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

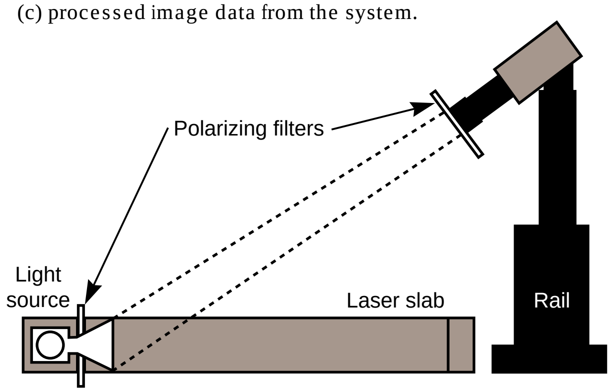
Graham Thomas, group leader for ultrasonics and surface techniques, has also instituted an automated inspection method, using ultrasonic technology, to replace "eyeball" inspections. He did this as part of a collaboration with private industry in work that also included product development monitoring, 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.

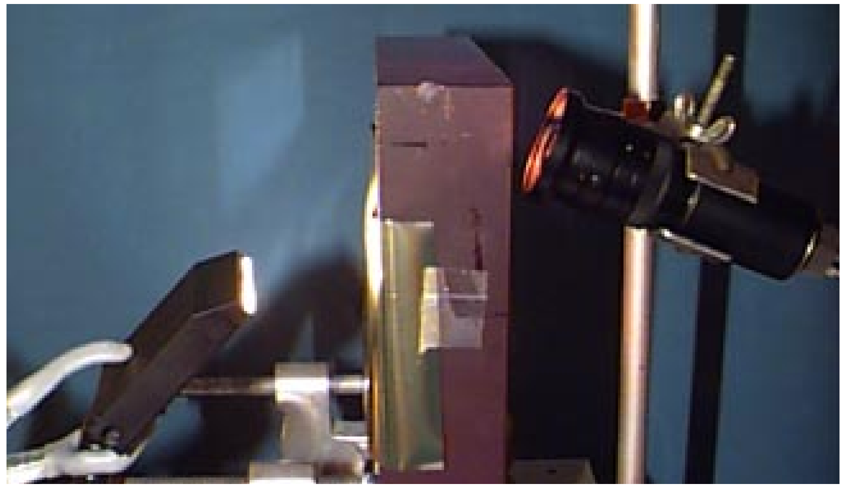
Thomas and his colleagues' first task was to select an inspection technique to assure the quality of the preforms. They tried five techniques (x-ray computed tomography, digital radiography, optical imaging, ultrasonic testing, and infrared imaging), discovering that while all can effectively detect 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.



(a)



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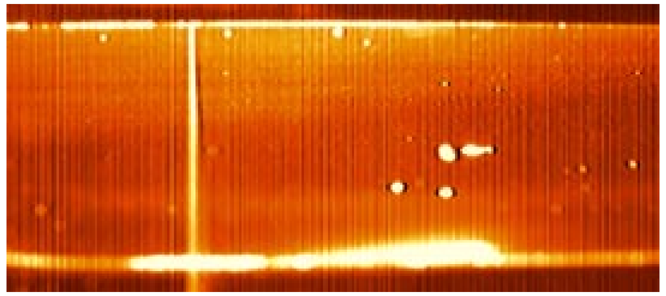

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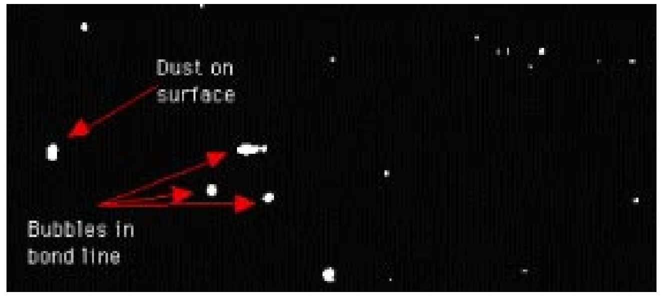

One manufacturing-line inspection study, still under way, will determine how to implement an ultrasonic system to detect porosity defects in pistons. Such defects cause piston surfaces to deteriorate during finish machining. If defective pistons could be culled before the machining process, production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

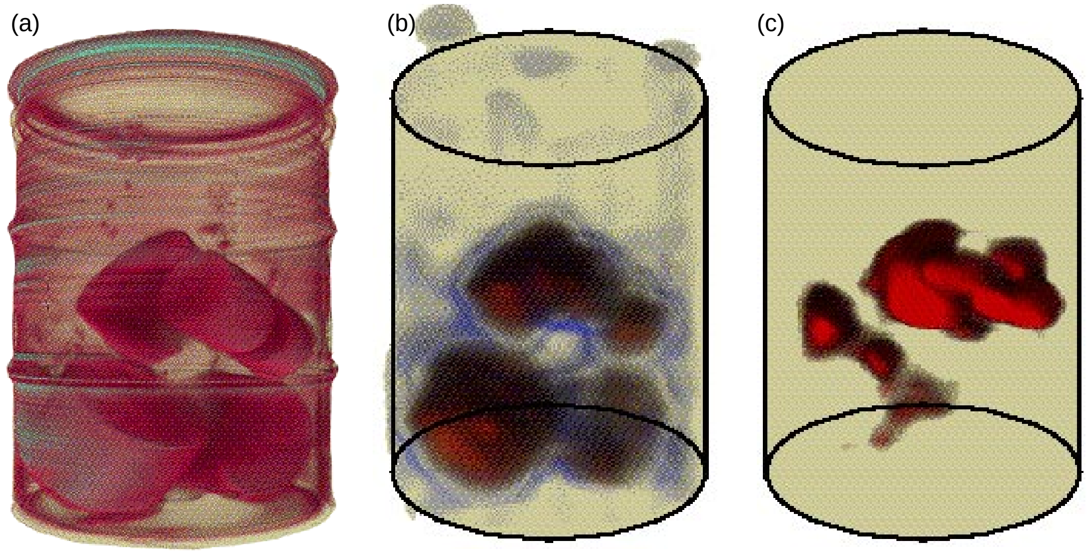

Figure 3. Assaying a container such as this transuranic waste drum is made easier with LLNL's active and passive computed tomography (A&PCT). Here, data are shown in rendered views of (a) a typical industrial transmission tomograph at high spatial and energy resolution, (b) the active data set, and (c) 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.

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.

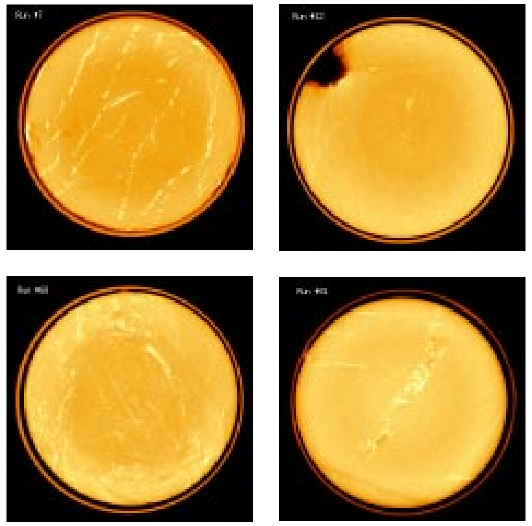

Figure 4. Radiographs of 1.5-meter cores of Geysers rock within sealed aluminum coring tubes show differing degrees of mineralization, texture, and fracturing.

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

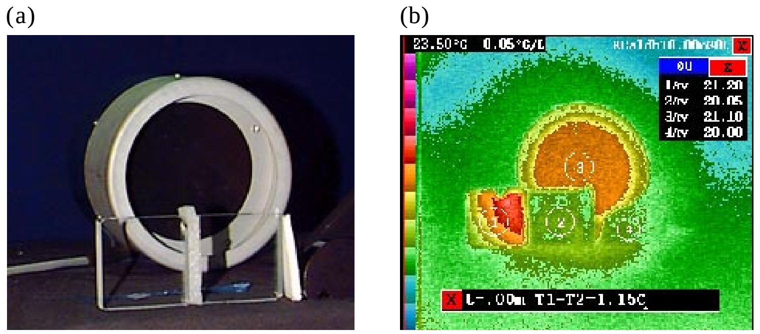
(a) (b)

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.

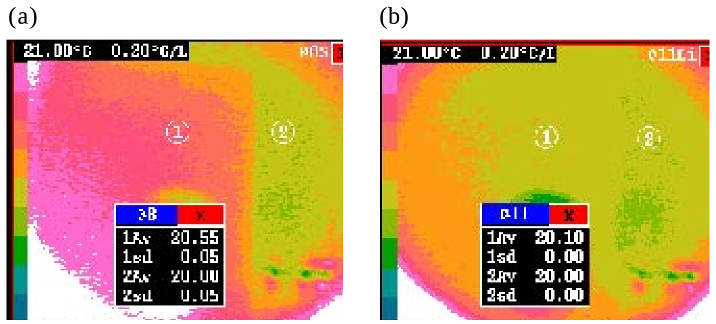
(a) (b)

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.

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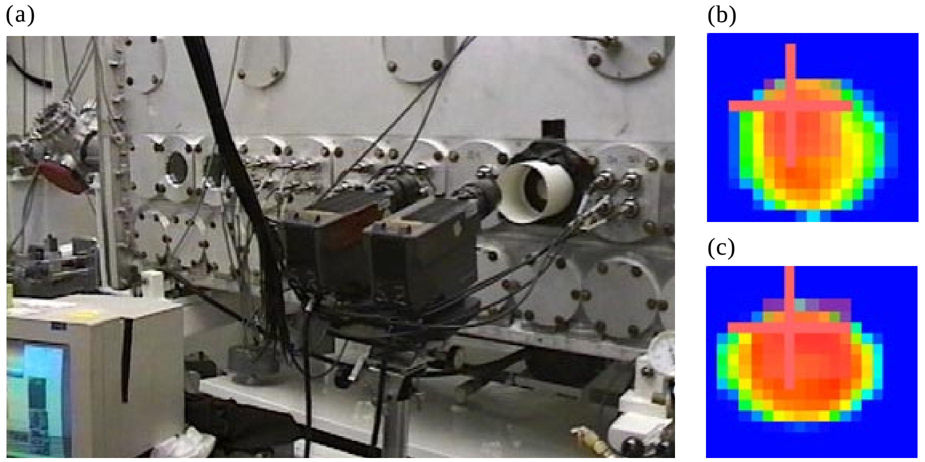
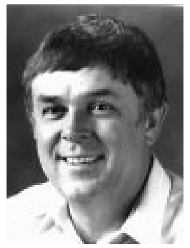

(a) (b) (c)

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.