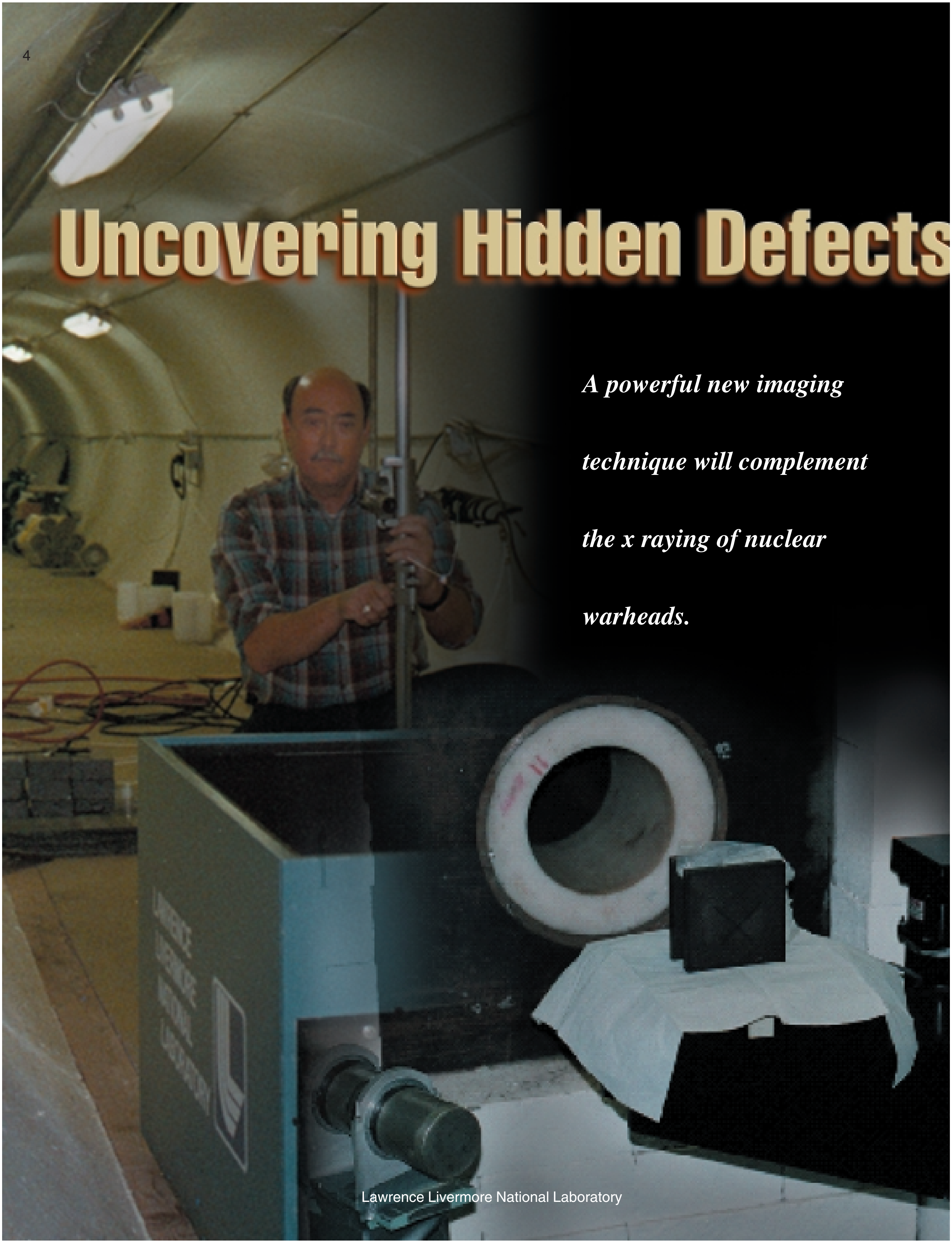
Uncovering Hidden Defects

A powerful new imaging technique will complement the x raying of nuclear warheads.



with Neutrons

FROM the dentist's office to the aircraft hangar, the use of x rays to reveal the internal structure of objects is a time-honored practice. However, during the past few decades, several industries have begun to use thermal, or low-energy, neutron imaging as a complementary technique to x-ray imaging for inspecting objects without taking them apart. Now Lawrence Livermore researchers have demonstrated the power of using high-energy neutrons as a nondestructive inspection tool for evaluating the integrity of thick objects such as nuclear warheads and their components.

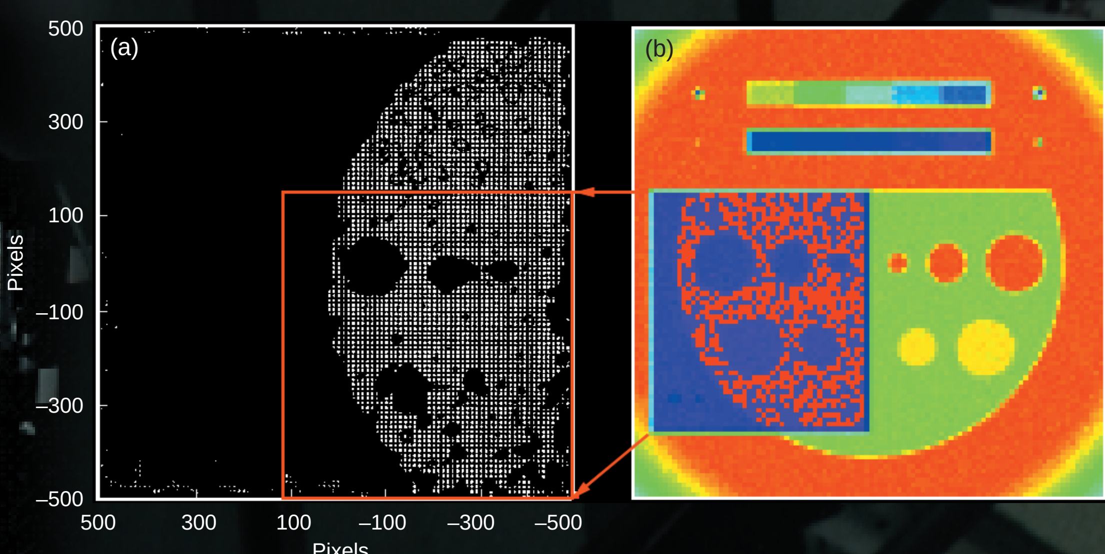
Experiments conducted over the past four years at Ohio University by a Lawrence Livermore team have demonstrated high-energy neutron imaging's considerable promise in probing the internal structure of thick objects composed of materials that are essentially opaque to x rays. Indeed, the results have proven more successful than computer models first indicated or than Livermore physicists had expected.

The neutron imaging project is funded through the Enhanced Surveillance Campaign, a key element of the nation's Stockpile Stewardship Program, which is managed by the National Nuclear Security Administration (NNSA) within the Department of Energy. Nondestructive surveillance—the search for anomalies from cracks to corrosion in aging stockpiled nuclear weapons systems to assure their continuing safety and reliability—is much more cost-effective than disassembling a warhead. Hence, the development of improved nondestructive surveillance techniques is crucial to the success of stockpile stewardship in the absence of nuclear testing and to the nation's defense.

Nondestructive surveillance relies on a range of techniques, including x-ray imaging. X rays are adequate for inspecting the condition of parts composed of what scientists call high-*Z* (high-atomic-number) materials such as lead, tungsten, and uranium. However, x-ray imaging is not always effective in revealing voids, cracks, or other defects in so-called low-*Z* (low-atomic-number) materials such as plastics, ceramics, lubricants, and explosives when these materials are heavily shielded by thick, high-*Z* parts. (See the box on p. 6.)

Neutrons Complement X Rays

Clearly, what is needed is a way to image shielded low-*Z* parts as a means to complement standard x-ray imaging

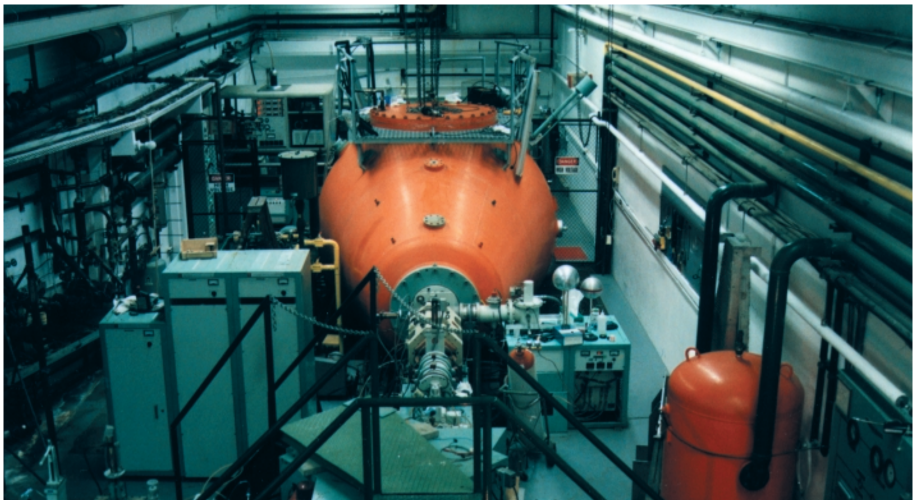


(a) Neutron image of an object with defects taken at the Los Alamos Neutron Science Center (LANSCE). (b) Computer simulations using Lawrence Livermore's COG Monte Carlo radiation transport code. The simulations show that neutron images taken at energy ranges between 10 and 15 megaelectronvolts could reveal defects in thickly shielded targets as well as LANSCE images, which were taken at much higher energies.

of nuclear warhead components for stockpile surveillance. The answer seems to lie with high-energy neutrons, which are able to easily penetrate high-*Z* materials to interact with low-*Z* materials, yielding clear, detailed images that are difficult to duplicate with x rays.

According to Lawrence Livermore materials scientist Jim LeMay, deputy program leader for Enhanced Surveillance, neutron imaging will be valuable to stockpile stewards on a number of fronts. He notes that weapons are randomly selected from the nation's nuclear stockpile for inspection. Neutron radiographs could be used as a means to screen these weapons and select one or more devices for complete disassembly and visual inspection. Also, neutron radiography could serve as a valuable inspection tool for identifying the warheads that actually need refurbishing as well as a valuable quality control tool for inspecting refurbished warheads before they are returned to the stockpile. Finally, neutron imaging of a statistically significant number of units could serve as a baseline assessment of the current state of a particular warhead.

Livermore physicist James Hall, the neutron imaging project leader, notes that imaging systems using thermal neutrons (average energy of about 0.025 electronvolt) are well established as nondestructive inspection tools in research and industry. However, these systems are generally limited to



Although larger in size than the proposed Lawrence Livermore neutron imaging system, the layout of the facility at the Ohio University Accelerator Laboratory in Athens, Ohio, is similar in configuration. The large orange vessel in the background is a Van de Graaff accelerator. It is used to accelerate deuterium ions into a cell containing deuterium gas to produce high-energy neutrons.

A Neutron Primer

All forms of radiation are attenuated (weakened) by a combination of slowing, scattering, and absorption processes as they pass through materials. The variation in attenuation through different parts of an object forms the basis for radiation imaging. The most widely used and commonly known form of radiation imaging is the x-radiograph in which an object is exposed to x rays and an image of the object (essentially a shadow) is recorded on photographic film or with a solid-state camera. Discovered more than 100 years ago, x rays today have a wide range of industrial and medical applications.

Neutrons, discovered in 1932, are electrically neutral particles similar in mass to a proton and present in the nuclei of all elements except hydrogen. Neutron imaging (conceptually similar to x-ray imaging) is commonly done today using neutrons that have an average energy of about 0.025 electronvolts. These neutrons are generated from fission neutrons produced in a nuclear reactor or from the decay of a radioisotope and then passed through thick layers of a hydrogen-rich material such as polyethylene to reduce their energy to thermal levels.

Most imaging applications using thermal neutrons exploit their strong interaction with hydrogen. For example, thermal neutrons can be used to inspect or detect explosives inside brass shell casings and search for corrosion in the aluminum skin of aircraft.

High-energy neutron imaging (for example, in the 10- to 15-megaelectronvolt range) is a relatively new technique that offers unique advantages over conventional x-ray and thermal neutron imaging, particularly for inspecting light (low-*Z*, or low-atomic-number) elements that are shielded by heavy (high-*Z*, or high-atomic-number) elements. These advantages are due in part to their greater penetrating power (that is, lower attenuation) through high-*Z* materials and, compared to x rays, their much stronger interaction (that is, higher attenuation) in low-*Z* materials.

Lawrence Livermore physicist James Hall emphasizes that neutron imaging yields different (and complementary) information to that obtained with x rays. "The use of one does not necessarily eliminate the need for the other," he says. Hall notes that although the ultimate spatial resolution attainable with high-energy neutron imaging—about 1 millimeter—is about 10 times less than the spatial resolution of x-ray imaging done with the most penetrating x-ray spectrum, it may be the only way that researchers can learn anything about the internal structure of some extremely thick objects.

inspecting objects only a few centimeters thick. In the early 1990s, scientists at Lawrence Livermore and Los Alamos national laboratories speculated that higher-energy neutrons could be used to image much thicker objects such as nuclear warhead components.

Proof-of-principle tests began in 1994 at the Los Alamos Neutron Science Center (LANSCE), a facility that produces neutron beams with energies of up to 600 megaelectronvolts (MeV), far greater than those used by industry. The test object consisted of a 2.54-centimeter-thick lithium deuteride (low-*Z*) disk that was sandwiched between two 5.08-centimeter-thick uranium (high-*Z*) slabs. Small holes ranging from 4 to 12 millimeters in diameter were drilled all or part way through the lithium deuteride to simulate defects. A detector recorded images of the neutrons transmitted through the object from the LANSCE source with a spatial resolution of about 1 millimeter, revealing the presence of all of the holes.

Simulations Bolstered Confidence

Encouraged by the success of these initial tests, Hall decided to model the LANSCE experiments using Livermore's three-dimensional Monte Carlo radiation transport computer code called COG. His computer simulations, however, focused on a lower energy range (10 to 15 MeV) because neutrons with these energies are known to penetrate high-*Z* materials effectively and yet interact more strongly with low-*Z* materials than the much higher-energy neutrons used at LANSCE. The COG simulations showed that neutron imaging in the 10- to 15-MeV energy range should be capable of revealing millimeter-size cracks, voids, and other defects in thick, shielded targets similar to the one tested at LANSCE.

Hall was also drawn to two other advantages of 10- to 15-MeV neutrons. The first is that neutrons in this energy range are much less expensive to generate than higher-energy neutrons such as those produced at LANSCE. Second, lower-energy neutrons are easier to detect because they allow the use of plastic scintillators, which are some 20 times more efficient than the conversion-type detectors required for much higher-energy neutrons.

One disadvantage of the lower energy range is the somewhat reduced penetrability of high-*Z* materials, which means exposure times of a few hours and sometimes longer are required for typical radiographs. However, says Hall, the greater detection efficiency and lower overall imaging costs more than make up for the longer exposure times.

Following the computer simulations, Hall joined forces with colleagues Frank Dietrich, Clint Logan, and Brian Rusnak to design and develop a full-scale neutron imaging system for stockpile surveillance that would be capable of acquiring both radiographic (single-view) and full tomographic (three-dimensional) images. The system has to be relatively compact (about 15 meters long), both as a prototype suitable for installation and use at Livermore and in its fully developed form for eventual installation at other NNSA weapons complex facilities.

The resulting design features three primary components: an accelerator-driven neutron source generating an intense beam of 10-MeV neutrons, a remotely controlled staging system to support and manipulate objects being imaged, and a detector system with relatively high efficiency (about 20 to 25 percent) that can resolve defects of about 1 millimeter in diameter. To expedite the system's development and minimize technical risks, the team decided to use commercially available components and proven neutron imaging techniques wherever possible.

Ohio University Test Bed

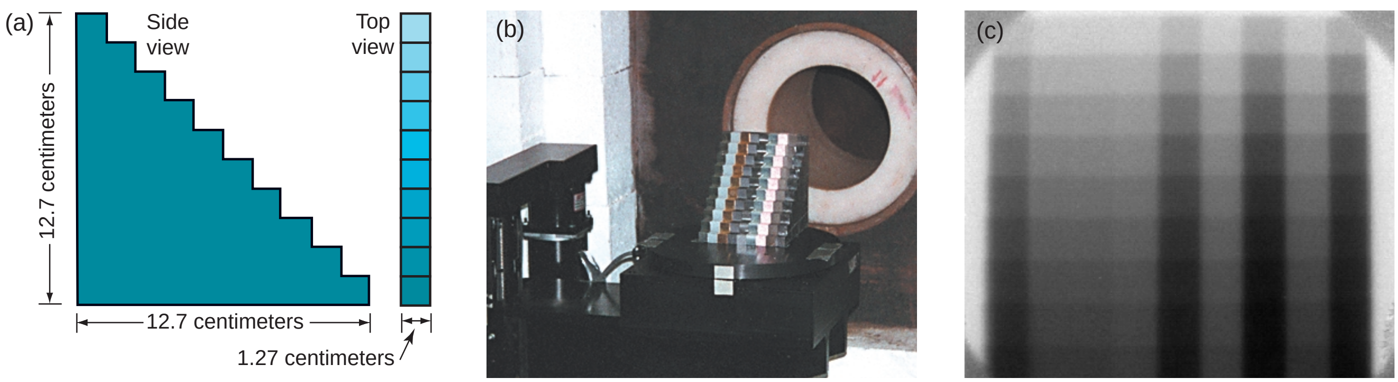
The team chose the Ohio University Accelerator Laboratory (OUAL) in Athens, Ohio, to evaluate the performance of a prototype imaging detector beginning in 1997. Although the accelerator facility at OUAL is much larger than that proposed in the Livermore design, its layout and configuration are similar. In addition, the OUAL staff has extensive experience in the production of accelerator-driven, high-energy neutron beams.

For the Lawrence Livermore experiments at OUAL, a 10-MeV neutron beam is generated by focusing deuterium ions into a cylindrical 1-centimeter-diameter by 8-centimeter-long deuterium gas cell attached to the end of the beam line. The gas cell is

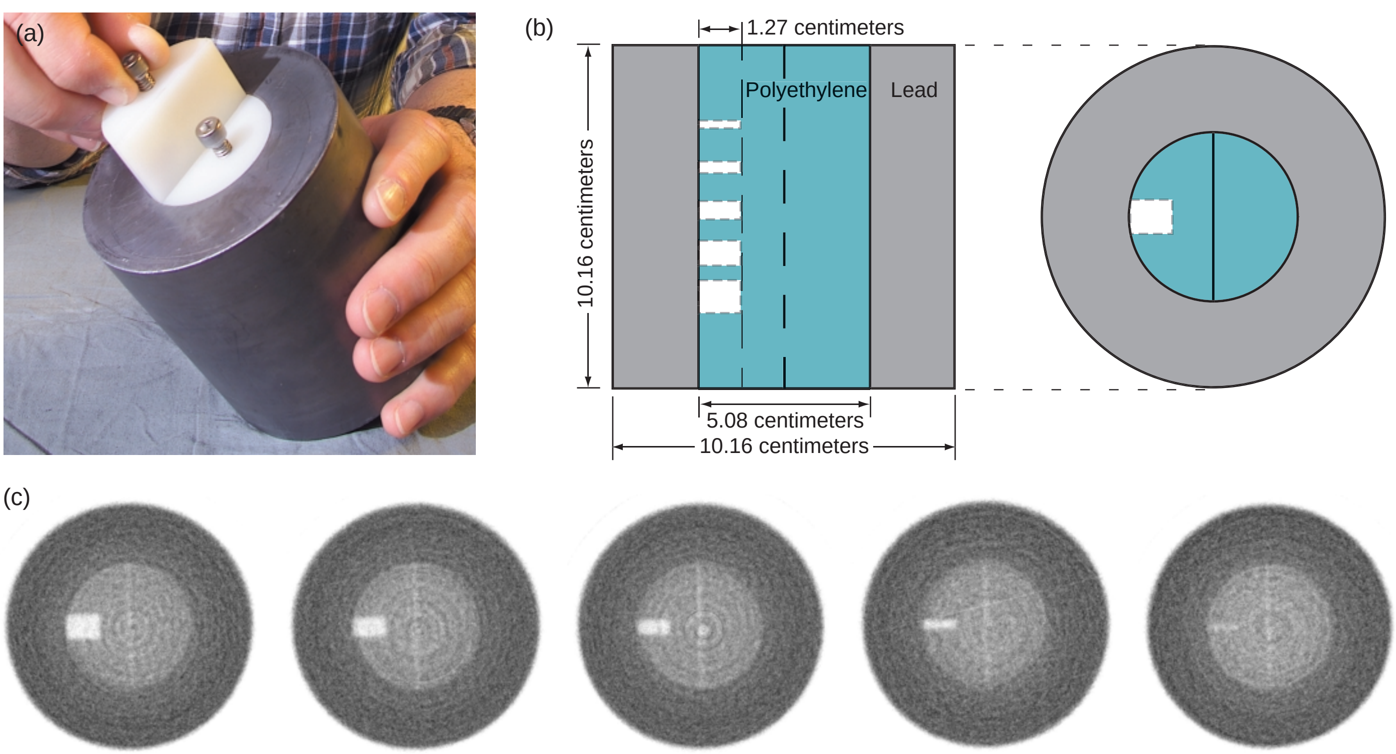
Lawrence Livermore physicist James Hall assembles a test object called a sandwich assembly for imaging at the Ohio University Accelerator Laboratory. Behind Hall is a prototype multiaxis staging system that secures and manipulates the test object. On its way to the detector, the neutron beam passes through the test object and immediately through a tapered polyethylene collimator set into a 1.5-meter-thick concrete and steel wall.

capped with thin entrance and exit windows and maintained at a pressure of about 3 atmospheres to limit the spread in energy of the resulting neutrons. The typical deuterium ion beam current arriving at the gas cell is on the order of 10 microamperes, which corresponds to about 60 trillion ions per second. In comparison, Lawrence Livermore's proposed design will feature a 300-microampere accelerator with a 4-centimeter-long deuterium gas cell.

The result is a neutron beam flux only 15 times less intense than the intensity called for in the full-scale system. As a



(a) Nine step wedges fabricated from lead, Lucite, mock high explosive, aluminum, beryllium, graphite, brass, polyethylene, and stainless steel were imaged. Each step wedge has 10 steps ranging in thickness from 1.27 centimeters to 12.7 centimeters. (b) The nine wedges were imaged as a single unit. (c) The radiographs clearly differentiated the various materials and steps.



(a) A lead cylinder with a 10.16-centimeter outside diameter, a 5.08-centimeter inside diameter, and a polyethylene core was imaged. (b) The polyethylene core was split into two half-cylinders. One served as a blank, and the other had a series of holes that were 10-, 8-, 6-, 4-, and 2-millimeter-diameter by 1.27-centimeter-deep machined into its outer surface. (c) The resulting tomographic reconstructions clearly showed the core's structure, including the slight gap between the two halves.

result, images take about 15 times longer to complete at OUAL than they will at Livermore. Nevertheless, the flux is sufficient to evaluate the performance of prototype detectors and for Lawrence Livermore researchers to gain valuable experience in neutron imaging. In many ways, says Hall, the Ohio University accelerator lab has been a "perfect test facility."

The experiments conducted thus far at OUAL have focused primarily on radiographic imaging of step wedges made of different materials and slab or sandwich assemblies, most with holes or other features machined into them to test the system's resolving power. The sandwich assemblies are typically composed of blocks of low-*Z* materials, such as polyethylene, that are shielded by various thicknesses of high-*Z* materials, such as lead or depleted uranium (D-38). Tomographic images of several cylindrical test objects composed of nested shells of high- and low-*Z* materials, with machined features, have also been obtained.

The test objects are mounted on a multiaxis staging system, which is located on the beam axis about 2 meters downstream from the neutron source and about 2 meters in front of the prototype imaging detector. The detector is housed in a shielded area behind a 1.5-meter-thick concrete and steel wall with a tapered polyethylene collimator to help minimize background radiation.

Sandwiches, Steps, and Cylinders

One of the first experiments conducted at OUAL involved imaging a 12.7-centimeter-thick lead and polyethylene sandwich (with features machined into the polyethylene) and a set of 9 step wedges (see top figure, p. 8) fabricated from lead, Lucite, mock high explosive, aluminum, beryllium, graphite, brass, polyethylene, and stainless steel. Each step wedge had 10 steps ranging in thickness from 1.27 centimeters to 12.7 centimeters. The nine wedges were grouped together and radiographed as a single unit (looking up the steps from thick to thin) in a series of two 1-hour exposures. The radiographs clearly differentiated the different materials and step thicknesses.

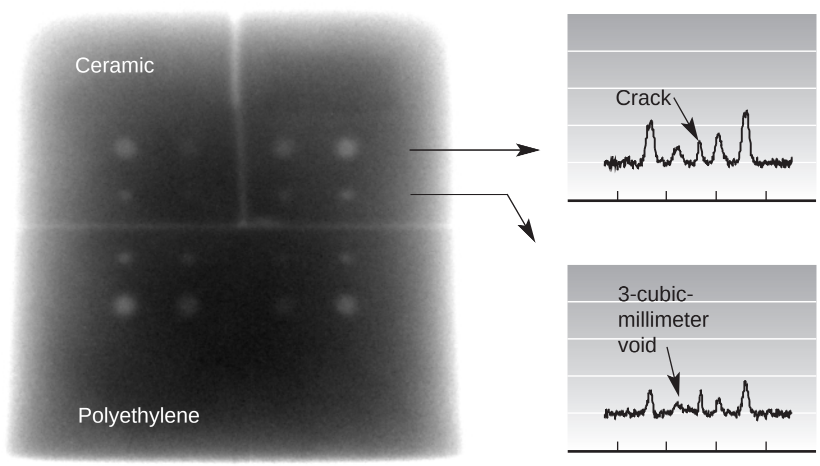
Another series of experiments involved imaging a 7.62-centimeter-thick D-38 and lithium deuteride sandwich (similar in design to the lead and polyethylene assembly previously described) and tomographic imaging of a lead cylinder with a 10.16-centimeter outside diameter, a 5.08-centimeter inside diameter, and a polyethylene core (see bottom figure, p. 8).

The polyethylene core was split into two half-cylinders. One served as a blank and the other had a series of holes machined into its outer (curved) surface that were 10, 8, 6, 4, or 2 millimeters in diameter by 1.27 millimeters deep. A series of sixty-four 10-minute exposures was taken of the cylinder at angles evenly distributed over 180 degrees. Resulting tomographic reconstructions clearly showed the core's structure. Although not well resolved, the narrow (less than 0.25-millimeter-wide) gap between the two halves of the polyethylene core was also visible in the reconstructed images.

Additional experiments at OUAL have focused on imaging objects made of other materials with a variety of machined features. One object consisted of a 10.16-centimeter by 5.08-centimeter by 2.54-centimeter-thick slab of ceramic set atop a polyethylene slab of similar size and shielded by 2.54 centimeters of D-38. The ceramic piece featured two sets of 4- and 2-millimeter-diameter holes machined to depths of 4, 2, and 1 millimeters (the smallest hole corresponded to a defect with a volume of about 3 cubic millimeters). The ceramic was carefully cracked along its centerline and then reassembled so that the fracture was barely visible to the naked eye. The polyethylene piece featured the same set of 4- and 2-millimeter-diameter holes but no crack.

The object was imaged in a series of forty-eight 30-minute exposures. The final processed image and associated lineouts clearly showed the crack in the ceramic slab and all of the machined features, including the smallest 2-millimeter-diameter, 1-millimeter-deep hole.

Hall says the contact gap between the two ceramic pieces was probably less than 0.01 centimeter wide, far less than the designed resolution of the imaging system. Yet, the gap can still be resolved. "We're very pleased we can see this kind of detail through more than 2 centimeters



This neutron radiograph of a fractured ceramic and polyethylene test object shielded by 2.54 centimeters of depleted uranium shows the crack separating the two ceramic halves as well as a series of 4-millimeter-diameter (top) and 2-millimeter-diameter (bottom) holes machined into the ceramic. (A narrow slot was cut in the top of the ceramic to a depth of 2.54 centimeters to facilitate cracking the piece along its centerline.)

The Making of a Neutron Imaging System

The design of Livermore's neutron imaging system consists of a high-energy neutron source, a multiaxis staging platform to hold and manipulate an object, and an efficient imaging detector. The development of these components has proceeded in parallel over the past several years.

Neutrons can be produced using accelerators, radionuclides, or nuclear reactors. To achieve a high-energy neutron flux sufficient to image thick objects of interest within reasonable imaging times (a few hours), an accelerator-driven source appears to be the most practical option for stockpile surveillance purposes.

The accelerator, based on a commercially available design, will be built to Livermore specifications. The unit will focus a narrow (1.25-millimeter-diameter), pulsed (75-hertz), 300-microampere beam of deuterium ions into a 4-centimeter-long cell containing deuterium gas. (Deuterium is an isotope of hydrogen containing one proton and one neutron in its nucleus.) The collision of the deuterium ions with deuterium gas in the cell will produce an intense, forward-directed beam of neutrons with an energy of about 10 megaelectronvolts.

Collaborating with MIT

The combined requirements of a high deuterium-ion current and small beam diameter preclude the use of typical thin-walled ("windowed") deuterium gas cell designs. At an average power of about 170 kilowatts per square centimeter, the incident deuterium ion beam would generate far too much heat for any window material to withstand.

As a result, Lawrence Livermore researchers have teamed with nuclear engineering professor Richard Lanza at the Massachusetts Institute of Technology (MIT) to develop a "windowless" deuterium gas cell that can be efficiently coupled to a high-current, pulsed, deuterium accelerator. One design under consideration features a high-pressure (3-atmosphere) gas cell mounted at the exit port of a vacuum system. The cell's several pumping stages are isolated from each other by a series of rotating disks with small holes synchronized to the pulse frequency of the accelerator. In this way, the holes in the rotating disks line up about 75 times a second to allow the ion beam to penetrate the cell without letting substantial amounts of deuterium gas leak out.

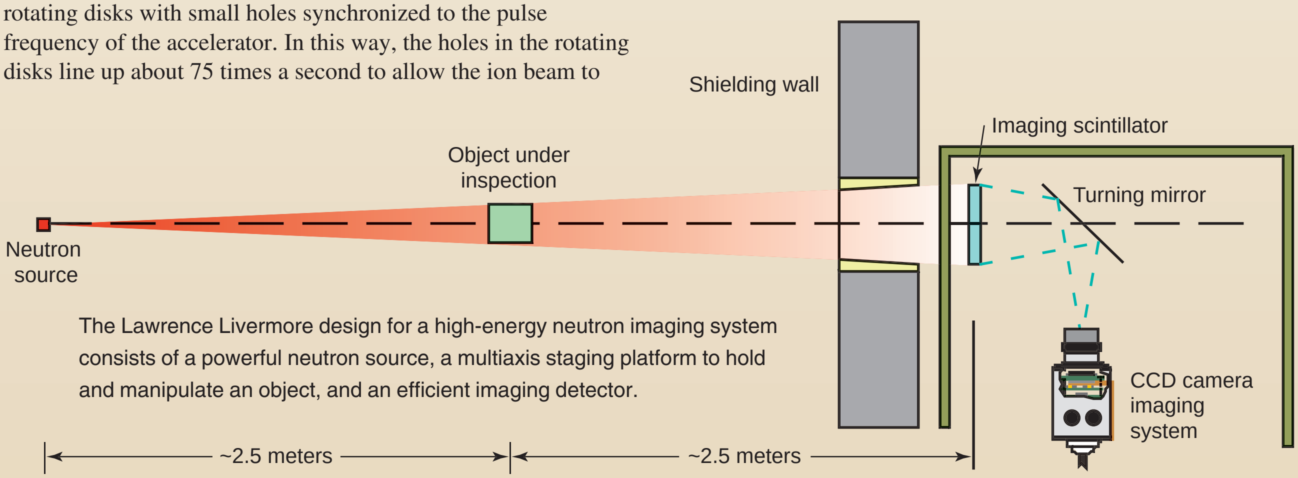
An alternative to the rotating aperture design is also being pursued by the Lawrence Livermore–MIT team. This approach, developed at Brookhaven National Laboratory, uses an intense plasma discharge to effectively plug the opening of the gas cell by rapidly heating and ionizing any deuterium leaking out. Similar "plasma windows" are being developed for use in electron-beam welding applications.

The object under inspection will be secured to a staging system that was originally designed at DOE's Y-12 Plant in Tennessee for x-ray imaging. The unit goes up and down and back and forth and rotates a full 360 degrees to permit both radiographic and tomographic imaging. Calculations and tests conducted at the Ohio University Accelerator Laboratory by Livermore researchers indicate that placing the staging system halfway between the source and the image plane of the detector will minimize the neutron scattering that can fog the image.

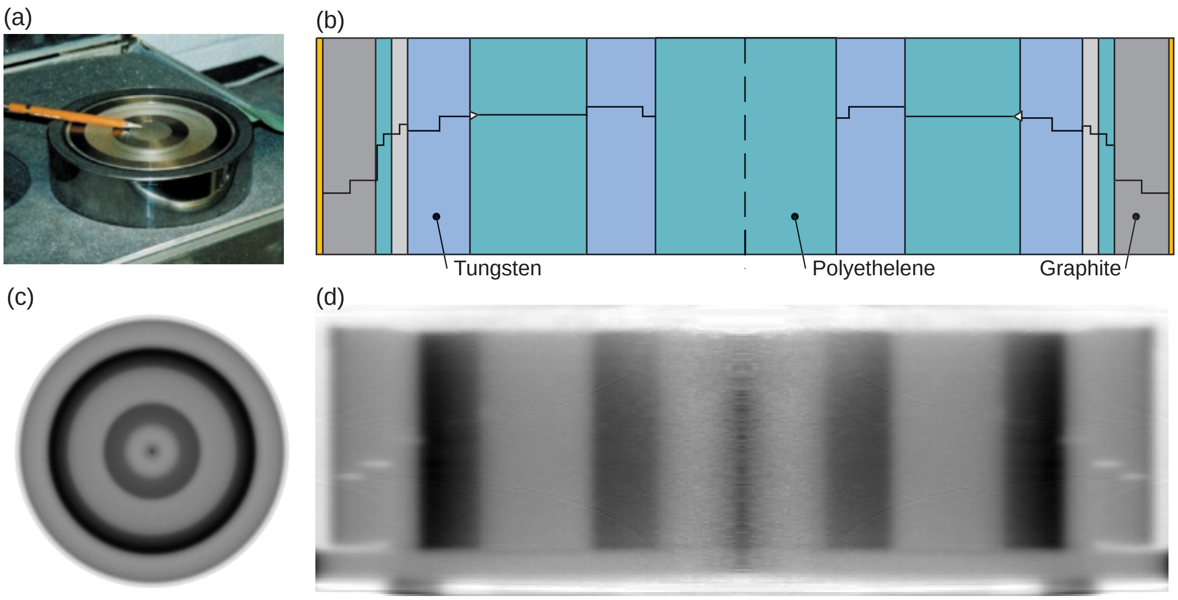
Imaging Detector Has Nevada Heritage

The design of the imaging detector will be based on technology originally developed by Lawrence Livermore's Nuclear Test Program for use at DOE's Nevada Test Site. The full-scale detector will consist of a 60-centimeter-diameter transparent plastic scintillator viewed indirectly by a camera with a high-resolution (2,048- by 2,048-pixel) charge-coupled device (CCD) imaging chip.

A thin turning mirror made of aluminized glass will be used to reflect the brief flashes of light generated by neutrons interacting in the scintillator into the CCD camera, which will itself be located in a shielded enclosure well out of the neutron beampath. The camera will be fit with a fast (*f*/1.00 or better) lens to enhance its sensitivity and cooled with liquid nitrogen gas to –120°C to minimize thermal electronic noise.



The Lawrence Livermore design for a high-energy neutron imaging system consists of a powerful neutron source, a multiaxis staging platform to hold and manipulate an object, and an efficient imaging detector.



A number of images have been taken of (a) the British Test Object (BTO), which consists of (b) a set of six nested cylindrical shells made of graphite, polyethylene, aluminum, and tungsten. A series of exposures was reconstructed into mock tomographic images, which show the BTO viewed (c) from the top and (d) through its side.

of uranium, even though we can't really quantify the gap," he says, adding, "we're seeing more than we ever expected."

A number of images have also been taken of the British Test Object (BTO), on loan from the Atomic Weapons Establishment in Aldermaston, United Kingdom. The BTO consists of a set of six nested cylinders of graphite, polyethylene, aluminum, tungsten, polyethylene, and tungsten (respectively) with a solid polyethylene core. Twelve 30-minute exposures were taken of one side of the assembly and then reconstructed into a mock tomographic image. The reconstruction clearly shows the gross structure of the object as well as the detailed joint structure in the outer shells.

Despite the experimental success enjoyed thus far, much work remains to be done to meet the goal of having a full-scale neutron imaging system in operation at Livermore by late 2003 or early 2004. Vendors need to be selected to build the accelerator, the detector's optics system, and the multiaxis staging system. Meanwhile, plans are under way to modify an existing Lawrence Livermore laboratory to house the system.

Once the system's performance is validated at Livermore, it will be transferred to other DOE facilities such as the Pantex Plant in Texas or the Y-12 Plant in Tennessee by late 2005 or early 2006. The continuing success of the Ohio University experiments makes it likely that neutron imaging will be serving the nation's stockpile stewardship needs within a few short years.

—*Arnie Heller*

Key Words: Brookhaven National Laboratory, COG Monte Carlo radiation transport code, deuterium, Enhanced Surveillance Campaign, lithium deuteride, Los Alamos Neutron Science Center (LANSCE), Massachusetts Institute of Technology (MIT), neutron radiography and tomography, Nevada Test Site, Ohio University Accelerator Laboratory (OUAL), Pantex Plant, scintillator, stockpile stewardship, x-ray imaging, x-ray radiography, Y-12 Plant.

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About the Scientist

JAMES HALL received his B.S. in physics and mathematics from the University of Southern Colorado in 1974 and his M.S. and Ph.D. in physics from Kansas State University in 1977 and 1981, respectively. He joined Lawrence Livermore in 1987 as a physicist charged with the design and execution of a variety of nuclear device diagnostic experiments, primarily neutron and gamma-ray measurements, for the underground nuclear test program at the Nevada Test Site. With the end of underground testing in 1992, Hall refocused his efforts on the development of detailed computer simulations of inertial confinement fusion diagnostics, flash x-ray systems, and a variety of nonintrusive inspection systems proposed for use in stockpile stewardship, cargo and luggage inspection, and nuclear counterterrorism schemes. As an outgrowth of this work, in 1994 he was selected to serve as the DOE representative and chief science advisor to the 8th Joint Compliance and Inspection Commission meetings associated with the Strategic Arms Reduction Treaty. Hall is currently a principal investigator for the development of high-energy neutron imaging techniques in support of nuclear stockpile stewardship applications.