APPLICATION OF ADVANCED RADIOGRAPHIC IMAGING TECHNIQUES FOR CHARACTERIZING LOW LEVEL NUCLEAR WASTE

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ABSTRACT

BIR is currently investigating the use of two advanced x-ray imaging techniques for characterizing containers of solidified nuclear waste. These techniques, digital radiography (DR) and computed tomography (CT), are performed by computerized imaging systems that can automatically inspect containers using a set of imaging parameters chosen by the operator. Both inspection techniques can be performed by the same imaging system. The inspection result is a computer image, or series of images, that can be manipulated by the operator to show a wide variety of features within the inspected object.

For the inspections performed so far, we have used the ACTIS CT/DR system that BIR designed and built for NASA's Marshall Space Flight Center. The inspections are being performed as part of a continuing Phase I/Phase II SBIR program for the U.S. Department of Energy. This paper discusses inspections performed on three types of waste containers: (1) a simulated waste drum imaged in Phase I; (2) 55 gallon drums of assorted waste items supplied by the DOE's EG&G Rocky Flats plant and by Westinghouse Hanford; and (3) several containers of glass used for solidifying radioactive substances, supplied by the DOE's Westinghouse Savannah River site. The Phase II work also includes investigating dual energy CT imaging and designing a mechanically simplified ACTIS system and mobile trailer specifically for waste inspection.

BACKGROUND OF WASTE INSPECTION AND THE ADVANCED TECHNOLOGIES

BIR is currently working on a Phase II SBIR program for the Department of Energy to validate two x-ray inspection techniques — digital radiography (DR) and computed tomography (CT) — for inspecting containers of low level nuclear waste (LLW)and high level waste (HLW). For the validation inspections, we have imaged several types of containers used for long term storage of nuclear waste. Some representative results are presented here. The Phase II work also includes designing a DR/CT system optimized for waste container inspection.

Current Radiographic Inspections of Low Level Waste

Of the current methods commonly used to inspect LLW containers, only one is noninvasive: real time radiography. Other methods, including coring and hardness testing, require opening the container to perform testing. This type of inspection is time consuming, costly, and, in the case of coring, makes it necessary to repackage the waste in a new container.

Currently used real time radiography (RTR) does not require opening or damaging the container, but it has limitations for waste inspection. The first is that the x-ray source energy is limited. X-ray detectors work by absorbing the x-rays that pass through an object and measuring their intensity through each part of the object. But the type of x-ray detectors used for RTR (image intensifiers, screen scintillators) have poor x-ray stopping power, which limits contrast resolution. The typical maximum source energy used for RTR has been 420 kV — but 420 kV x-rays will not penetrate more than about 10 cm of steel or 50 cm of cement. (There is one site using MeV-range sources for drum inspection.) The result of this is that there is no image detail in dense objects within a container, and a large or dense container cannot even be imaged. Our experience has shown that a source energy of 2 MeV or above is required for barrels of cement, glass, or other densely packed materials.

The limited contrast resolution of RTR means that there is a small number of intensity levels that are detectable in the image. (The image intensity levels correspond to the density levels in the object.) Contrast resolution for an RTR system is usually no better than about 60 intensity levels, and that is achievable only with a perfect exposure. With this range of contrast, it is not possible to see the difference between, for example, plastic and glass.

A further limitation of RTR is that there is no three-dimensional information in the images. The projection image on a real time monitor has the same appearance as a conventional film x-ray — features in the object being inspected are overlapped, and it is difficult if not impossible to determine which features are in front of others. A dense feature that absorbs all x-rays will also completely obscure any other features in front of or behind it.

RTR does have two advantages over the more advanced x-ray techniques of DR and CT: imaging speed and equipment cost. The RTR image is produced instantaneously, since the detector system has a simple video output to a TV monitor. In-motion RTR can depict moving liquids in a can. For DR, data has to be collected and digitized, then displayed on a computer screen in a freeze-frame mode. CT requires taking data from all angles around the object, meaning that the object must be moved back and forth past the detector system at different angles; CT also requires mathematical reconstruction of the digital data that is collected during inspection. DR/CT system costs are several times higher than RTR system costs because they require sophisticated computers, very precise mechanical systems under computer control, and detectors with much higher dynamic range.

Computed Tomography and Digital Radiography

X-ray computed tomography was developed in the 1970s as a medical diagnostic technique, used in the popularly known "CAT scanner." CT collects x-ray data through axial planes, or "slices," through an object. The concept of CT is illustrated in Fig. 1. The object translates between the source and detectors, rotates, and then translates back. Data is collected during the translation phase. Enough passes are performed to collect data from all around the object. After collecting a complete set of x-ray projections around an object, the CT system mathematically combines the data to form a two-dimensional image. This image represents a cross section of the object, without the overlapping of features seen in projection x-ray techniques. In the 1980s, CT was applied to many industrial uses, and CT scanners for general industrial applications were designed and built.

Since most CT systems use a linear array of small x-ray detectors to collect one-dimensional x-ray projections, they were easily adaptable to perform digital radiography. This technique produces an image similar to a projection radiograph, by moving the x-ray source and detectors linearly past the entire length of the object and collecting narrow lines of data at brief time intervals, similar to the technique used by airport baggage inspection systems. (The object can also be moved past the stationary source and detectors.) The concept of DR is illustrated in Fig. 2. The x-ray measurements are digitized and then displayed as a two-dimensional image. While a DR image is similar to an RTR image, it has much higher contrast resolution because of the detectors used – as many as 65,000 intensity levels can be present in a DR image. In addition, having the image in digital form allows a wide range of image enhancement functions to be performed.

INSPECTIONS IN THE PHASE I PROGRAM

During the Phase I SBIR program, we constructed a phantom to simulate an actual waste storage container. The phantom consisted of a 55 gallon drum containing cement and other materials, with various inclusions and internal features. We then inspected the phantom using the ACTIS high-energy CT/DR scanner designed and built by BIR and installed at NASA's Marshall Space Flight Center (MSFC). Figure 3 is a photograph of the phantom after it was disassembled, showing its different sections. Figure 4 shows the ACTIS scanner, which is designed to inspect aircraft and aerospace components as large as 2 meters in diameter and 2 meters high, and weighing up to 2,500 kg. It has three radiation sources, including the 420 kV x-ray tube and the 2 MeV linear accelerator used to produce the images in this paper.

Figure 5 is a DR image of the Phase I phantom. Six of the phantom's seven layers are shown in the image; inhomogeneity of the cement in the second layer from the top and the plywood separators between the layers are visible. Figure 6 is a CT image of one of the phantom's seven layers. The layer is cement with a 13 mm wide water rim around half the circumference; the cement is saturated with water as well. From such an image, the volume of water can be calculated; the volume of the rim is estimated to be approximately 622 cc.

The successful Phase I results have led to the award of a Phase II program. We have reported the Phase I results in the Phase I final report and in a previous paper.

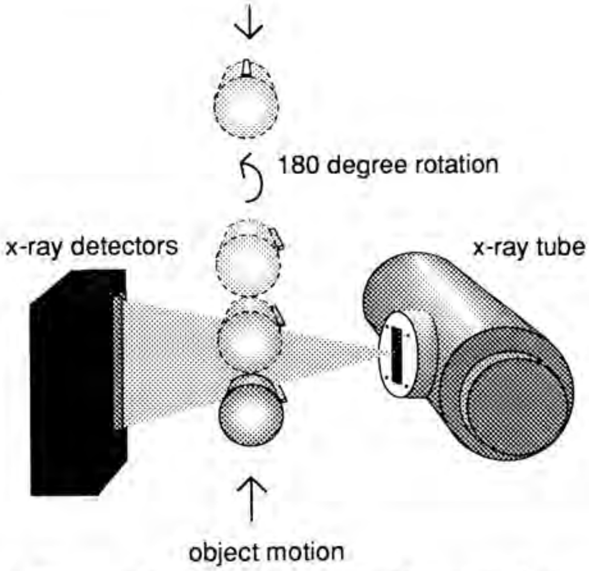

Fig. 1. The drawing shows the concept of computed tomography (CT) scanning as performed by ACTIS, viewed from the top.

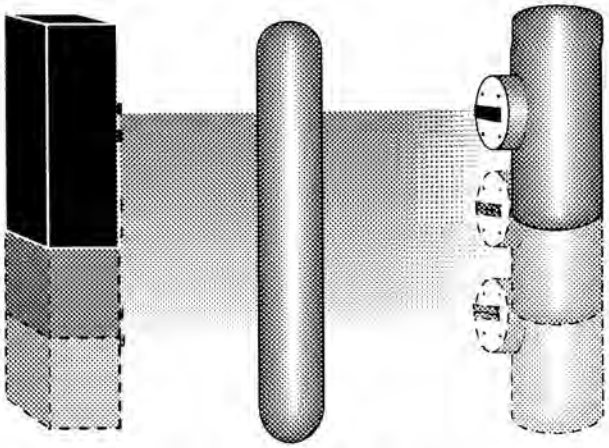

Fig. 2. This drawing shows the concept of digital radiography (DR) scanning, viewed from the side.

Fig. 3. The photo shows the disassembled phantom used for the Phase I inspections. The sections were mounted inside the drum.

Fig. 4. The photo shows the ACTIS CT/DR scanner.

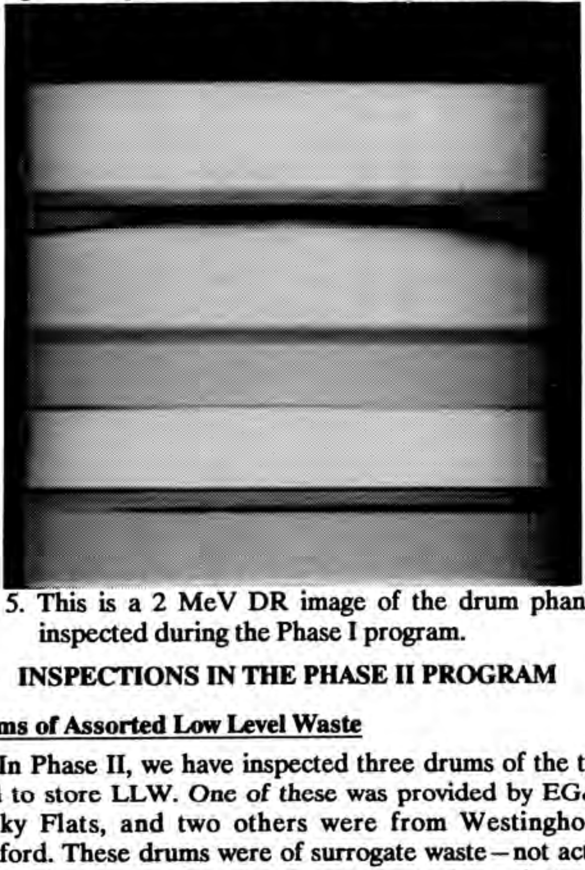

Fig. 5. This is a 2 MeV DR image of the drum phantom inspected during the Phase I program.

INSPECTIONS IN THE PHASE II PROGRAM

Drums of Assorted Low Level Waste

In Phase II, we have inspected three drums of the type used to store LLW. One of these was provided by EG&G Rocky Flats, and two others were from Westinghouse Hanford. These drums were of surrogate waste — not actual radioactive waste — but the drums, contents, and storage method are representative of actual LLW containers. Figure 7 shows one of the drums mounted on the ACTIS turntable for inspection.

Figure 8 is a DR image of the drum from EG&G. It was prepared with several layers, which are separated by plywood dividers. The scan was made using a 2 MeV source energy, and on the ACTIS system took about four minutes. (A scanner designed specifically for the application will be much faster.) Figure 9 is a CT slice through the lower part of the drum, where a large dense (white) mass is visible in the DR image.

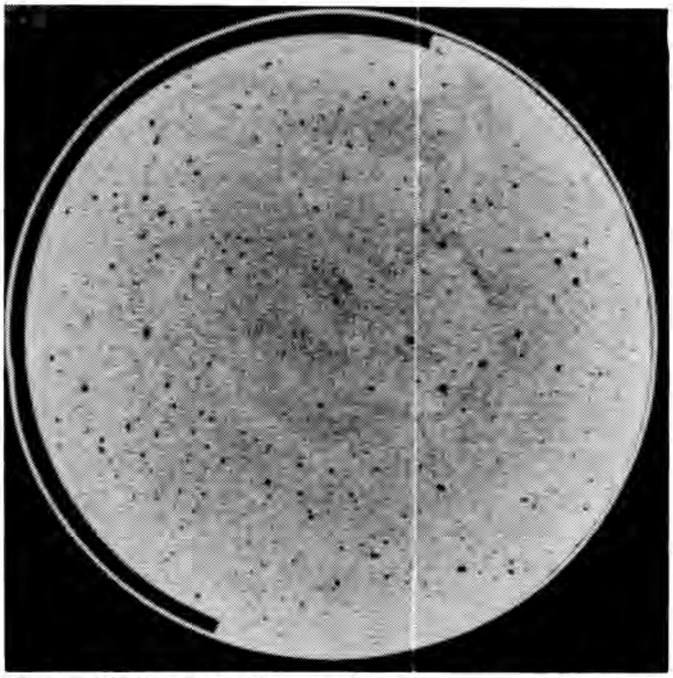

Fig. 6. This 2 MeV CT image of the drum shows a water-saturated cement disk with a water rim along the left edge. The smallest pores visible are only fractions of cubic millimeters in size.

This mass, a cylinder of cement, is the white circle in the CT image. Next to it is a lead-lined glove containing a filter; cross sections of the glove's fingers appear as circles at the far left.

Figure 10 is a DR image of one of the drums from Westinghouse Hanford; it is displayed in reverse video, making it look like a conventional film radiograph or RTR image. The numbers at the upper left are made of lead; they are part of a radiography test object. A glove is visible at the upper right. The second level contains several spray cans (two of which are partially full), the third level contains bottles with varying levels of different substances,and the bottom level contains several unidentifiable objects as well as a scissors and a can lying on its side. The separators between the levels are supported by the three threaded rods clearly visible in the image. Figure 11 is a CT image of the drum through the second level. The one spray can standing appears as a circle, and the three cans lying down are shown in longitudinal cross section. The can with the gray interior is full (at least to the slice height). Figure 12 is a CT image through the bottom level, showing the internal structure of a square filter and a cross section of an empty paint can with a lid on it. The three supporting rods are visible, and the bright white object beside the rod at the top of the image is the scissors. All of the objects are contained within a liner, which is not apparent in the DR image.

Figure 13 is a DR image of the second Hanford drum. The dense white mass at the bottom is probably a crumpled lead-lined cloth or actual sheet of lead. Several cylindrical objects are visible above this. Figure 14 is a CT image of the drum. The long cylinder is a fire extinguisher, partially full; the objects at the top left of the image are part of the nozzle and handle assembly.

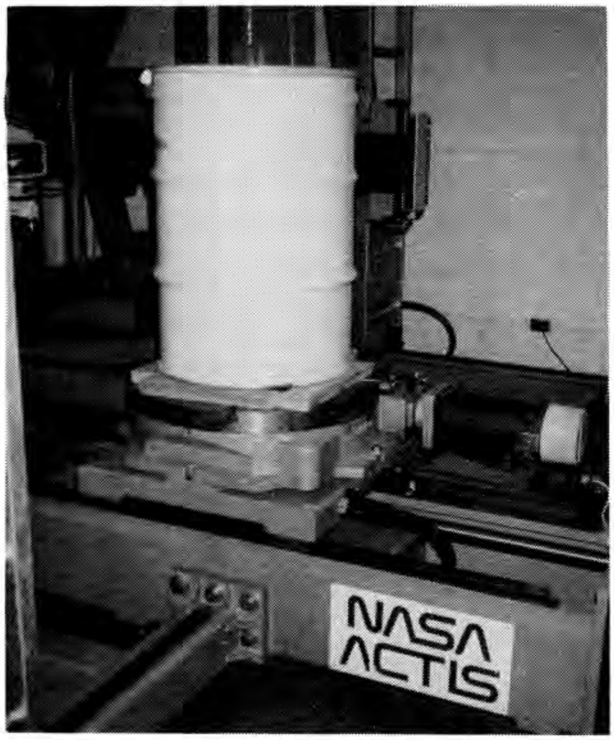

Fig. 7. The photo shows a 55 gallon drum of surrogate LLW mounted on the ACTIS turntable for inspection.

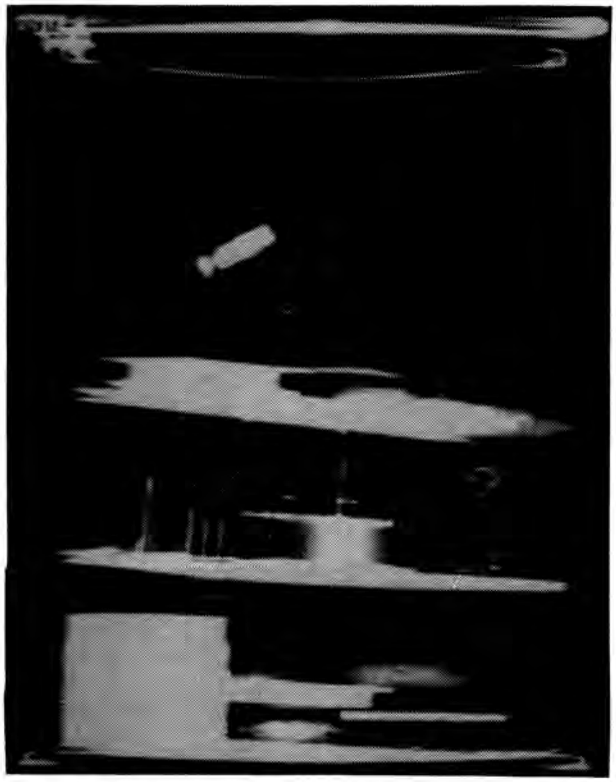

Fig. 8. This DR image of a 55 gallon drum of assorted waste clearly shows the drum liner, a number of cans and bottles, and a dense cylinder at the lower left.

Fig. 9. The white circle in this 2 MeV CT image is the dense object at the bottom of the DR image. A lead-lined glove containing a filter is in the center.

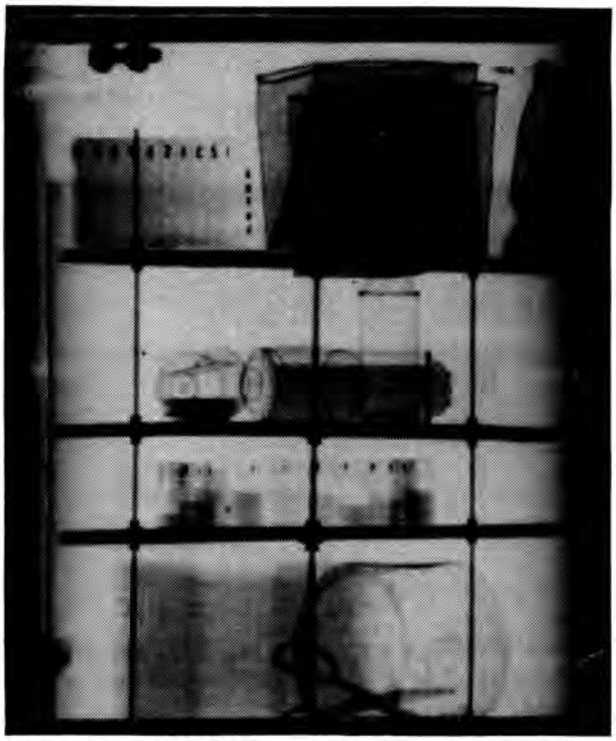

Fig. 10. This 420 kV DR image shows four layers, with separators supported by threaded rods between them. Many items are easily identifiable.

Solidifying Waste Forms for Radioactive Materials

During Phase II we have also inspected several glass forms used to solidify radioactive materials. These, like the drums, have been surrogate forms, without the actual radioactive material. The CT/DR inspection is valuable to compare techniques used for pouring and curing the glass, as well as to check individual containers for faults in the medium.

Fig. 11. This zoomed 420 kV CT image shows spray cans visible in the DR image. The can at the top is full; the circle is a can standing upright.

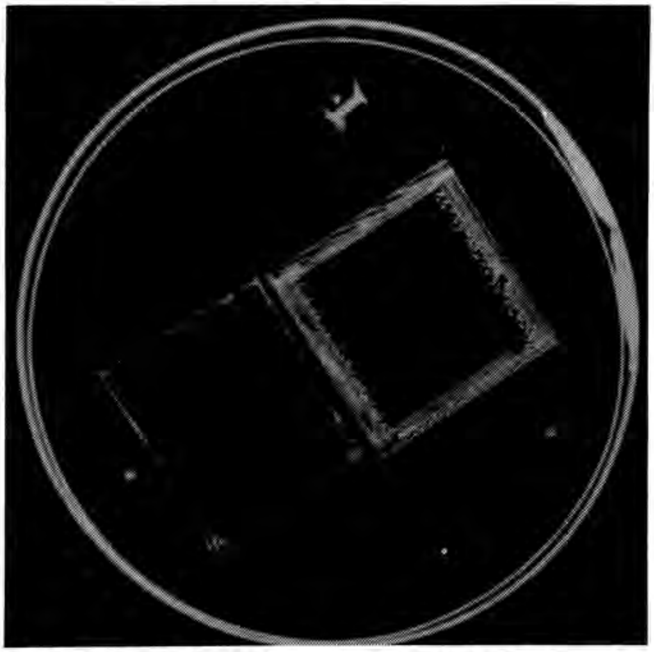

Fig. 12. This 420 kV CT *image* is through the bottom of the drum, showing the cross section of a paint can and a square filter.

Figure 15 is a photograph of three stainless steel beakers of glass mounted on the ACTIS turntable for inspection. These beakers are about 10 cm in diameter, and contain test pours of the glass material, each having been poured or cured in a different way. Figure 16 is a CT image of the beakers; in this image, different types of defects are visible in each beaker. Figure 17 is a DR image of the beakers. The image is shown at two window levels, the first to show detail in the single beaker at the left, and the second to show detail in the two superimposed beakers at the right (with the left beaker completely windowed out).

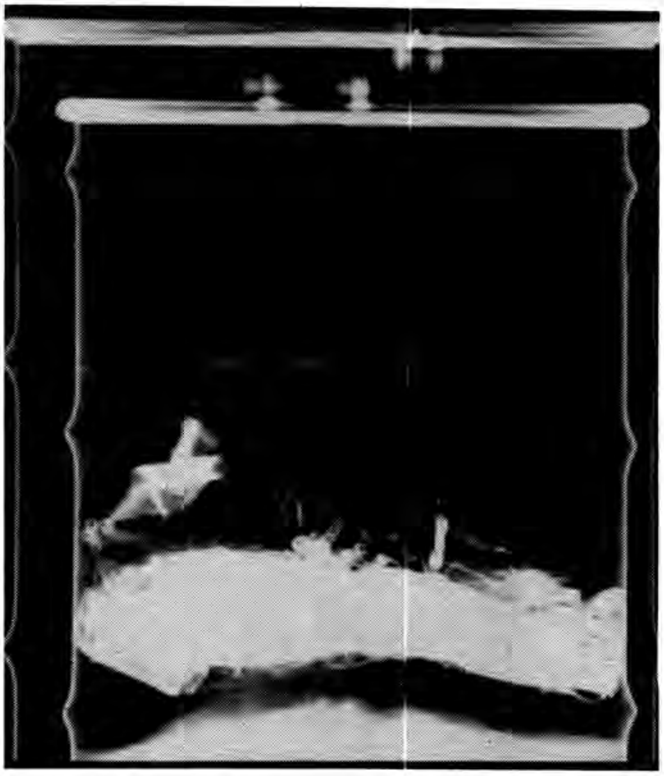

Fig. 13. This 420 kV DR image is of another drum, with a smaller drum used as an inner liner. The white mass at the bottom is probably lead sheet or cloth, which almost completely stopped the x-rays.

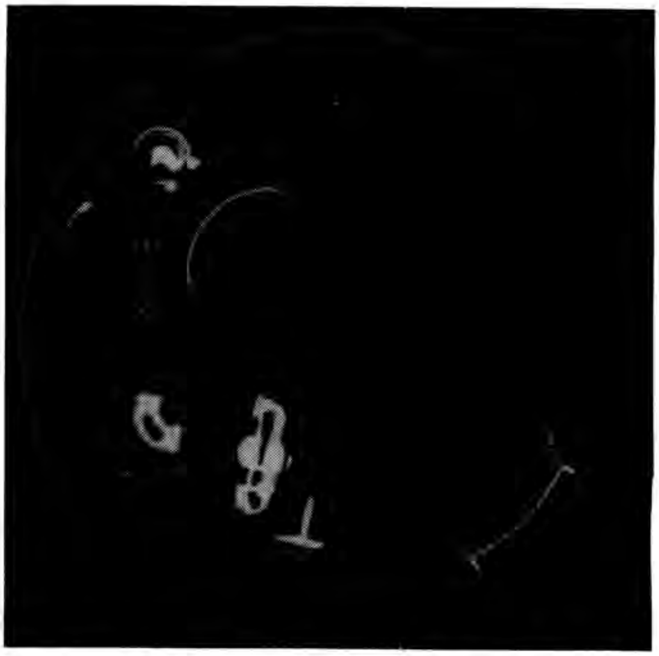

Fig. 14. This 420 kV CT image of the drum from Fig. 12 shows a fire extinguisher that is partially full. Part of the nozzle and handle are visible; another dense object (probably steel) is at the lower left.

Figure 18 is an image of a set of three cans of different types of solidifying plastic. The specific gravities of all three

Fig. 15. This photo shows three stainless steel beakers mounted on the ACTIS turntable for scanning. The beakers contain a type of glass used to solidify high level radioactive waste.

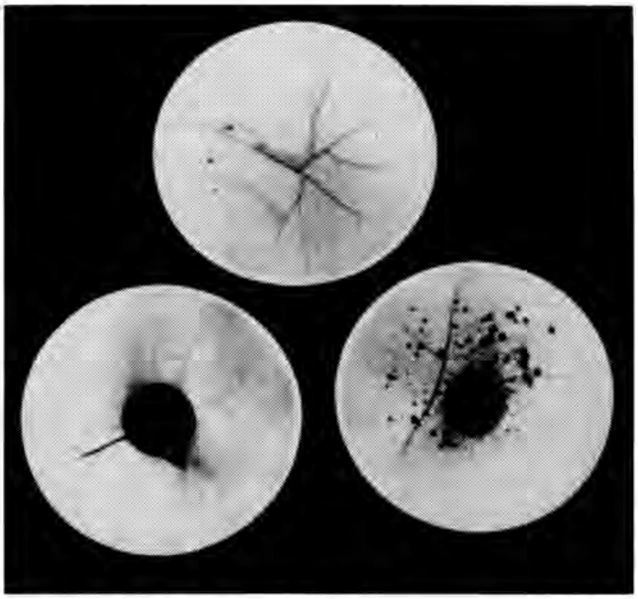

Fig. 16. This is a CT image of the beakers shown at the left. The three different types of pours show different types of flaws.

of the materials are very close, between 0.9 and 1.0; however, the density differences among the three are clearly distinguishable in the image.

Figure 19 is an image of a 30 cm diameter glass form, showing many cracks, separations, and low density areas in the glass. Figure 20 shows a 60 cm diameter glass form; the grain structure is visible, and there is a separation at the lower left and a hairline crack near the center.

CONTINUING PHASE II WORK

Scanner Design

We are currently designing a DR/CT scanner that will be optimized for inspecting the waste containers described in this paper. This scanner will be similar to ACTIS, but it will not require ACTIS's mechanical complexity; this will make the system less expensive than ACTIS. We are also incorporating new technology to increase the scan speed by several times. The system will be able to inspect four to six 55 gallon drums per hour (depending on the number of CT images taken), or a larger number of smaller containers.

While some waste handling sites will have need for a dedicated inspection system for continuous use, others will only need a system for a short time or during certain operations, such as cleaning up waste sites and repackaging the contents of damaged containers. To make short-term use of a scanner cost effective, we are designing not only a fixed-site scanner but also a transportable unit. This approach is popular with medical imaging systems, which are too expensive for small hospitals to buy and maintain; the scanner and its entire facility are housed in a semi-truck trailer that is specially designed and equipped to support the system. We are working with a major manufacturer of these mobile scanner facilities to design a fully transportable inspection system. It will be installed in a radiation-shielded 12 meter trailer with all the required power supply equipment.

The inspection scenario will involve loading each container and performing two DR inspections with the barrel turned 90_ between them. Collecting the data and displaying it will take about one minute for a 55 gallon drum. The operator will then review the DR image in much the same manner as reviewing an RTR image, though it will be possible to change the DR image windowing attributes to emphasize features in the object. If there are no questionable features in the container, the operator can go on to the next one. If there are indications of improper solidification, breaches in the liner, or other problems with the container, the operator can mark locations on the DR image where CT images can be taken to gather more precise data. The system will then automatically move the object to the marked location(s) and perform a CT scan. Collecting and displaying a CT image will also take about a minute; if more than one CT image is being made, the operator can review the first image while data for subsequent images is being collected.

Dual Energy CT Scanning

While CT images can clearly show small density differences between features in an object, they are limited in the information they can give about the actual material of which the features consist. We are developing a technique known as dual energy scanning that will enable us to gather information about the effective atomic number of materials in a waste container.

To perform dual energy scanning, two reference materials are first scanned at two different energies. This produces calibration data that is used for the dual energy data processing. The object being inspected is then scanned at two energies, and the data collected is processed using the calibration data. The final result is a CT image that maps the atomic numbers of the object's constituent materials, and an image

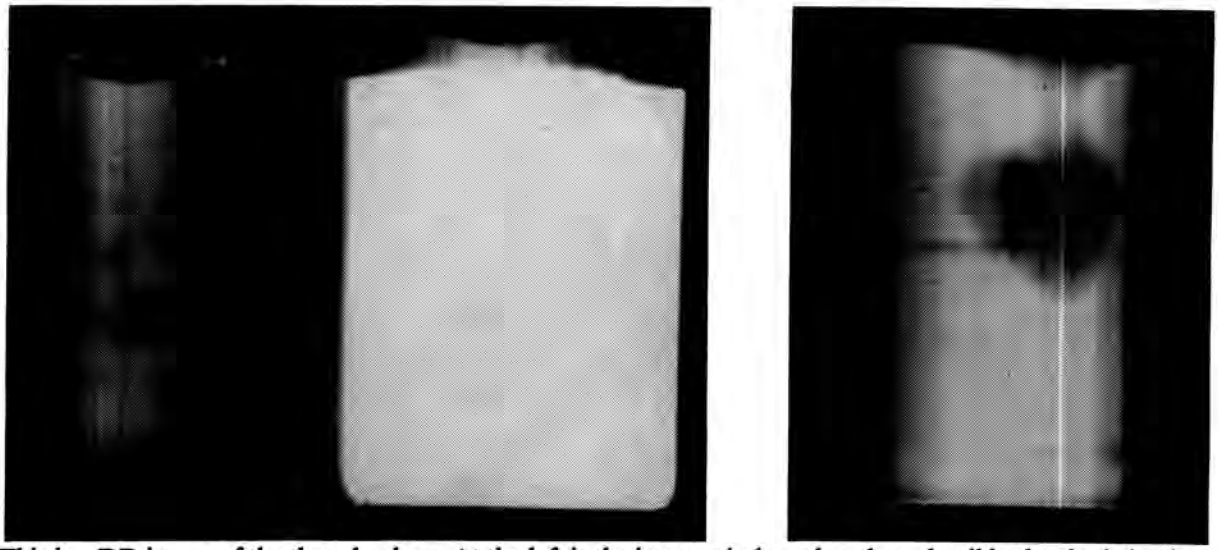

Fig. 17. This is a DR image of the three beakers. At the left is the image windowed to show detail in the single beaker; the two beakers superimposed are the bright white form. At the right the window level has been changed to show detail in the two superimposed beakers. Note that it is not possible to tell which beaker contains the large void (the dark area in the middle).

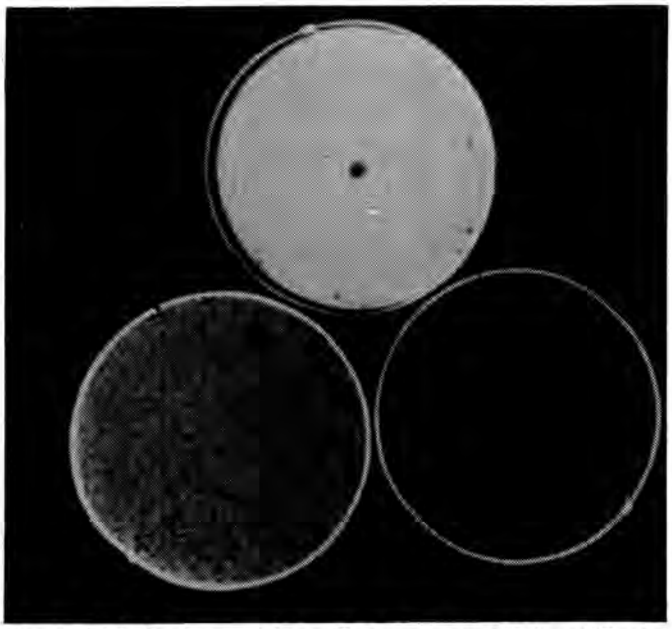

Fig. 18. This CT image shows three cans containing different types of solidifying plastics. All three have a specific gravity between 0.9 and 1.0; the image clearly shows differences in the density and grain structure.

that displays the actual physical density of the materials. The "density" that is said to be displayed by a conventional CT image is actually an unknown function of the values for each of these two properties.

Figure 21 is a CT image of a dual energy phantom, which is made of sand containing seven bottles. Each bottle contains a different liquid, each having a different effective atomic number. We scanned this phantom and are using the data collected to generate a standard dual energy processing technique, with the known atomic number values of the liquids serving as reference data. The specific gravities of the fluids in these bottles range from 1.0 to 1.15, and the effective atomic numbers are between 7 and 10.

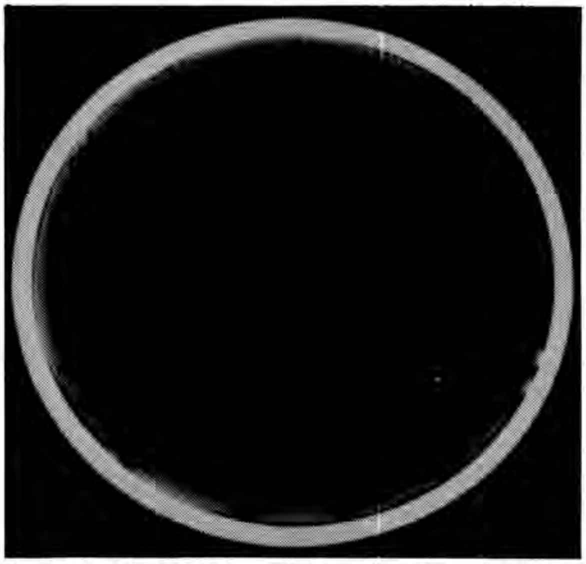

Fig. 19. This CT image shows a 30 cm diameter glass form. The glass has many cracks and voids.

CONCLUSION

The research we have performed so far have verified that x-ray digital radiography and computed tomography provide much more information about the materials in a LLW container than can be obtained by other currently used inspection technologies. Phase II is designed to demonstrate specifically that DR and CT can quantify density, dimensions of volumes, and atomic number. The primary drawbacks of DR and CT to this point have been inspection speed, and equipment cost and portability.

With the system design we are creating during the remainder of the Phase II program, we are addressing all three of these of these limitations. Designing a mechanical system optimized for the containers to be scanned and using an improved computer and image processor developed by BIR will increase the speed; either a DR or CT image can be collected and displayed in a minute or less. The simplified

Fig. 20. This CT image shows a 60 cm diameter glass form. There are gaps between the glass and the container, and cracks in the glass.

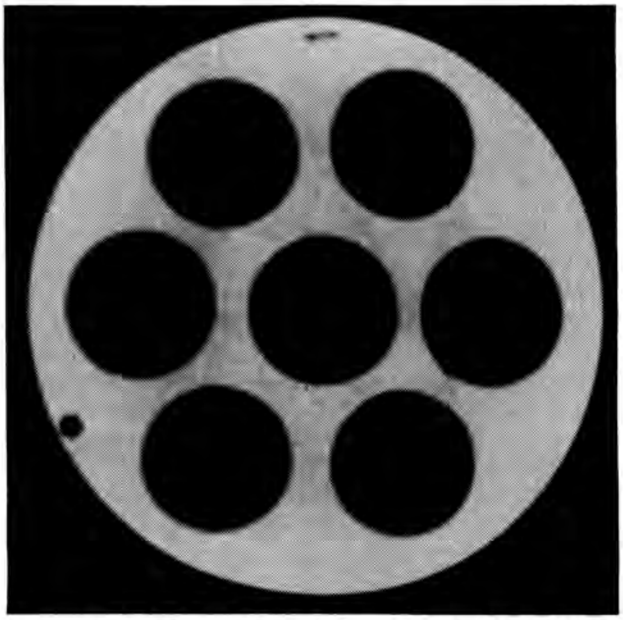

Fig. 21. This CT image shows a phantom used to collect data for dual energy processing. Each dark circle is a bottle containing a different fluid with a different effective atomic number. The fluids in the bottles are water with different percentages of dissolved salts.

mechanics and BIR's new PC-based computer system will both contribute to significant cost savings; the single most expensive component will be the linear accelerator source required to penetrate large, dense containers. If only smaller containers are to be inspected, using a 420 kV x-ray system would lower the cost even further. The system design for a transportable scanner installed in a truck trailer will allow one system to be used at many sites that do not have the need for continuous inspection.

ACKNOWLEDGMENTS

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The dual energy work for this program is being performed by Dr. Ilan Zmora of BIR.