirconium mix (each layer is 325 angstroms, or 156 atoms, thick) and 3,550 layers of a copper–zirconium mix (each layer is 18 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 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 molybdenum, 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 re flectivity, minimizing the demands on the stability of the mating sputtering process. These materials proved to be very effective and have been a staple of the interferometry technique. 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) illustrate the advantages gained by adding even a small quantity of a different material.
predicted for a perfect structure.

the multilayer is essentially equal to that shows that the measured reflectivity of 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

The image (Figure 3a) shows that the...plasmas created by high-power lasers. The technique provides the only workable diagnostic tool to directly

Multilayer optics make possible "Using multilayer 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 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 left 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 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.

Figure 5. Where no other systems have worked, multilayered optics allow x-ray interferometry measurement of electron-density, colliding-plasma experiments relevant to inertial confinement fusion.
“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 neutron work at Livermore and elsewhere. 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.

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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.

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.

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.

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.

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

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.

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Electron-Beam Ion Trap facility
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 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.

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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 malignent 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 film. 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
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...
Patents

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<tr>
<th>Patent issued to</th>
<th>Patent title, number, and date of issue</th>
<th>Summary of disclosure</th>
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<tr>
<td>Anthony F. Bernhardt</td>
<td>Repairable Chip Bonding/Interconnect Process U.S. Patent 5,653,019 August 5, 1997</td>
<td>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 co-planar transmission lines. The chip or die attachment and lead bonding are repairable so that chips can be removed without damage to any component.</td>
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<td>Robert A. Riddle</td>
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<td>Abraham P. Lee</td>
<td>Polymer Micromold and Fabrication Process U.S. Patent 5,658,515 August 19, 1997</td>
<td>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 3 to 6 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.</td>
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<tr>
<td>M. Allen Northrup</td>
<td>Method of Forming a Spacer for Field Emission Flat Panel Displays U.S. Patent 5,658,832 August 19, 1997</td>
<td>A method for forming spacers that use a dielectric mold formed on a substrate and mold release agent. The spacers are formed of dielectric-containing sponges or spongiform. 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 shrinking 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.</td>
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<td>Paul E. Ahre</td>
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<td>Peter C. Dupuy</td>
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<td>Robert A. Riddle</td>
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<tr>
<td>Anthony F. Bernhardt</td>
<td>Moving Zone Marangoni Drying of Wet Objects Using Naturally Evaporated Solvent Vapor U.S. Patent 5,640,642 August 26, 1997</td>
<td>A contactless drying process whereby a surface tension gradient driven flow (a Marangoni flow) is used to thin the 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, non-flammable rinsing agent. Used in conjunction with cleaning, developing, or 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.</td>
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<td>Jerald A. Britton</td>
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<td>Abraham P. Lee</td>
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<td>Jerald A. Britton</td>
<td>Window-Closing Safety System U.S. Patent 5,641,385 August 26, 1997</td>
<td>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 top 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 pulse, 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.</td>
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<td>Thomas E. McEwan</td>
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<td>Patents and Awards</td>
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<td>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.</td>
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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.

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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.

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