DEVELOPMENT AND USE OF FIELD-PORTABLE DIGITAL RADIOGRAPHY FOR NONINTRUSIVE TANK INSPECTIONS

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ABSTRACT

In the last three years, the Idaho National Engineering and Environmental Laboratory (INEEL) has developed field-portable digital radiography for the nonintrusive examination of tanks, boxes, and piping for the INEEL Voluntary Consent Order (VCO) Program. The equipment consists of a continuous high-output x-ray generator, an amorphous-silicon flat-panel area imager, and control hardware/software. All components act as an integral whole to allow near real-time radiographs to be viewed for components in the field.

Although off-the-self equipment was used, the integration of the equipment into a single, portable unit that could be easily used by field technicians proved to be a technical challenge. This paper addresses the technical and administrative challenges of equipment selection, and its integration into a compact system. Technical challenges included portability, a wide variation in object size and configuration, and software development for a user-friendly imaging interface. Administrative challenges included writing and securing approval for a safety analysis report.

In field applications, conventional radiography collects single images that must be viewed independently. By using a small field-of-view digital x-ray imaging device, and multiple exposures, multiple images can be mosaiced together to form a single, large field-of-view image that more clearly defines the objects of interest in relationship to other nearby objects. This paper also discusses the technical challenges and solutions that were employed to develop the software necessary to allow easy integration of multiple x-ray images.

The benefits of this device are numerous. The field portability allows for images to be collected in situ without transferring the object to a shielded x-ray cave. Use of an x-ray generator, rather than a radioactive source, provides a much greater margin of safety, eliminates a radioactive waste disposal problem, and provides high-resolution images. Digital imaging allows for images to be gathered and interpreted in the field without the troublesome problems of chemical waste disposal and the delay of film development. Shots that are mistakenly collected can be observed and corrected in the field without waiting for film to be processed.

The current use of the Digital Radiography System (DRS) at the INEEL has been limited to interrogation of pipes and tanks to determine if residual liquid remains. The equipment has also been used to identify the previously unknown contents of a waste box. Data provided by the system can enable a field technician to easily discern if the container is completely full, partially full, or completely empty. Radiographs have resulted in the characterization being performed at a much lower cost with very low radiation exposure to those involved.

Future uses of the equipment include waste characterization, suspect waste packages characterization, and package interrogation for enhanced security. In addition, x-ray characterization of waste packages is anticipated to reduce or eliminate the need to breach a container. If container breaching is still needed, then the images produced enhance efforts to identify other safety issues.

INTRODUCTION

In June 2000, the INEEL and the Idaho Department of Environmental Quality (IDEQ) entered into a Voluntary Consent Order (VCO) [1] to address potential compliance issues with the Idaho Hazardous Waste Management Act (HWMA)/Resource Conservation and Recovery Act (RCRA). One of the issues covered by this consent order is a group of over 700 tanks and associated piping systems at the INEEL Site that require further characterization. The VCO tanks range in size from a few gallons to 300,000 gallons, with the majority in the 5,000 gallon or less size range.

The INEEL must determine whether each of these tanks is empty, or whether the contents are RCRA hazardous. Process/product tanks and pipes that are determined to be empty can be administratively removed from the VCO. Process/product tanks that are not empty, and waste tanks, must be further characterized to determine if the contents are RCRA hazardous. For tanks found to contain hazardous waste, the next actions (e.g., RCRA closure) will be negotiated under the consent order.

Determining if a tank or associated piping is empty became troublesome because historical records were not always reliable. Many of the tank systems contain radioactive and hazardous materials. Therefore, breaching a tank or pipe became a complex logistical and safety-related problem. Incorrectly assuming a tank is empty when, in fact, it contains hazardous materials could result in stipulated penalties and worker exposure when the tank system is ultimately removed. Conversely, incorrectly assuming a tank is not empty could result in costly efforts to breach and characterize nonexistent contents. Therefore, a tool or method was needed to confirm the presence or absence of material in tanks and pipes without having to breach the system. The presence of insulating materials on many of the tank systems complicated the use of simple technologies such as ultrasonic detection.

In 1999, a technology search was conducted that quickly identified the INEEL's digital radiography capability as a possible solution. This technology was, and is, being used by the U.S Army's Product Manager for Nonstockpile Chemical Materiel. A field-portable x-ray generator and digital scanning system are used to interrogate munitions to help ascertain if they contain chemical agents or other hazardous compounds. The radiography unit used for the Army was developed specifically for a unique set of field conditions. Adapting that system for use at the INEEL for interrogation of tanks and pipes had some interesting technical and administrative challenges.

TECHNICAL CHALLENGES

The VCO tank x-ray inspection system consists of four components:

- An amorphous-silicon, flat-panel digital area x-ray detector
- A portable 300-kV x-ray generator
- Configurable mounting hardware used to position the x-ray source and detector about the object to be imaged
- A portable computer that is used to control the detector and process the acquired images.

These components (see Fig. 1) have been integrated into an imaging system that is used to inspect a variety of tanks and pipes at the INEEL. Component choices and system design addressed concerns about developing a system as flexible as possible in order to be useful in the widest variety of inspection situations without needing to develop or cart around too much hardware. The system is modular in the sense that other components (source, detector, or mounting hardware) can be substituted in place of existing hardware when circumstances such as object configuration, location, or size require a change.

Fig. 1 System components

The x-ray detector is a 250-mm × 200-mm two-dimensional amorphous-silicon array with a pixel pitch of 127 μm and a bit depth of 12-bits/pixel. The detector is capable of readout rates of 1 to 7.7 frames/sec in an unbinned mode. In a 2 × 2 binning mode, the detector can read out as fast as 30 frames/sec (though the system is seldom used in that mode). The amorphous-silicon array is coupled to a cesium-iodide scintillator and has shielding sufficient to protect the electronics up to about 2 MeV. The weight of the detector with shielding is approximately 50 pounds. An additional padded enclosure has been provided to protect the detector from dings.

Alternative detector configurations were considered. A scanning linear diode array (LDA) could be used and may be less a expensive, lighter weight alternative. But an LDA would require coordinated motion hardware and software adding complexity to the system. Also, the true advantage of an LDA is the elimination of a large component of scattered radiation; however, this requires collimation and synchronous motion of the source as well. Another option would be two-dimensional CMOS imaging arrays. These arrays are typically smaller and would require more images to characterize many of the INEEL tanks, and may not be able to withstand the radiation dose. Lens-coupled phosphor screen systems or x-ray image intensifier systems would probably not be suitable for many of the spatially confined imaging scenarios that will be encountered at the INEEL. The obvious disadvantage of film is the long turnaround time and requirement for image-developing chemicals.

The x-ray source was chosen to be as portable as possible yet still generate enough flux to image through tanks as large as 10 ft in diameter. As described above, one of the main objectives of the VCO Program is to determine if a tank is empty or partially fluid-filled. This requirement means that the source need not penetrate a fluid-filled region (we do not need to image objects within the fluid), but it may be required to penetrate thick-walled containers. The x-ray unit has an adjustable peak potential from 50-kV to 300-kV at currents ranging from 0.5 to 3 mA. The maximum unfiltered output exposure rate is 1,000 R/hr at one meter. X-ray generators capable of achieving a higher potential require more hardware (external high-voltage generators and cooling units), while lower-energy units, while even more portable, would not be as useful in the full range of expected imaging situations. However, as indicated above, if it is determined that a small x-ray generator would be of benefit, then it could easily be integrated into the system. In fact, the system has been demonstrated on test objects using a battery-powered pulsed x-ray unit. Isotopic sources could also be incorporated into the system.

It is anticipated that the x-ray imaging equipment will be used in a wide variety of configurations: imaging vertical pipes (searching for a fill level), tanks or containers in odd locations (near the ceiling, in corners), or boxes inside and outdoors. Though it is impossible to build a single mount for the source and detector that can be utilized in all situations, a set of reconfigurable mounts for the source and detector were provided to meet an anticipated subset of the imaging scenarios. The mounts provided include:

- Adjustable, flat-bottomed tripods that securely position the source or detector up to a height of about 2.5 m from the floor. A smaller set (1.5 m height) has also been provided for imaging objects of smaller height. The smaller tripods are wheeled to assist in collecting mosaic images. The source and detector are moved vertically using a self-braking winch.
- An attachment for the detector that allows it to be affixed to a pipe and easily moved along the pipe. This could be used in conjunction with the source mounted on a tripod to image pipes running vertically along the wall.
- A strap-and-block attachment for securing the detector to a large-radius tank or drum.
- Each of these mounts easily attach to the source or detector and can be used alone or in combination.

A portable computer controls the detector and image processing. Depending on the imaging environment, the system can be controlled from a laptop via an Ethernet connection or using a portable (lunchbox) PC that connects to the detector through a frame grabber. The frame grabber option allows images to be displayed as they are collected (at up to 7.5 fps). Using the Ethernet option allows images to be collected as rapidly, but the image transfer is slow, and images are updated on the computer every 15 seconds. The advantage of the laptop/Ethernet option is that it allows the operator to be significantly further from the x-ray generator, which may be necessary when sufficient shielding is unavailable. It is also possible to control the lunchbox PC with the laptop computer using a remote PC application that allows the control of one PC from a distant PC via Ethernet.

A graphical user interface (GUI) was developed for image acquisition, display, and processing. The GUI was built using the Interactive Data Language (IDL) software package. A set of Dynamic Link Libraries (DLLs) were developed in the C language to communicate with the detector (calibration, start and end image acquisition, and transfer images). These DLLs are called directly from the GUI. The GUI was designed to hide as many detector details as possible from the end user (radiographer) yet allows full control of detector calibration and diagnostics for an experienced user. Feedback from radiographers was used to incorporate changes in the interface design, and it is anticipated that other changes will be requested as the system is utilized more.

Image acquisition is initiated by selecting the control mode of the system by choosing either operation from the laptop or the lunchbox computer. If the lunchbox option is chosen, a live image of the detected image and a histogram of pixel intensities is displayed. The live image can be used to interactively set the exposure (kV and mA) to optimize image quality, or could be used to image a moving object. The histogram is useful for adjusting exposure to stretch the gray levels in the image. When the exposure settings have been determined, a static image can be "snapped" with a single mouse click. The static image is the sum of from 1 to 16 individual detector reads. This summation increases the image quality of the final image. The operator is prompted to save the image and then the image is displayed and can be manipulated. The initial image is saved in a full bit-depth mode (16 bits/pixel). After manipulation, the image can be exported as an 8-bit TIFF file compatible with image-display programs available on most PCs. In laptop mode, the image is snapped immediately and adjustment of exposure is made iteratively over several image acquisitions.

After an image has been acquired, the user has a number of image-processing options:

- Gray-level adjustment through interactive sliders on a histogram of pixel intensities, or through maximum/minimum gray level intensity sliders, or by stretching the gray levels to intensities in a region of interest
- Logarithmic mapping to linearize the display gray levels with respect to the thickness-density product raypath of x-rays through the object
- The image can be displayed as a positive or a negative
- The image orientation can be changed to match the detector orientation
- Extraction of regions of interest.

In addition, a tool has been provided to allow multiple images to be combined together to form a single mosaic image. This tool is quite useful in cases where the object to be imaged is much larger than the detector width or height. A set of images that cover the width or height of the object, or that are strategically placed and spatially connected, can be combined to provide an informative visual description of a large object. An example is shown in Fig. 2.

ADMINISTRATIVE CHALLENGES

A significant feature of the INEEL DRS is that it uses a portable x-ray generator instead of an isotopic source. The x-ray generator has several advantages over isotopic sources: (a) it is a high-flux source that can produce sharp images with shorter exposures, (b) the x-rays can be immediately terminated, (c) the source strength is variable, and (d) there are no radioactive waste disposal problems.

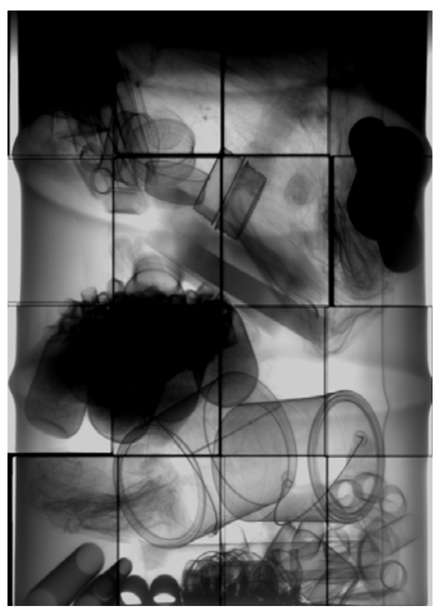

Fig. 2 Example of digital radiograph of simulated waste drum. The large field-of-view image consists of a mosaic of 16 individual small field-of-view projection images.

Unfortunately, the INEEL safety basis documentation for field radiography was based upon a low-dose isotopic source. Previously, the INEEL was authorized to use a 100 Ci source of Ir-192 or Co-60, which were primarily used for weld inspections and fixed location x-ray cameras. The radiation exposure rate from the 100-Ci source of Ir-192 is approximately 48 R/hr at 1 m. The x-ray generator selected for the VCO project was a Yxlon Smart 300 HP.[i] When running at full power (300-kV, 3 mA), the x-ray generator can provide a maximum exposure rate of 1,000 R/hr at 1 m. Because of the significantly higher dose potential, the INEEL Radiological Engineering and Safety organizations were naturally apprehensive.

The hazard assessment process prescribed by DOE-ID Order 420.D [2] and 10 CFR 830 Subpart B [3] resulted in a determination that the activity is classified as a "moderate hazard" activity. This classification was based upon the potential to exceed the DOE order dose limit of 2 rem in a single event. The Department of Energy (DOE) Orders further require that moderate hazard activities require further safety analysis to ensure that appropriate safety measures are in place. Coincidentally, other x-ray activities at the INEEL were receiving increased scrutiny. As a result, the VCO Program was tasked with writing a safety analysis document and seeking approval from internal safety resources as well as the DOE Idaho Operations Office.

The safety analysis report approval process was the critical path activity to full deployment of the equipment.

RESULTS AND FIELD DEPLOYMENT

To date, the DRS has been used three times in the field at the INEEL Site. The first use was on a waste box at the Test Reactor Area. The 4 × 4 × 8-ft box was suspected of containing a saw used for underwater cutting of fuel rods. Documentation was lacking that would allow disposal. Therefore, the VCO program was tasked with characterizing the contents. Due to radiation readings and other safety concerns, opening the box in the outside storage yard was problematic.

As shown in Fig. 3, the VCO Program used the DRS to collect an image of the box contents. The resolution was sufficient to allow persons familiar with the fuel cutting work to easily confirm that the contents was, in fact, a canal saw. Although a variety of administrative field delays were realized during this first deployment, setup and image collection took less than one working day. The actual image collection was just over two hours for 22 individual exposures, roughly 10 exposures per hour including moving the detector between each exposure.

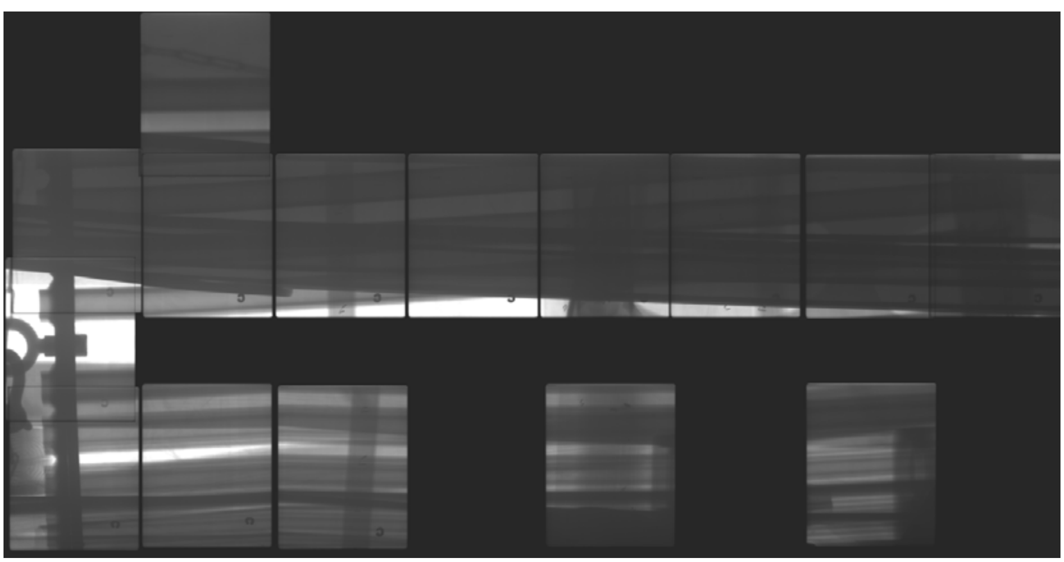

Fig. 3 Mosaiced radiograph of a small section of a waste box containing a canal saw

The second deployment of the DRS unit was at the abandoned Water Reactor Research Test Facility (WRRTF). A tank system included a pipe that was suspected of containing residual diesel oil. If the line was confirmed to be empty, line removal would be trivial; however, a line with contents would alter the work activities to ensure spillage was contained and to add additional protection to workers cutting into the line.

The radiography crew was deployed to the WRRTF and collected the image shown in Fig. 4. On the left side of the image, both the inner and outer pipe wall are apparent, whereas only the outer wall is apparent on the right side of the pipe; the density gradient on the right side of the image indicates that material is present in varying thickness that does not exist on the left side of the pipe. This Figure clearly shows the presence of sludge caked onto the inside, right side of the pipe.

Fig. 4. Radiograph of a pipe at the WRRTF.

A third deployment of the DRS unit was at the Idaho Nuclear Technology and Engineering and Center (INTEC) FAST Facility. Pipes were that were suspected of containing cadmium solutions or cadmium crystals were interrogated and confirmed to contain those materials. Figure 5 shows the valve with a material of higher density in the pipe on the left side of the valve than the pipe on the right. Operators then concluded that the cadmium solution was present on the left side of the valve but that the right side was empty. This knowledge will enable the VCO Program to better plan line cleanout activities.

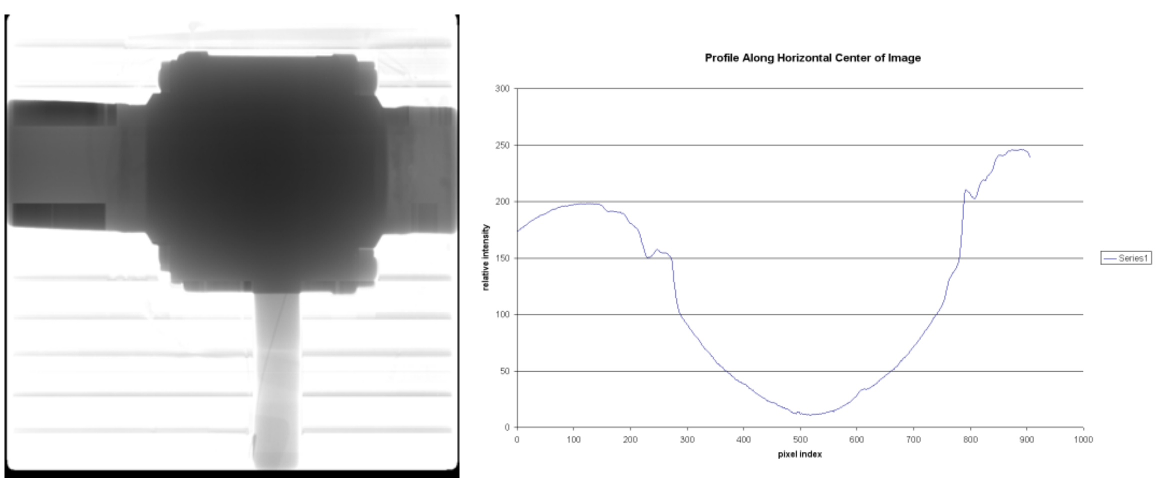

Fig. 5. Valve with cadmium-containing material in the pipe on the left, with no material in the pipe on the right.

The trace shown to the right represents the data values along the center line of the valve and pipe. Note that the higher intensity values on the right hand side of the valve are higher than those on the left, indicating lower density.

FULL VERSUS EMPTY

A question that frequently arises is: How can an operator tell if an item is completely full or completely empty? A comparison of the right tank with the left tank in Fig. 6 clearly illustrates this problem. To answer this question, an experiment with a different x-ray inspection scanner called the Digital Radiography and Computed Tomography (DRCT) System (built for the U.S. Army) was conducted to verify that a digital x-ray system can determine the fill status of a test tank.

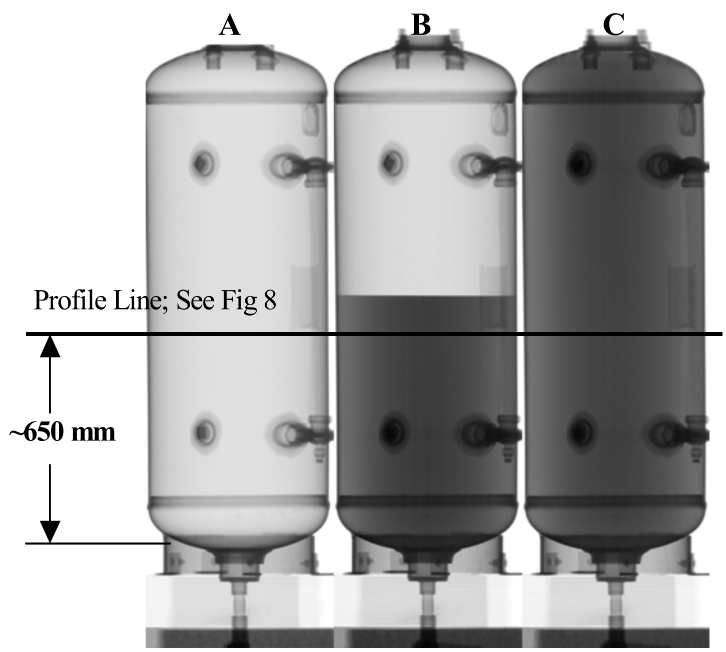

Fig. 6 Digital radiographs of test tank at three fill levels

Figure 6 shows three radiographs of a surrogate VCO tank. In these images, the tank is either empty (left image), partially full of water (middle), or full of water (right). An x-ray system that uses an LDA and acquires images by scanning a collimated x-ray source synchronously with the detector past the object was used to collect these images. The source was identical to the x-ray generator used in the VCO system. The advantage of the LDA is that it is collimated to reduce scatter resulting in a crisper image. Also, by scanning the source and detector, combined magnification artifacts are reduced in the image. However, the source and detector configuration do not impact the problem addressed by this discussion: given only the image on the right (the image of a tank full of water), is it possible to tell whether the tank is empty or full?

The pixel intensity at a point in radiograph is roughly proportional to the pathlength through object and the density of the material along that pathlength. Denser materials in an object attenuate (absorb or scatter) x-rays more than less dense materials, and thus, fewer x-rays will be detected in the region of an image that is in the shadow of denser materials compared to regions outside that shadow. Similarly, a longer path through a material (the more material that is "in the way"), results in a more attenuated x-ray beam.

The detector signal is proportional to the number of x-rays that interact in a detector element, and thus, is related to the amount and density of material between the x-ray source and detector. After the data from the detector have been processed, the pixel intensity in the image is roughly proportional to the thickness and density of the object. When the image is displayed, it is the operator's preference as to whether long pathlengths are displayed as bright or dark intensities.

Consider the image of the empty tank (Tank A in Fig. 6). In cross section, the center of the tank can be considered to be a cylindrical shell. As shown in Fig. 7, the longest pathlength through the metal portion of a cylindrical shell is the path that is tangent to the inner wall of the shell while the shortest path is through the center of the shell. The cylindrical shell is a reasonable approximation to the geometry of a cross section of a tank. This variation in pathlength can be observed by plotting the pixel intensities along a line through an image of the tank. This type of plot is called a profile through the image. Figures 8 and 9 are profiles through different regions of the images shown in Fig. 6. These profiles are plots of the variation in pixel intensity for one line across the images.

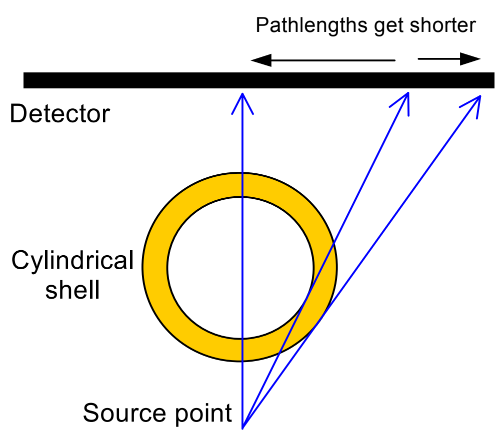

Fig. 7 Geometry describing the attenuation of x-rays through a cylindrical shell

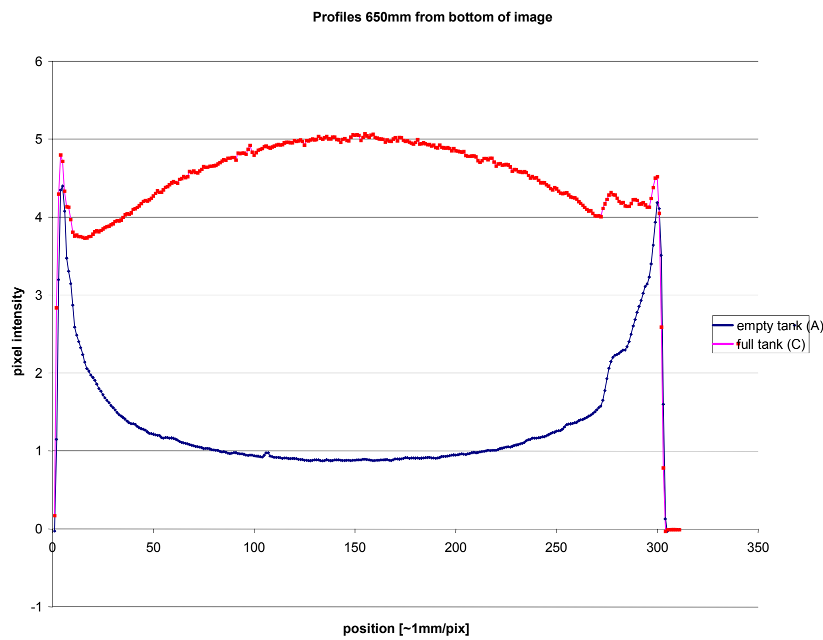

Fig. 8 Profile plot along a line through Tank A and Tank C in Fig. 6

The plot through the empty tank shows a peak near the edge and a lower intensity (thickness) at the middle. The profile of the water-filled tank shows a higher intensity (thickness) near the middle where the water pathlength is longest.

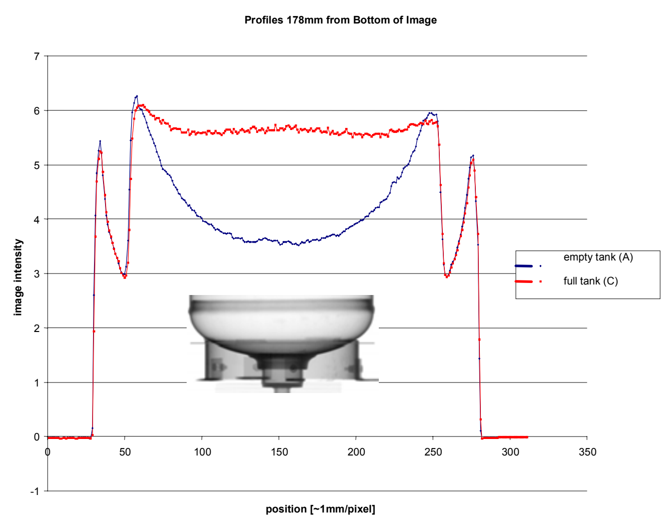

Fig. 9 Profile through the empty and full tanks near the bottom (see the bottom horizontal line in Fig. 6)

Even though the region near the bottom of the empty tank could be mistaken for a liquid in the image, the profile through that region shows a minimum at the center characteristic of an empty cylindrical shell.

The vertical axis of the pixel profiles can be considered to be roughly equivalent to a measure of the thickness and density of the object along the profile line. For example, examination of the profile through the empty tank (Tank A of Fig. 6) at 650 mm from the bottom of the image (Fig. 8, blue line) from right to left reveals the following:

- The pixel intensity on the very right side of the profile is close to zero – this region is outside the tank so effective thickness of the tank is zero
- Moving to the left, the intensity increases dramatically as the edge of the tank is "seen" by the detector
- The intensity peaks (at the position corresponding to the location of the inner wall where the pathlength is the longest) and then falls off to a minimum at the center of the tank before rising again toward the opposite edge.

If the tank was a uniform solid, then the pixel intensity (thickness through the solid object) would increase monotonically from the edge to the middle.

Now consider the profile through the water-filled tank (Fig. 8, red line). A similar intensity variation is apparent at the edges of the tank (the tank is identical in both cases), but in the center, the filled tank displays a higher intensity, corresponding to a longer effective thickness. The higher pixel intensity is due to the thickness of the metal wall and the thickness of the water fill in the interior of the tank. If the fill material were a lower density than water, then the peak in the center would not be as high (the pathlength would be the same but the density would be less), and if the material were more dense than water, the intensity in the center would be higher. Finally, as noted above, if the fill material were the same as that of the walls of the tank, then the peak at the position corresponding to the interior wall of the tank would not be apparent.

Thus, by looking at a profile through an image of a tank it can be determined if the tank is empty or full of some moderate-density material. Note that with this type of x-ray system, it will not be possible to tell if the tank is full of gas. Also, a tank with a thick enough wall to attenuate most of the x-ray beam (wall thickness of ~18-25 mm steel for this system) will appear in profile to be a solid metal tank and it will not be possible to tell if there is any fluid inside.

Finally, consider a region near the bottom of the empty tank (denoted by the horizontal line in the inset image of Fig. 9). It is not clear if that region near the bottom of the tank represents a fluid or a thicker wall on the tank. The two peaks near the edges of the profile through the empty tank (Fig. 9) correspond to the edge of the tank itself and to the cylindrical base on the outside of the tank. Once again, in the center of the empty tank the effective path length (intensity) falls off, while in the full tank the intensity is nearly constant toward the center of the tank. (The intensity is not as high in the center as in Fig. 7 since the tank bottom is not as thick, and thus the water path is not as long.) Since the profile through a uniform cylindrical shell must be lowest at the center, this tells us that there is fluid in the profile through the full tank, and more importantly, that the empty tank is indeed empty.

FUTURE USES

The INEEL anticipates a variety of uses for this equipment. The INEEL Waste Generator Services may use the system to interrogate suspect boxes or drums. Security Services may use the device to interrogate suspect packages. The Decontamination and Decommissioning Program may use the system to verify emptiness of pipes, drums, tanks, or other equipment.

REFERENCES

1 B. R. Monson, IDEQ, to D. N. Rasch, DOE-ID, Enclosure: "Consent Order," Idaho Code § 39-4413, June 14, 2000.

2 DOE-ID Order 420.D, "Requirements and Guidance for Safety Analysis," U.S. Department of Energy Idaho Operations Office, July 17, 2000.

3 10 CFR 830 Subpart B, "Safety Basis Requirements", *Code of Federal Regulations*, Office of the Federal Register, February 4, 2002.

FOOTNOTES

i References herein to any commercial product, process, or service by trade name, trademark, manufact8urer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government, any agency thereof, or any company affiliated with the Idaho National Engineering and Environmental Laboratory.