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Waste Inspection Tomography (WIT)

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2.4 Waste Inspection Tomography (WIT)

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Introduction

Waste Inspection Tomography (WIT) provides mobile semi-trailer mounted nondestructive examination (NDE) and assay (NDA) for nuclear waste drum characterization. WIT uses various computed tomography (CT) methods for both NDE and NDA of nuclear waste drums. Low level waste (LLW), transuranic (TRU), and mixed radioactive waste can be inspected and characterized without opening the drums.

With externally transmitted x-ray NDE techniques, WIT has the ability to identify high density waste materials like heavy metals, define drum contents in two- and three-dimensional space, quantify free liquid volumes through density and x-ray attenuation coefficient discrimination, and measure drum wall thickness. With waste emitting gamma-ray NDA techniques, WIT can locate gamma emitting radioactive sources in two- and three-dimensional space, identify gamma emitting isotopic species, identify the external activity levels of emitting gamma-ray sources, correct for waste matrix attenuation, provide internal activity approximations, and provide the data needed for waste classification as LLW or TRU. Objectives

The mobile feature of WIT allows inspection technologies to be brought to the nuclear waste drum storage site without the need to relocate drums for safe, rapid, and cost-effective characterization of regulated nuclear waste. The combination of these WIT characterization modalities provides the inspector with an unprecedented ability to non-invasively characterize the regulated contents of waste drums as large as 110 gallons, weighing up to 1,600 pounds. Any objects that fit within these size and weight restrictions can also be inspected on WIT, such as smaller waste bags and drums that are five and thirty-five gallons.

Background Information

X-ray imaging is an established method for waste container inspection. The technique generally used is real-time radiography (RTR) using a 420 kV radiation source, in which a TV camera is coupled to a two-dimensional, light-producing x-ray detector, such as an image intensifier or a scintillation screen. The camera output provides a TV image that is viewed on a monitor during x-ray exposure which, as an example, can see the motion of a moving liquid surface. However, RTR systems have several

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disadvantages. Area x-ray detectors typically suffer from blooming artifacts that limit spatial resolution. RTR systems have limited contrast discrimination with a true dynamic range of usually less than 14-bits (16,384 gray levels in the image), meaning that contrast in a single exposure is limited. RTR typically does not provide quantitative information, since the data is not in digital form. It limits geometric depth perception because of super-positioning, and it lacks quantitative information including two- and three-dimensional spatial measurements and density measurements. The combination of 420 kV source and a restricted detector dynamic range limits RTR penetrating and discrimination capability for inspecting the denser waste containers including cement-solidified drums, glass, and sludges, which make up nearly half of DOE's inventory of nuclear waste drums.

Emerging technologies for nondestructive evaluation (NDE) of low level, transuranic, and mixed nuclear waste like WIT include high-energy 2 MeV x-ray computed tomography (CT) and digital radiography (DR). In its conventional approach, WIT CT/DR imaging uses a curved linear array of solid-state x-ray detectors. The array is composed of individual, closely aligned detection channels. The channels are separated by thin septa that minimize crosstalk and blooming, while offering superior spatial and contrast resolution with high image quality, compared to real-time approaches. These detectors have enough dynamic range to provide contrast sensitivity of 18-bits (up to 262,144 gray levels). The greater the dynamic range and penetrating radiation, the greater the advantage in examining denser waste forms mentioned above. Thus, the WIT approach can image nearly all dense DOE waste streams with even faster throughput for the lighter waste forms. This cannot be said for the more commonly used RTR x-ray imaging systems.

For WIT CT, x-ray projection data is collected from a thin plane of the object, using a linear detector array on the arc of a curve while the object rotates within a thin x-ray fan beam with spiral-like motion capability. This technique is called third-generation CT. The data are mathematically combined to form a cross-sectional image of the thin, irradiated plane or slice. Slices can be stacked to form a volume rendering of drum content. In WIT DR, the drum is moved vertically in front of the linear detector array while projection data is collected one line at a time. These techniques measure the x-ray attenuation of the waste matrix and drum. The lines are then displayed as a two-dimensional, freeze-frame projection image (like a baggage inspection x-ray) for DR.

Active CT on WIT is similar to the conventional x-ray CT techniques. The difference is that a radioisotopic source and single channel high purity germanium detector are used with a first-generation CT approach. A CT data results in the absolute determination of the attenuation of the drum and its contents.

Two emission imaging techniques are employed on WIT for characterizing materials in waste containers. The first of these is gamma emission tomography, commonly called single-photon emission computed tomography (SPECT). Rather than measuring gamma-rays from an external radiation source, SPECT measures the gamma-ray emission inherent in the radioactive waste emitting from within the drum. In this case, emission from actual nuclear waste within a container can provide three-dimensional volume or slice data of the radioactive sources within the container. SPECT uses large area sodium iodide crystals with a two-dimensional array of photomultiplier tube (PMT) detectors for rapid localization of gamma-ray emissions in two-dimensional space and 3-D with SPECT. These area cameras are called Anger cameras.

The second WIT emission technique uses

an energy sensitive single channel high-purity germanium detector for gamma-ray nuclear spectroscopy. This technique, called nondestructive assay (NDA), can directly identify the emitting isotopic species and the external radioactivity.

Project Description

Bio-Imaging Research, Inc. (BIR), from Lincolnshire, Illinois has completed Phase I over 23 months involving the design, fabrication, factory testing, and evaluation of WIT. BIR has designed the trailer and multiple inspection techniques including DR, CT, SPECT, and area gamma-ray imaging. BIR has also developed the WIT operational software, the computer hardware, and the gantry mechanical systems. Lawrence Livermore National Laboratory (LLNL), as a subcontractor to BIR under a Work-for-Others agreement with BIR, has developed the A&PCT scanning technique and is participating in WIT evaluation.

Phase II, beginning in August, 1995, is a twelve month program for the integration and DOE site demonstration of WIT. Early BIR efforts prior to WIT involved investigating the feasibility of using CT to characterize nuclear waste between 1990 and 1993 under Small Business Innovative Research (SBIR) grants from DOE. WIT is a Program Research and Development Award (PRDA) contract number DE-AC21-93MC30173. The WIT PRDA is funded by Environmental Management's (EM) Office of Technology Development (OTD/EM-50) for the United States Department of Energy (DOE). DOE has in excess of 1,000,000 nuclear waste drums currently stored at nearly 50 sites within the United States that need to be characterized over the next few years before permanent disposition.

The three WIT detection technologies include a linear array of solid-state high-energy x-ray detectors, two area gamma-cameras, and a single high purity germanium detector. The throughput of WIT inspection is dependent on the physics of the drum being inspected. As an example, the lighter the drum weight, the faster the WIT NDE inspection, and the higher the drum radioactivity, the faster the NDA inspection. The reverse is also true where heavier drums with little radioactivity will require longer inspection times. Ideally, WIT is designed to inspect four drums per hour. Throughput extremes could yield inspection times of between one and seven drums per hour for each technology employed.

The WIT linear detector array is curved and consists of 896 individual channels of cadmium tungstate ($CdW4$) crystals mounted on individual photodiodes with thin septa between channels to eliminate crosstalk, blooming, and in-plane scatter. These detectors have an 18-bit (262,144 gray levels) dynamic range for analog-to-digital conversion. The wide dynamic range is used in WIT to image the variety of material densities and geometries found in DOE waste streams, including combustibles, glass, cement, sludges, and metals that may be present in the same drum. The linear array utilizes a 2 MeV high-energy accelerator as an externally transmitted radiation source using a thin fan beam output with a measured flux of 70 rads per minute at one meter. This high-energy source is needed to penetrate the denser and thicker DOE waste forms like glass logs, sludge, and cemented drums, while allowing for an optimum inspection throughput. The use of energies above 2 MeV is not practical for WIT because of WIT's mobile requirements resulting in weight restrictions for radiation shielding limiting close operator interaction.

The WIT linear detector array and 2 MeV source provide for single pass digital radiography (DR), which yields a freeze frame projection x-ray image (e.g., like a chest x-ray) using an imaging technique similar to x-ray baggage inspection systems with the drum elevating through a stationary horizontal fan beam of x-rays. A single DR drum view at 2 MeV with wide dynamic range can be acquired in less than 30 seconds with only one x-ray technique. Unlike RTR, both high and low density objects can be examined with WIT DR using a single DR image due to the wide dynamic range.

The linear array and 2 MeV source also provide for transmission computed tomography (CT or TCT) with cross-sectional (two-dimensional) slice and volume (three-dimensional) imaging of drum content based on density distribution. WIT TCT slice thickness ranges from 2 mm to 10 mm through the drum. CT images are acquired by simple drum rotation for data collection and drum elevation for slice location. CT is used for waste drum content identification with a spatial resolution of nearly 2 mm and a density sensitivity of nearly 1%. Typical CT reconstructions and DR images have formats of 256 by 256, 512 by 512, or 1024 x 1024 pixels. Individual CT slice scan times for data collection can be as short as eight seconds for a slice or eight seconds for two slices with an optional dual array for imaging lightweight (S.G.>,1) combustible waste. WIT has slower CT scan times (as long as 20 minutes per CT slice) for dense solid glass logs (S.G. 2.7). As a bench mark, 100 slices for a low-density combustible waste filled 55 gallon drum could be acquired and volume rendered in less than ten minutes (with a dual array), whereas a glass log with a density of equal dimensions could take nearly eight hours for 100 slices. A cemented drum (S.G. 2.1) could require a scan time of less than 0.5 hours. Drum wall thickness resolution using WIT TCT is between 0.125 and 0.25 mm. Volume measurements (i.e., for free liquids) of pixels with similar density indications has nearly cubic centimeter resolution with WIT TCT.

WIT's two large area (14" x 17") detectors are each single crystals of sodium iodide in what are typically called Anger cameras. These detectors provide for rapid gamma emission drum area imaging and single photon emission computed tomography (SPECT or ECT) for slice and three-dimensional volume localization of gamma-ray emissions from a drum. Both crystals have a combined total of 110 photomultiplier tubes (PMT) for two dimensional gamma ray emission localization within the waste drum with a spatial resolution of nearly 25 mm over a cross-sectional area of the drum. An emission slice through the drum may also have a thickness of nearly 25 mm. Typical gamma emission projection images and SPECT slice reconstructions have image formats of 32 x 32, 64 by 64, and 128 by 128 pixels. Typical inspection times for a single drum can range from seven minutes to one hour, depending on the emitted gamma ray activity. The higher the activity, the faster the scan time and the reverse is also true.

The single channel, high efficiency, (>100% of that of sodium iodide), high purity, germanium detector (HPGE) uses a 50 mm on a side square collimator and an active source of 1.25 millicuries of Holmium(^{166}Ho). The HPGE detector and ^{166}Ho provide for active and passive computed tomography (A&PCT) with excellent energy sensitivity (of less than 2 kV) for nuclear spectroscopy. A&PCT on WIT are each first-generation CT techniques, each using a single channel energy sensitive HPGe detector. WIT can detect energies between 10 kV and 1.33 MeV using an 8,000 discrete channel multi-channel analyzer (MCA). This detector and source are used to determine an absolute linear attenuation coefficient of the waste drum and matrix. PCT identifies and localizes the radioactivity. The ACT data is used to correct the passive CT data for attenuation caused by the waste matrix and drum itself. The combination of both techniques results in a more accurate nondestructive assay of the waste drum. LLNL has developed the A&PCT techniques. This single detector has a spatial resolution of nearly 50 millimeters over the area with slice thicknesses of nearly 50 mm. Typical A&PCT reconstructions have formats of 14 by 14, 28 by 28, and 42 by 42 pixels. Determination of internal radioactivity approximations for waste drums have thus far shown errors between 5 and 10%. Scan time for a single slice can range from one minute to one hour, depending on the level of radioactivity.

Results

The images included in this paper were taken on-board the trailer and demonstrate CT, SPECT, and A&PCT capabilities. Fused data displays define the waste matrix surrounding gamma emitting sources within the container. WIT can quantify the internal radioactivity which has been corrected for attenuation caused by the waste matrix solely with external measurements without opening the drum.

These Phase I results shown below illustrate the visualization capabilities possible with fusion of transmission and emission images from computed tomography and projection radiographic imaging. The WIT system's combination of inspection technologies lets inspectors choose an appropriate level of characterization for each site or waste container.

Future Activities

The WIT program is managed by the government from the DOE Morgantown Energy Technology Center (METC) in Morgantown, West Virginia. During Phase II, site demonstrations of WIT are planned at LLNL in Livermore, California, Westinghouse Savannah River Company (WSRC) in Aiken, South Carolina, and at the Idaho National Engineering Laboratories (INEL) in Idaho Falls, Idaho. These demonstrations will involve characterizing real waste to validate the system's ability to identify regulated contents and to verify system throughput.

BIR plans to commercialize WIT with the successful conclusion of the PRDA contract. BIR plans to offer drum scanning/characterization services to DOE and other sites requiring mobile capabilities.

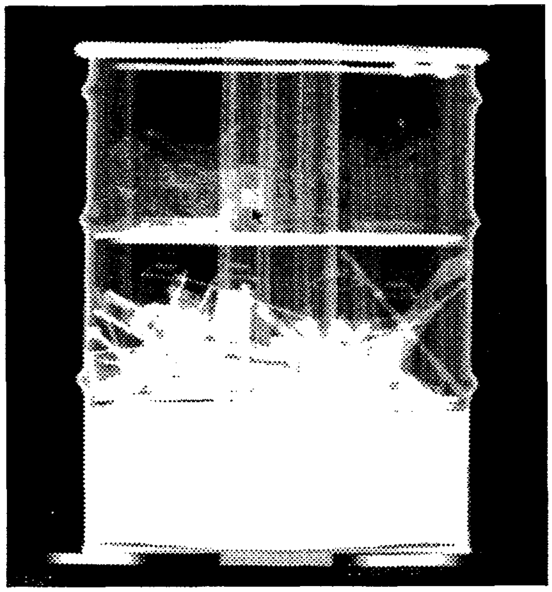


Figure 1 is a 2 MeV transmission DR projection image of a 55 gallon drum phantom. Clothing in the top layer simulates low density combustible waste. Cans of liquid, metal rods and plastic in the mid-section simulate higher density waste. Cement in the bottom layer simulates solidified high-density waste. The 133Ba isotope bottle is visible in the upper left plexiglass tube.

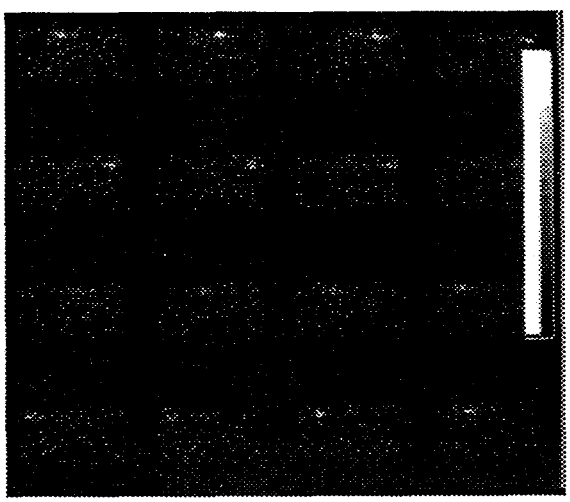


Figure 2 is a series of 16 gamma emission projection images from an Anger camera taken every 22.5 degrees of rotation from a centered radioactive test source. The emission source was 133Ba with a 360 kV peak and 250 microcuries of activity. The window used was 30% and the integration time was one minute for a single view. Shorter data collection times are possible.

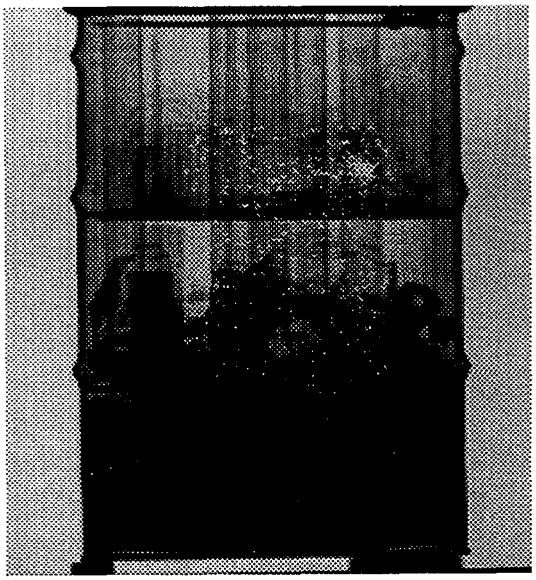


Figure 3 is a DR fused image of an emission source in the upper section of the drum The dots are the locations of actual photon counts, which are denser near the emitting source.

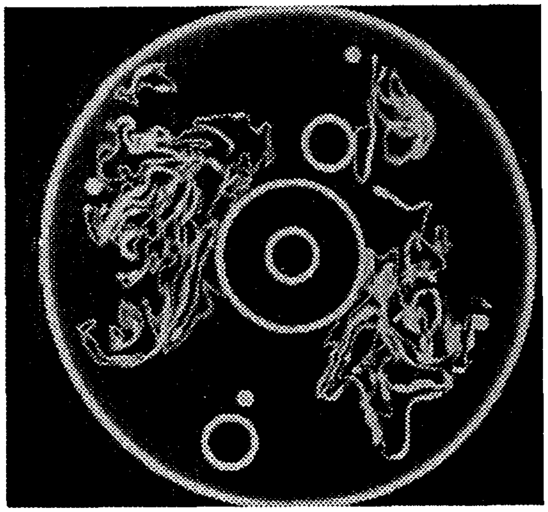


Figure 4 is a 2 MeV transmission CT slice 10 mm thick through the middle level of the drum, with a 1024 x 1024 reconstruction. The Plexiglas tubes are evident, as are acrylic rods and clothing. The steel ball bearing in an aerosol paint can is evident at 1 o'clock.

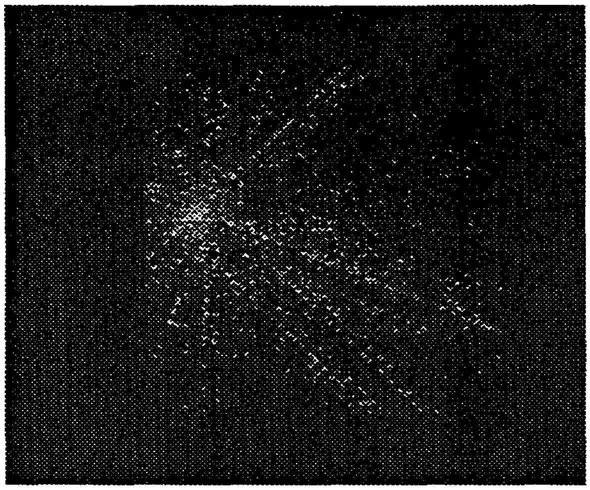


Figure 5 is a SPECT reconstruction 10 mm thick with a 256 x 256 image showing the 133Ba radioactive emission location.

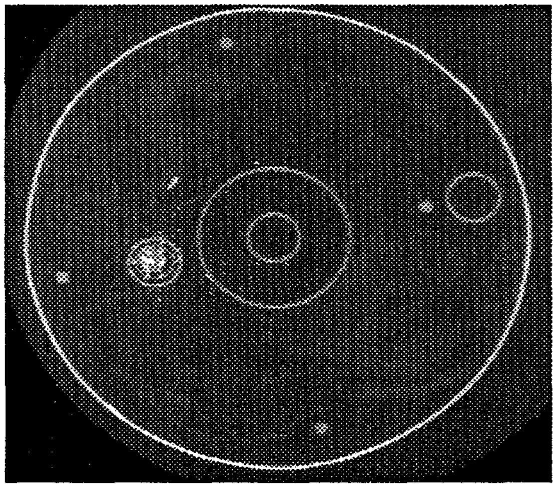


Figure 6 is the data fusion result of combining the transmission CT data with the emission SPECT image.

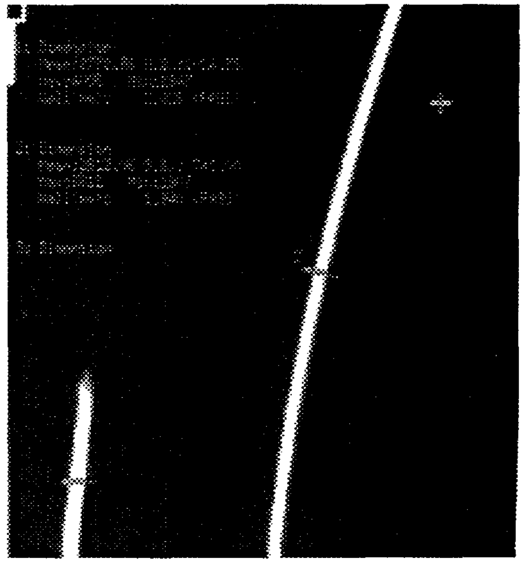
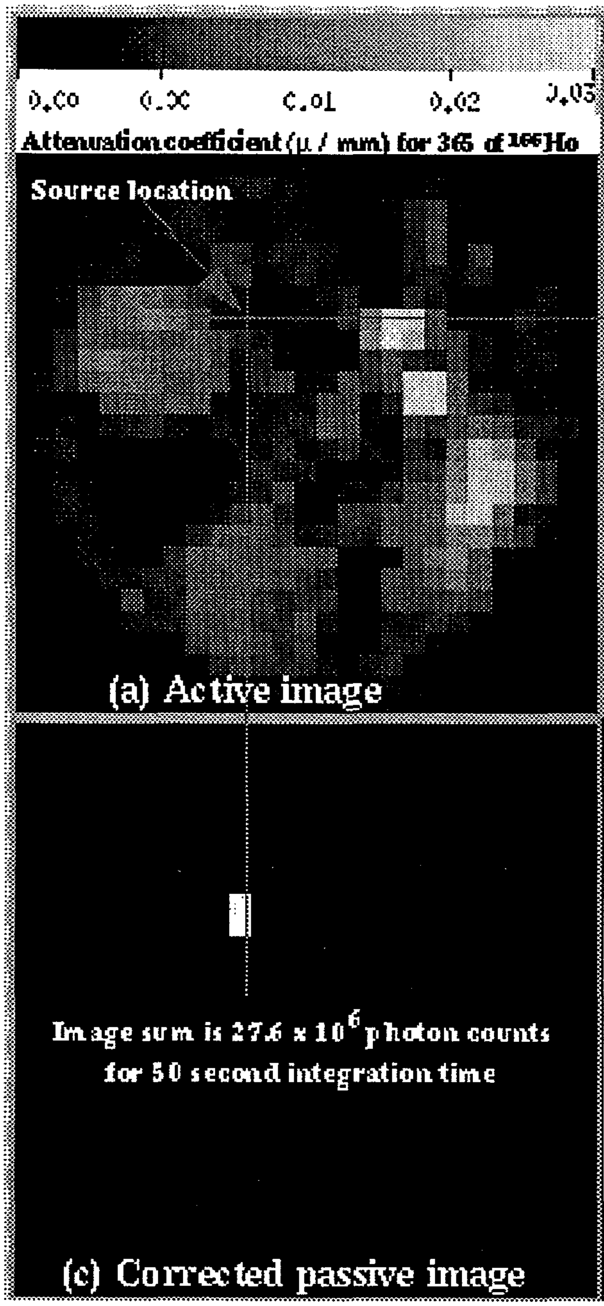
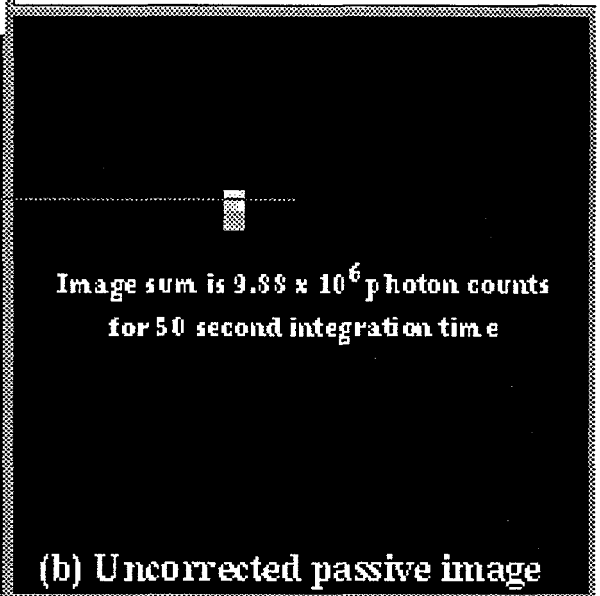


Figure 7 shows a zoomed CT image of a section of a drum wall. Positions of line cursors indicate measurement positions of varied phantom drum wall thicknesses.

Figure 8 is a volume rendered image with fused SPECT reconstruction. The 133Ba source is clearly visible as a white spot in the upper layer. A transparent bottle with free liquid laying on its side is also evident to the left of the 133Ba source. Aerosol can and liquid level is rendered transparent in the center section of the phantom.

A & PCT Determination of Measured Internal Radioactivity from a Mock 55 Gallon Drum





Midsection of TRU drum with - 65% average attenuation for 356 peak of 133 Ba emission source.

TABLE 1.

	Curies	Photon Counts	Error
Ideal	68.2µ Ci	26.19 E+6	
Measured	71.9µ Ci	27.6 E+6	+5.4%

Figure 9 shows the results of an LLNL experiment using active and passive CT to measure internal radioactivity from a mock 55 gallon waste drum.

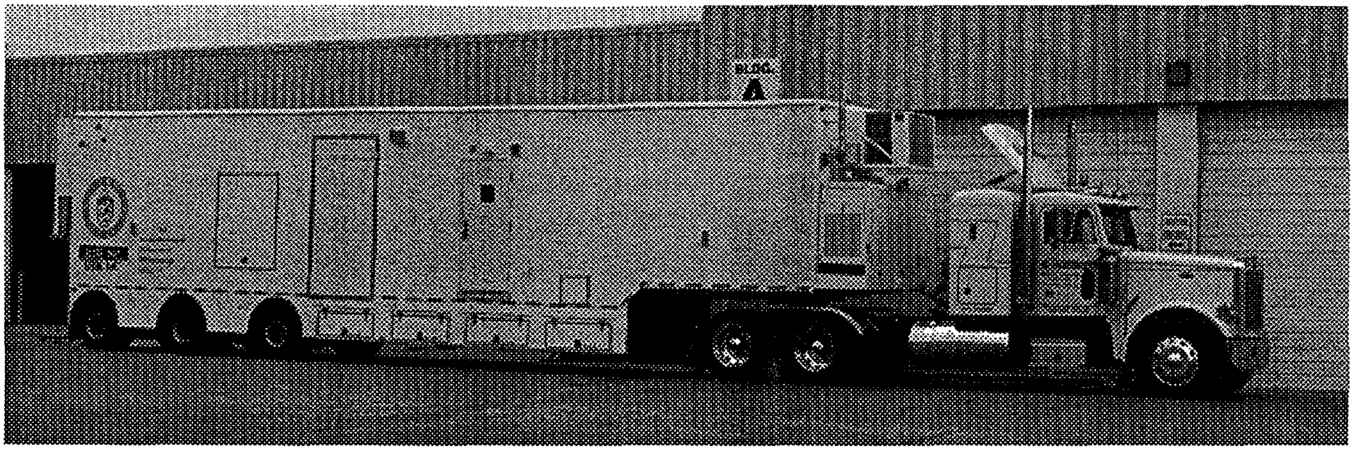


Figure 10 shows trailer which houses the WIT inspection system.

Figure 11 shows the WIT control room and operator's workstation.

Acknowledgments

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