A CAT SCANNER FOR NUCLEAR WEAPON

A new x-ray inspection system gives scientists a three-dimensional view inside nuclear weapon components.

THE Department of Energy's National Nuclear Security Administration (NNSA) is looking to accomplish even more within its budget constraints, as it pursues a smaller, safer, more secure, and less expensive nuclear weapons complex. Meeting that goal means relying on advanced scientific tools and procedures to assure a high level of confidence in the performance of aging weapons in the stockpile. The longer confidence in the performance of an aging weapon system can be assured, the longer the nation can keep the system as part of a credible nuclear deterrent without having to refurbish the weapons or produce replacements.

In response to NNSA's needs, Livermore physicists, engineers, and computer scientists have developed a new computed tomography (CT, also known as computerized axial tomography or CAT) x-ray system to image nuclear weapon components removed temporarily

COMPONENTS

from the stockpile for inspection. The Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS) consists of a scintillator (a material that emits light when struck by ionizing radiation); a pyramid-shaped central mirror; four turning mirrors; and four high-resolution, low-intensity visible-light charge-coupled-device (CCD) cameras. The system's software assembles the collected digital radiographs into a large three-dimensional (3D) image that scientists can "walk through" to discover any problems or anomalies.

CoLOSSIS was recently installed at NNSA's Pantex Plant near Amarillo, Texas. The overall CT system includes a 9-megaelectronvolt (MeV) linear accelerator and a tungsten target (built by Varian, Inc.) that produce the x-ray beam, three tungsten collimators that shape the x-ray beam and prevent unwanted scatter, and a positioning table that securely holds the test object and rotates it in precise increments for the CoLOSSIS detector.

A typical CoLOSSIS inspection comprises about 1,500 separate radiographic images taken of an object from all sides. The radiographs are then assembled, using Livermore-developed tomographic image algorithms, to provide a 3D reconstructed image with greater resolution than previously achieved using a 9-MeV x-ray system. Nearly all elements of the inspection system—x-ray source, collimators, positioning table, detector, and tomographic algorithms—contribute to its high-resolution capability.

Pantex is the nation's only nuclear weapons assembly and disassembly facility. To maintain the reliability of the nation's nuclear weapons stockpile, weapons are randomly selected and transported to Pantex for testing and evaluation. X-ray radiography is used to probe inside the nuclear pit of a weapon in a nondestructive manner; that is, the weapon does not have to be dismantled. Plutonium pits are one of the most important components routinely inspected. Tests on these pits can reveal structural variations arising from so-called birth defects (manufacturing flaws) or from aging. Potential variations include cracks, voids, gaps, and density variations.

Livermore chemist Pat Allen, deputy program manager of the Laboratory's enhanced surveillance effort, says, "Without x-ray diagnostic tests at Pantex, we would have to resort to destructive evaluation of these very expensive weapon components. With the right diagnostic tools, we can conserve valuable resources by eliminating some destructive procedures and disassembly operations."

"Livermore's role in helping to develop CoLOSSIS reflects the strong nondestructive evaluation capability at the Laboratory," says Allen. A core competency at Livermore, nondestructive evaluation

X rays from a 9-megaelectronvolt (MeV) linear accelerator (far right) travel through three tungsten collimators to the heavily shielded Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS).

is a means of examining and identifying flaws and defects in materials without damaging them. Laboratory engineers routinely use x-ray, ultrasonic, acoustic, infrared, microwave, visible-imaging, and other noninvasive techniques to examine defects, measure properties, and accurately determine part thicknesses of materials for a variety of research programs.

CoLOSSIS is currently undergoing final qualification at Pantex. Future inspections at Pantex will generate important data for scientists and engineers at Lawrence Livermore and Los Alamos national laboratories, the two centers of nuclear weapon design and engineering.

Quest for Higher Resolution

Allen notes that although current x-ray inspection procedures at Pantex are working well, scientists would like to achieve even better contrast and resolution. "We want to see finer detail and be able to differentiate one material or feature more easily from another," he says.

Livermore physicist Jim Trebes says that traditional black-and-white film can exceed the resolution of digital radiography in a single image. However, film has certain drawbacks. For example, many people with film expertise have retired, the film industry is in deep decline, and environmental controls on film-processing chemicals are increasing. The biggest drawback to film, though, is that it does not lend itself easily to processing 3D views. Trebes says, "If we know a feature exists in a certain location, we can easily record it with film. However, if we are performing a survey to look for problems, 2D film radiography is not sufficient because a subtle region can be obscured by another material or component."

Recognizing film's limitations, NNSA managers urged the development of a CT system to be installed in an existing x-ray inspection bay at Pantex with a goal of obtaining greater resolution and contrast to detect even the slightest manufacturing flaws and changes in materials from aging. With 3D imaging, scientists could examine any discrepancies from many different angles. "We want to see features as small as 2 or 3 mils (thousandths of an inch), equivalent to 50 to 75 micrometers, in very-high-density components," says Allen. "The best resolution for 9-megelectronvolt x-ray CT has until recently been 6 to 8 mils, or 150 to 200 micrometers."

CT scanners are commonly used in the medical field to take multiple radiographic views of a patient and then compute them into 3D images. More than 30,000 CT scanners worldwide are in use, mostly in hospitals. A medical CT scan is performed by rotating the x-ray source and detector around the patient. In contrast, CoLOSSIS does just the reverse: The x-ray beam and detector remain stationary, while the object is rotated 0.25 degrees for each succeeding picture.

Trebes notes that Livermore researchers regularly perform CT x-ray scans to examine tiny fusion targets for the National Ignition Facility, the world's most energetic laser. They also certify critical components for the National Aeronautic and Space Administration and for U.S. manufacturing companies.

Applying digital CT to weapons inspection poses a particular set of challenges. The procedure requires a source of x rays (typically an electron accelerator), a stage to position and move the object, a detector (scintillator), cameras to capture the image, and software to process the images. The source-object-detector configuration must be both thermally and vibrationally stable to avoid blurring the image. The room must be shielded to reduce backscatter into the detector and to protect the electronics and any personnel located in adjacent rooms. The x rays must penetrate thick, dense materials with much higher energy than a medical x ray (9 MeV instead of less than 100 kiloelectronvolts). Also, the inspection must achieve a much higher resolution of 75 to 100 micrometers compared to the millimeter scale sufficient for medical applications.

Three collimators shape the x-ray beam into an inverted pyramid, which penetrates the test object and casts an x-ray shadow on the glass scintillator. The scintillator converts the x-radiation to green light, which is reflected by mirrors (not shown) onto four charge-coupled-device (CCD) cameras.

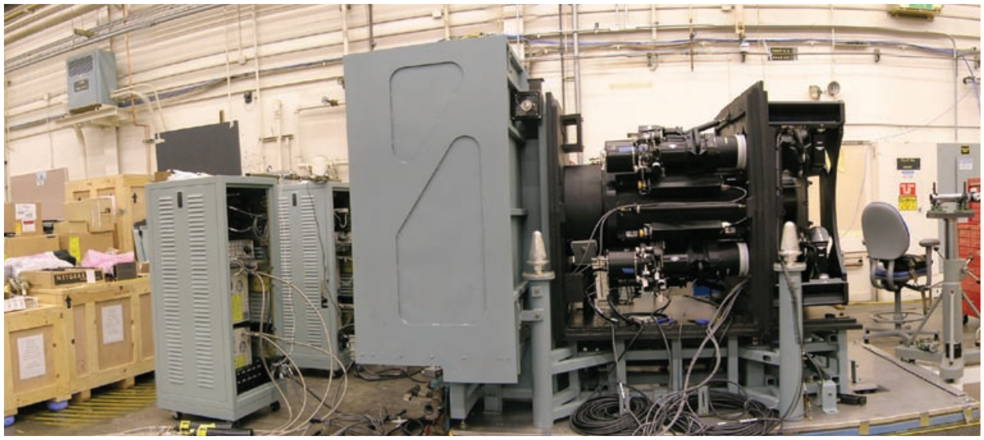
Prototype in 2000

Early work on a CT system for diagnosing weapon components began at Livermore in 2000. As proof of principle, physicist Gary Stone built a prototype system similar in overall design to CoLOSSIS, but it had just one camera instead of four and was capable of only 250-micrometer resolution. The prototype system's mechanical, electrical, and optical components worked well, and the feasibility of scanning was demonstrated using mock warhead components.

The initial results provided the impetus to build a more refined system with improved resolution. NNSA asked a team of Livermore scientists to work with Pantex managers in designing a CT system and to oversee its manufacture, assembly, and qualification. The resulting CoLOSSIS inspection system was built by OPTICS 1, Inc., with Livermore researchers and Pantex engineers providing technical assistance in specifying system requirements, design, setup, and operator training. Livermore computer scientist Dan Schneberk led the development of tomographic software.

In developing the optical and electronic requirements for CoLOSSIS, Livermore researchers originally specified one camera with an 8,000- by 8,000-pixel field of view. However, Trebes and Schneberk discovered that such a camera was not available commercially and would cost about $25 million to design and build. As a result, OPTICS 1 designed an instrument using four 4,096- by 4,096-pixel digital cameras and a novel optical configuration for collecting and transferring images.

The movable CT system weighs almost 16 tons, excluding the x-ray source. Much of this weight comes from the lead shielding used to protect optical lenses, CCD camera chips, and sensitive electronics from the powerful x rays. The shielding includes a core of three lead "exhaust" tubes with 3.5- to 4.0-centimeter-thick walls and an outer array of large lead-lined removable shields supported by a steel exoskeleton. (See the figures on p. 17.) The removable shields permit personnel access to internal CoLOSSIS components.



CoLOSSIS was first assembled and tested at Livermore (shown here), then shipped to the National Nuclear Security Administration's Pantex Plant near Amarillo, Texas, where it was reassembled last year in a large x-ray inspection bay.

CoLOSSIS at Work

A CoLOSSIS CT scan begins with the compact linear accelerator generating about 2,500 to 3,000 rads (unit of absorbed dose of ionizing radiation) per minute. Three sets of 2-inch-thick collimators shape the radiation source to precisely form an inverted pyramid of x rays optimized for the test object located about 6.5 meters away. The beam expands as it travels and is shaped by the collimators. Upon arrival at the test object, the beam delivers about 50 rads per minute.

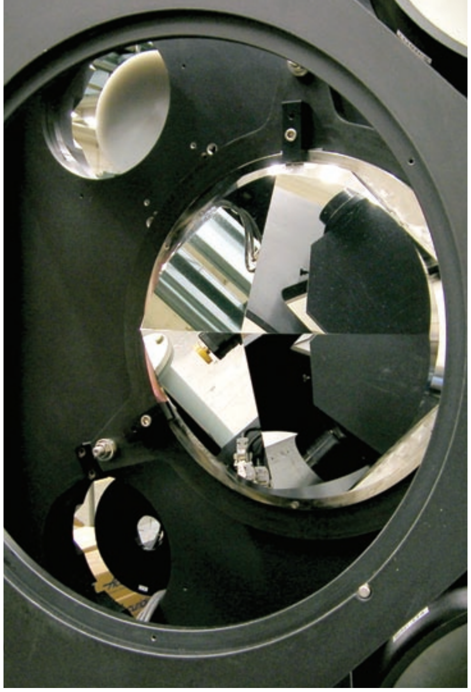
The collimators are supported on a steel support frame attached to a linear rail transport system, allowing for easy movement forward and backward. Each collimator features four adjustable jaws made of tungsten alloy, an x-ray absorbing material. Once aligned, the collimators and jaws are locked into position because errors in alignment or the movement of collimator components could cause excessive x-ray scatter and possibly damage the CCD cameras.

The shaped x-ray beam inscribes a cube measuring about 24 centimeters per side. A heavy, stable platform with a precision-leveling system aligns the test object and holds it in position for CT data collection. The x rays penetrating the test object cast a shadow on a glass scintillator that converts the x radiation to green light (a wavelength of about 540 nanometers).

The light emitted from the scintillator is then bounced off a pyramid-shaped mirror. The light bounces in four different directions onto four identical 20-centimeter-diameter turning mirrors.

The turning mirrors then reflect the light onto four 16-megapixel CCD cameras. The cameras, similar in design to those used for terrestrial astronomy, are cooled to minus 100° C. OPTICS 1 designed the custom lenses, while the cameras were built by Spectral Instruments, Inc., with help from the University of Arizona. Each lens comprises eight elements arranged into six groups. The lenses image light onto each camera's 16-megapixel (4,096 by 4,096 pixels) CCD chip, equal to an active area of about 6 centimeters per side. The CCD chip converts light to voltage and provides 65,000 levels of gray.

The turning mirrors can be adjusted so that the light falls upon the four CCD cameras in perfect registration. By using two mirrors in each optical chain, the CCD cameras are shielded from the direct x-ray beam. "The CCDs have been pulled out



A pyramid-shaped mirror bounces green light from the scintillator in four different directions onto four identical turning mirrors. Fabricated by Corning, Inc., the pyramidal mirror was diamond-turned to an extremely smooth surface, plated with nickel, and then diamond-turned again to final optical specifications.

of the main beam path with a neat optical trick," says Allen. Schneberk compares the mirror geometry to a periscope that permits observation without being in harm's way.

Each digital image from the four CCD cameras is immediately downloaded to the adjoining control room, where four computer servers, one for each camera, are located. Control electronics for the cameras and cryogenic refrigeration systems are housed at the rear of the system, shielded from the direct x-ray beam. During operation, personnel remotely adjust the mirrors, lenses, and cameras from the control room.

The pyramid-beam-splitting architecture allows for the four images from the cameras to be seamlessly stitched together using Schneberk's software. Each quadrant of the scintillator has a small overlap (20 to 50 pixels, about 1 percent) with the adjacent quadrant to assist the stitching procedure. The software stitches the four separate images into one by eliminating the overlap and creating an 8,000- by 8,000-pixel radiograph.

Each of the four images contains 32 megabytes of information, for a total of 128 megabytes per stitched view. A typical scan comprises 1,500 digital radiographs, each requiring up to 90 seconds, and each separated from the next by a 0.24-degree rotational change. In all, the data set is about 192 gigabytes. Each image takes 30 to 90 seconds, with 1,500 views requiring about 72 hours, spread over several days.

The complete data set is transferred to Lawrence Livermore or Los Alamos, where the individual images are reconstructed into an approximately 1-terabyte 3D file using

Seeing the Invisible with X Rays

X rays, a form of electromagnetic radiation, have a wavelength ranging from 10 to 0.01 nanometers (billionths of a meter), which corresponds to frequencies ranging from 30 petahertz to 30 exahertz (30×10^{15} to 30×10^{18} hertz) and energies ranging from 120 electronvolts to 120 kiloelectronvolts. Their discoverer, Wilhelm Conrad Röentgen, called them x rays, meaning an unknown type of radiation.

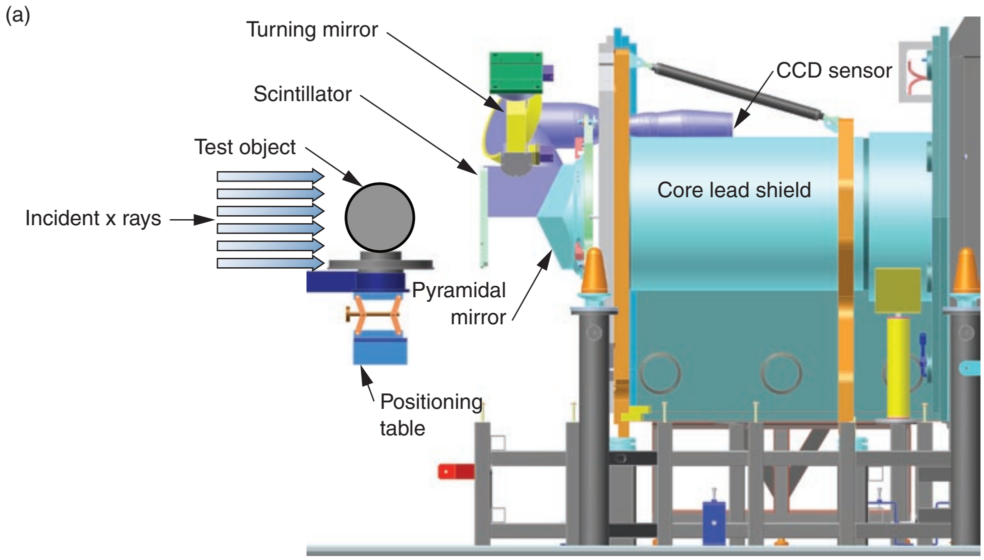
X-ray radiography is a nondestructive testing technology used to examine the interior of objects. It operates on the principle of dissimilar transmission of x rays through different materials. The ability of a material to block x rays increases with its density. Therefore, images of different materials will have varying contrasts.

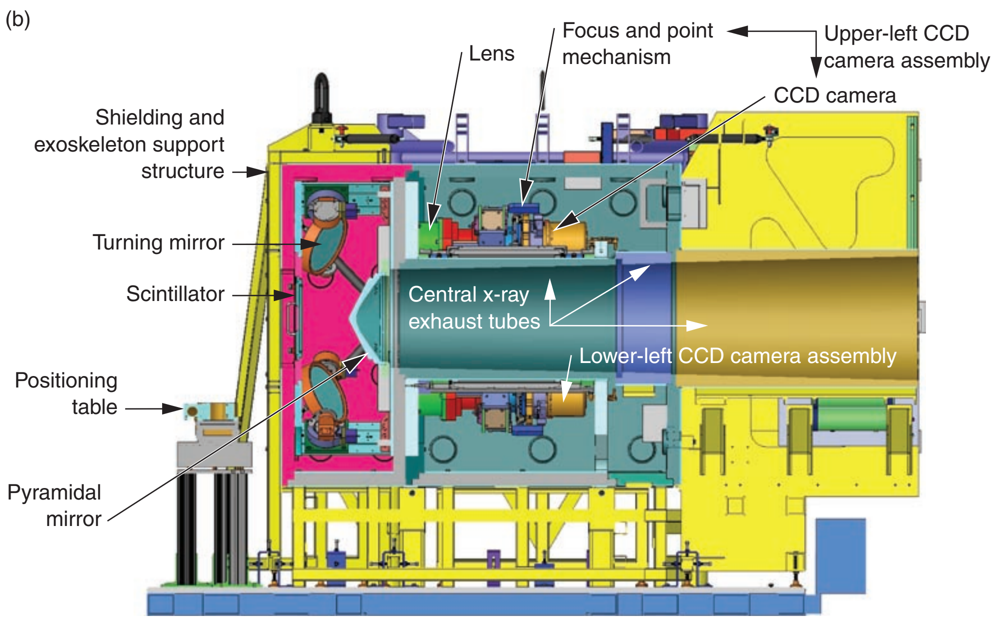
Using x rays is a long-established method to see inside objects, from human limbs to airplane parts. Because x rays are highly penetrating, they are useful in medical diagnostics, where x rays pass through organs onto a photographic cassette. Areas where radiation is absorbed appear as lighter shades of gray.

A typical modern x-ray machine has a filament that produces an electron beam used to excite a target into producing x rays. The transmitted x rays pass through an object, are collected by a detector, and then translated into amplified electric signals. These signals are then transformed into an x-ray image. The densities of the various materials comprising a specimen allow different amounts of x rays to pass through, resulting in varying grayscale levels on the x-ray image.

Livermore scientists use x rays to understand the properties of matter, from nuclear weapons to viruses to black holes. On a large scale, scientists are developing high-energy tomographic systems with spatial resolutions significantly better than anything currently available, requiring specialized computers and advance image-analysis methods. For example, they are developing systems for nuclear weapons stockpile surveillance, cargo container inspection for the Department of Homeland Security, spacecraft component certification for the National Aeronautics and Space Administration, and a wide range of industrial applications. On a much smaller scale, researchers are developing x-ray optics for cameras with a resolution as small as 10 microns to image mice used in research. On the very smallest scale, they are collaborating with others on developing x-ray free-electron lasers with atomic resolution to image single molecules, protein complexes, and viruses.

Livermore researchers require powerful x rays for such applications as backlighting inertial confinement fusion experiments for the National Ignition Facility and for imaging still or exploding materials for the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program. Unlike x-ray radiography used to image stationary objects at NNSA's Pantex Plant, the flash x-ray facility at Livermore's remote Site 300 produces powerful x rays to freeze the motion of materials moving at ultrahigh speeds. These nonnuclear "hydrodynamic" experiments study the behavior of a nuclear weapon from high-explosive ignition to the beginning of the nuclear chain reaction. These experiments consist of imploding inert (nonfissile) material with a high explosive. The explosive compression replicates the effects in the core of a nuclear device. (See *S&TR,* September 2007, pp. 4–11.) Flash x-ray tests combined with x-ray radiography of nuclear components at Pantex are two critical procedures aimed at ensuring the reliability and safety of the U.S. nuclear deterrent.





(a) A side view diagram of CoLOSSIS without its outer lead shielding shows the location of major components. A beam of x rays penetrates the test object positioned in front of the detector's scintillator. The scintillator converts the x radiation to green light, which is then reflected by a pyramidal mirror to four turning mirrors that bounce the light onto four identical charge-coupled-device (CCD) cameras. The positioning table rotates the object 360 degrees in increments. About 1,500 radiographic images are then assembled using Livermore-developed software into one large three-dimensional image for viewing. (b) A cutaway view shows the central x-ray exhaust tubes. This view includes just two of the four cameras and two of the four turning mirrors.

Livermore-developed software. "Joining all 1,500 2D images into an incredibly detailed 3D image takes several days of computer time," says Stone.

To view the 3D image, computer scientists combine four 3,200- by 2,300-pixel monitors to form essentially one large monitor. A weapons scientist can "walk through" the test object for an overall look in any direction or zoom in on a tiny subsection and proceed micrometer by micrometer deep into a part.

15-MeV System on the Horizon

CoLOSSIS is currently undergoing final shakedown prior to beginning scheduled inspections. "The goal is to make sure the system is usable by Pantex technicians," says Stone. In the meantime, discussions have begun on designing one or more 15-MeV CT scanners for Pantex. Much of the motivation for higher-energy systems is the possibility that scan times could be reduced, perhaps dramatically. Stone notes that higher energy will require more space in a larger bay and thicker shielding.

For the next several years, however, the 9-MeV CoLOSSIS system will provide a vital opportunity for NNSA to inspect stockpiled weapons more efficiently and thoroughly than current technology permits as well as provide scientists with a technical basis for future CT designs. Says Allen, "We're seeing more than ever before." For weapons scientists, seeing more means greater confidence in aging nuclear weapons—and in America's national security.

—Arnie Heller

Key Words: Combined Large Optical Scintillator Screen and Imaging System (CoLOSSIS), computed tomography (CT), nondestructive evaluation, Pantex Plant, radiography, stockpile stewardship, x ray.

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