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Waste Inspection Tomography (WIT)

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Introduction

Waste Inspection Tomography (WIT) consists of a self-sufficient mobile semi-trailer for Non-Destructive Evaluation and Non-Destructive Assay (NDE/NDA) characterization of nuclear waste drums using X-ray and gamma-ray tomographic techniques. WIT is a Program Research and Development Announcement (PRDA) contract funded by the Environmental Management's (EM) Office of Science and Technology (OST/EM-50) for the United States Department of Energy (DOE). Bio-Imaging Research, Inc. (BIR), of Lincolnshire, Illinois has completed Phase I involving design, fabrication, factory testing, evaluation and demonstration of WIT. The recently completed 23-month WIT Phase I included the design, fabrication, and initial testing of all WIT subsystems installed on-board the trailer. Initial test results include 2 MeV Digital Radiography (DR), Computed Tomography (CT), Anger camera imaging, Single Photon Emission Computed Tomography (SPECT), Gamma-Ray Spectroscopy, Collimated Gama Scanning (CGS), and Active and Passive Computed Tomography (A&PCT) using a 1.4 mCi source of ^{166}Ho. These techniques were initially demonstrated on a 55-gallon phantom drum with three simulated waste matrices of combustibles, heterogeneous metals, and cement using check sources of gama active isotopes such as ^{137}Cs and ^{133}Ba with activities between 9 µCi and 250 µCi Waste matrix identification, isotopic identification, and attenuation-corrected gamma activity determination were all demonstrated nondestructively and noninvasively in Phase I. The currently ongoing phase 2 involves DOE site field test demonstrations at LLNL, RFETS, and INEL with real nuclear waste drums. Current WIT experience includes inspecting 55 gallon drums of cement, graphite, sludge, glass, metals, and combustibles. Thus far WIT has inspected drums with O to 20 gms of ^{239}Pu. The minimum measured by WIT was O.131 gm ^{239}Pu in cement. The measurement of gram loadings from 100 nCi/gm up to 200 gm ^{239}Pu is expected later in Phase 2.

The United States Department of Energy 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. The contents of these drums must be characterized as either high-level waste (HLW), low-level waste (LLW) or transuranic waste (TRU), before the drums are assigned to one of three permanent storage locations. Strict permitting regulations also require information to be gathered about the condition and contents of the waste containers.

The Problem

X-ray imaging is an established method for nondestructive waste container examination. 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.

RTR systems have several disadvantages however. Area X-ray detectors typically suffer from blooming artifacts. Blooming is caused when a saturated signal spills over into neighboring sensor elements resulting in excessive brightness and limited 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. An image intensifier is also limited to a small area of the drum.

RTR limits geometric depth perception because of super-positioning, and it lacks quantitative information such as two and three dimensional spatial and density measurements because the data is not in digital form. The combination of 420 kV source and a restricted detector dynamic range limits RTR penetrating and discriminating capability for inspecting the denser waste containers including cement-solidified drums, glass, sludge, and soils, which make up over half of DOE's inventory of nuclear waste drums.

Currently installed baseline gamma and neutron assay systems are limited to assumption of waste matrix homogeneity which yield assay errors with increased assay uncertainty for heterogeneous matrices, which is the majority of the waste.

The Solution

The emerging technologies in WIT are designed for nondestructive evaluation (NDE) of low level, transuranic, and mixed nuclear waste, include high-energy 2 MeV X-ray computed tomography (CT) and digital radiography (DR), with 18-bit dynamic range. Figure 1 shows a 2 MeV transmission with a DR projection image of a 55-gallon drum of TRU waste in cement, assayed by WIT with nearly 20 gms ^{239}Pu.

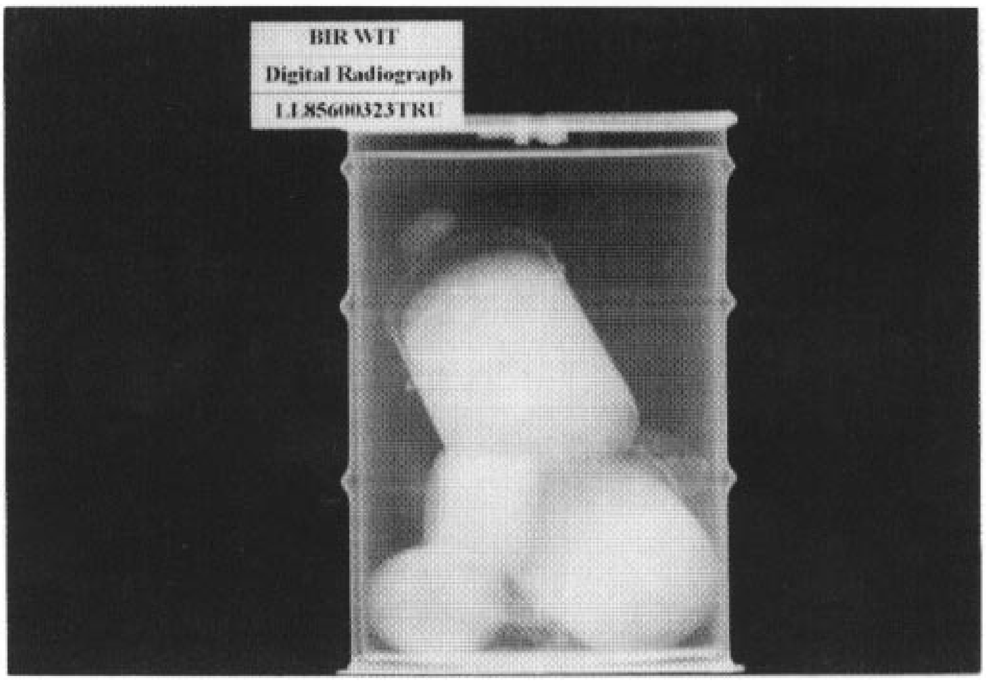

Figure 1 - 2MeV transmission DR image of 55-gallon TRU waste drum from LLNL, with nearly 20 gms ^{239}Pu.

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 images most dense DOE waste streams with faster throughput for the lighter waste forms. This cannot be said for RTR baseline X-ray imaging systems currently used within the DOE complex. 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. WIT DR requires 60 seconds per image as is shown in Figure 1. To image free liquids, a DR is acquired with a tilted drum to image the liquid surface on WIT. 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.

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 CT image of a thin, irradiated plane or slice. The image in Figure 2 is a 512 x 512 10 mm thick slice through a LLNL TRU waste drum showing two different densities of cemented waste. Each 10 mm thick CT image slice is scanned and reconstructed between 8 and 30 seconds per slice.

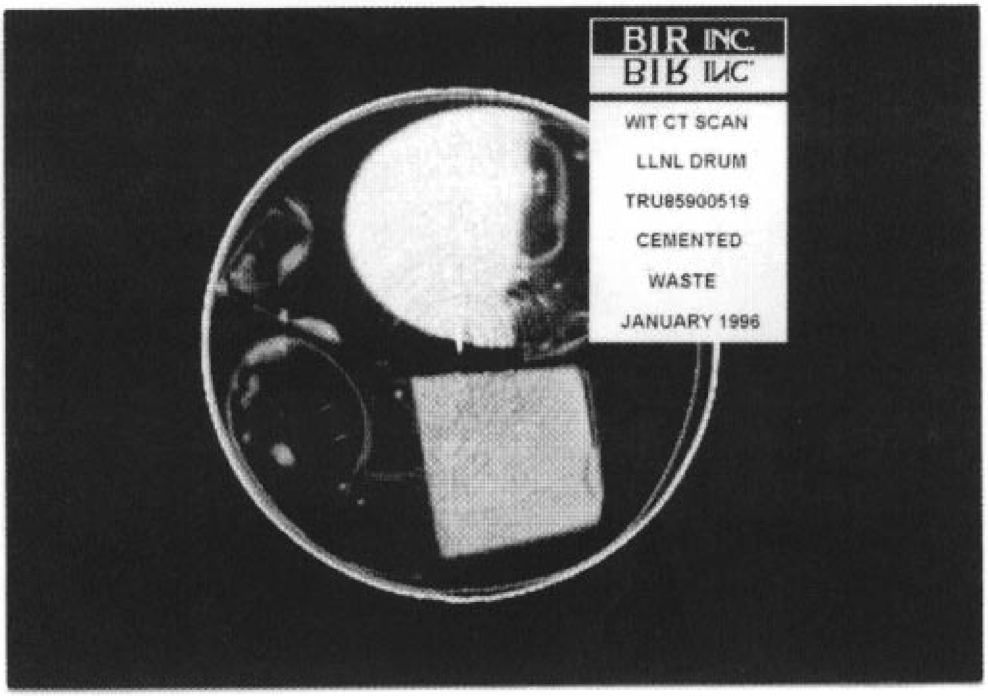

Figure 2 - 2 MeV 10 mm thick CT slice, through LLNL cemented TRU waste with varying density.

Up to 90 CT slices can be stacked by WIT to form a volume rendering of drum content, light shaded and cutaway, such as the one shown in Figure 3. Each volume rendered view requires 45 seconds of post processing. WIT processes up to 50 views at equal drum rotation angles to provide a cinematic presentation of rotating drum content.

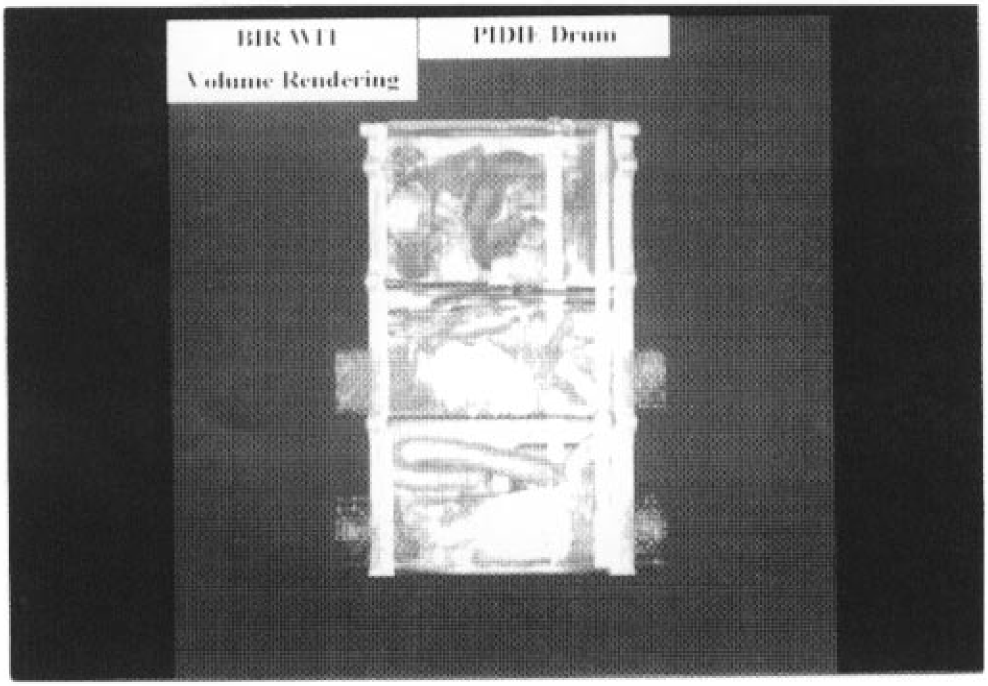

Figure 3 - Volume rendered image from WIT CT of a LLNL phantom drum, showing combustibles, metals, and cement matrices.

With a cinematic presentation of rotating drum contents, volume rendered CT could possibly replace invasive visual examination for verification of drum contents with radiography.

Two emission imaging techniques are employed on WIT for characterizing gamma emitting 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 from within the drum matrix. In this case, emission from actual nuclear waste within a container can provide three-dimensional volume or slice data of the radioactive source(s) within the container. SPECT uses large area sodium iodide crystals with a two-dimensional array of photo multiplier tube (PMT) detectors for rapid localization of gamma-ray emissions in two-dimensional space and in 3-D with SPECT. These area cameras are called Anger cameras. Figure 4 shows 32 gamma camera views of 5 gamma sources in the figure 3 drum. Each WIT SPECT view can require between 1 and 60 seconds of data collect time.

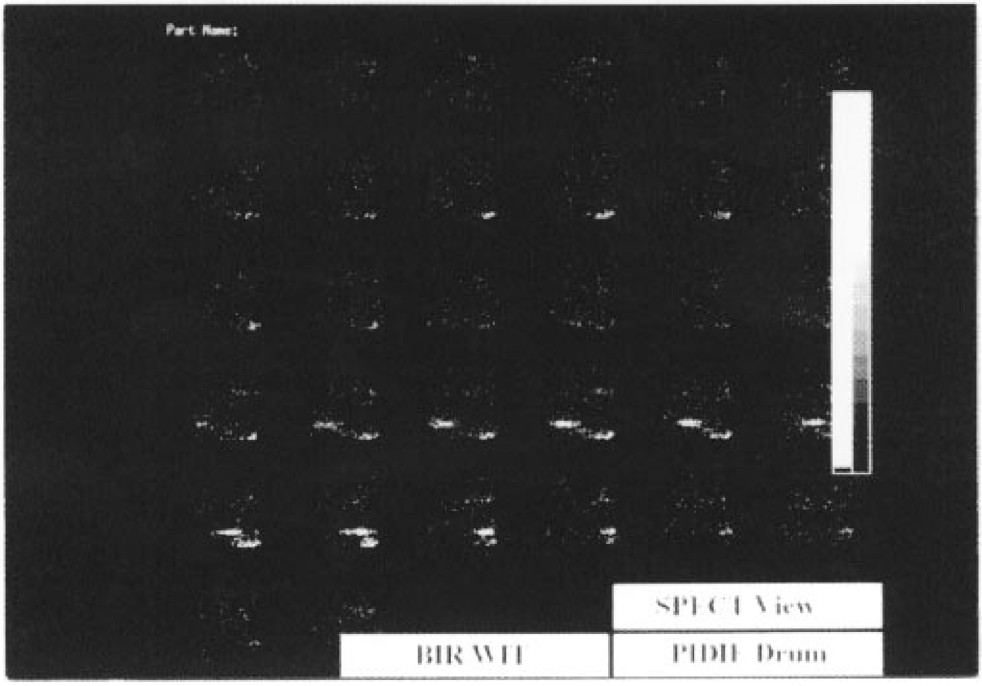

Figure 4 - WIT provides 32 gamma SPECT views of the LLNL PIDIE drum with a total of 1.5 gm ^{239}Pu. The "hottest source shown is only 0.131 gm ^{239}Pu in a cement matrix, with a total equivalence of 220 nanoCuries per gram in cement.

The gamma spectroscopy and assay techniques on WIT are called Collimated Gamma Scanning (CGS) and Active and Passive CT (A&PCT), both developed by LLNL. CGS is similar to SGS with a homogeneous matrix assumption. However, A&PCT corrects for a heterogeneous matrix. Active CT on WIT is somewhat similar to the conventional X-ray CT techniques. However, the differences are that a radioisotopic source and single-channel high-purity germanium detector are used with a first-generation active CT approach. Active CT data result in the absolute determination of the attenuation of the drum and its contents. As is shown in Figure 5, A&PCT provides for energy specific geometry and matrix corrections down to drum volume elements that are cubic with 50 mm sides to decrease assay uncertainty. Depending on the waste stream and activity, each WIT gamma assay, using either SGS or A&PCT could require between 0.5 and 65 hours per drum.

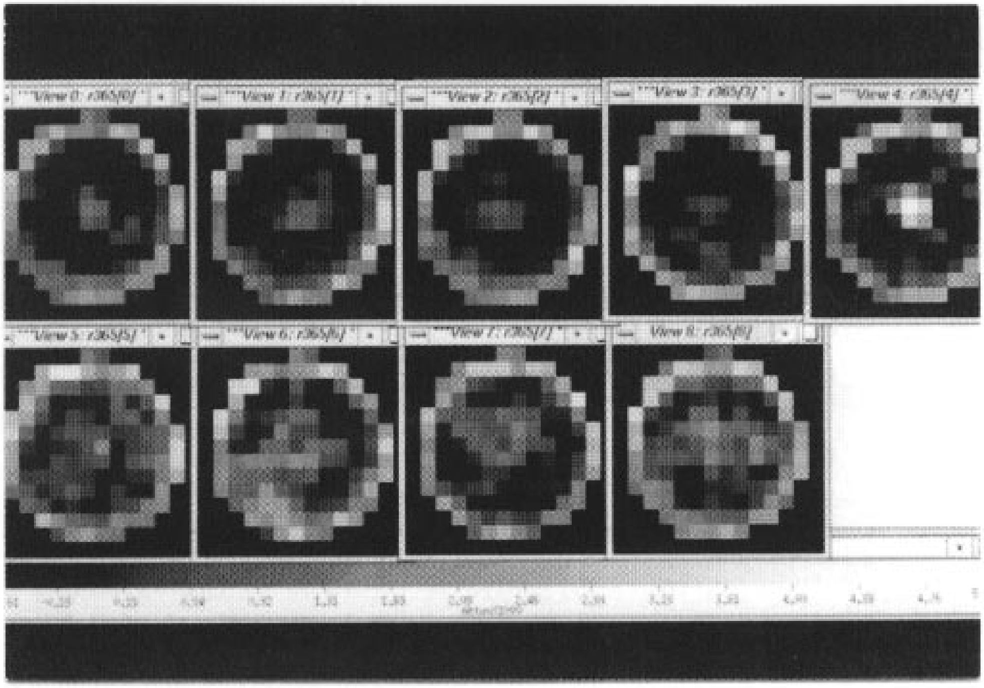

Figure 5 - Active CT from WIT showing energy specific attenuation in a drum with a 19.6 gm source of ^{239}Pu, with 9 slices, each 50 mm thick.

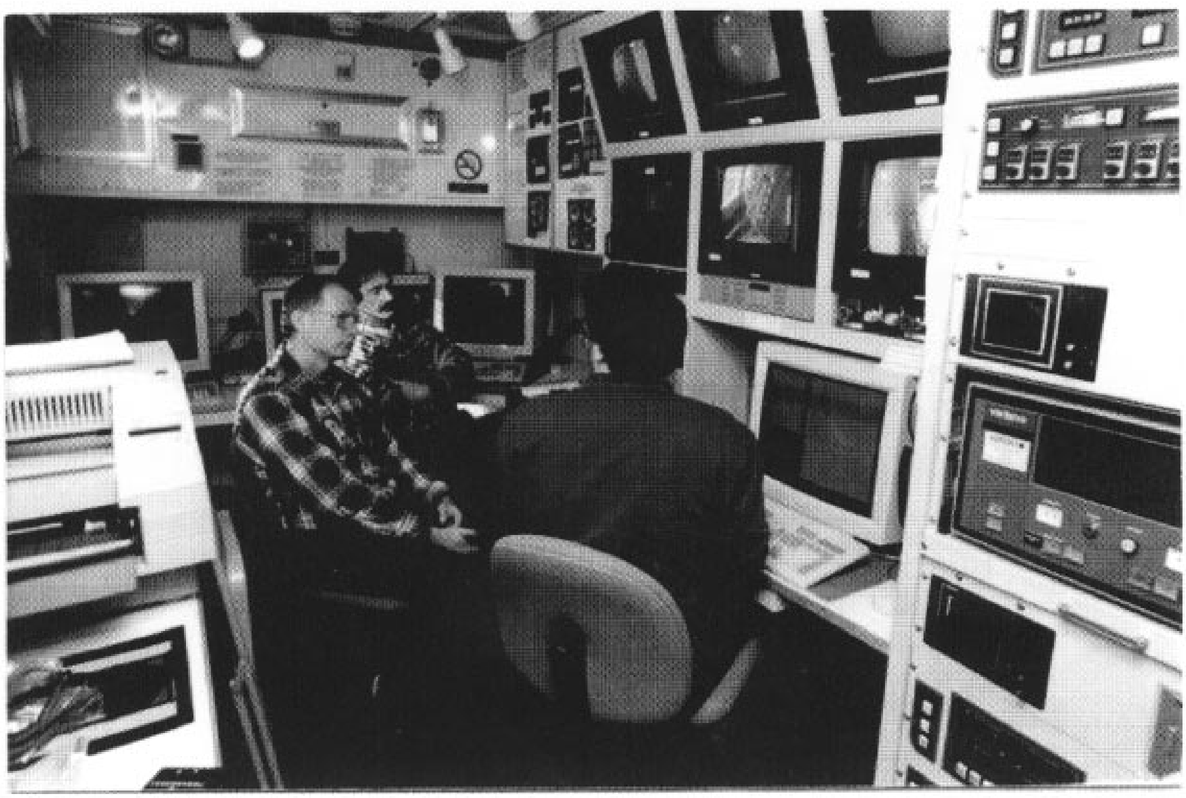

Figure 6 - The WIT control room.

A&PCT uses an energy sensitive single-channel high-purity germanium detector for gamma-ray nuclear spectroscopy. This technique, for nondestructive assay (NDA), can directly identify the emitting isotopic species and the total gram content of ^{239}Pu equivalent for drum assay.

Figure 7 - The trailer which houses the WIT system.

Applications

The mobile feature of WIT, shown in Figures 6 and 7, 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 noninvasively characterize the regulated contents of waste drums as large as 416 liters (110 gallons), weighing up to 726 kg (1,600 lbs). 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 19 and 132 liters (5 and 35 gallons). WIT can inspect LLW, TRU, and MW for all DOE matrices from low density combustibles up through high density matrices like glass, cement, sludge, and metals, which includes most, if not all, DOE waste streams.

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. 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.

The data presented in this text are the initial phase 2 results from LLNL in early 1996. Throughout 1996 WIT is continuing demonstrations at Rocky Flats and Idaho National Engineering Laboratory, both DOE facilities. A summary of Phase 2 results up to INEL findings can be found at the end of this text.

Future Work

A second PRDA contract has been awarded to BIR to integrate Neutron based waste drum characterization capability with WIT. Though WIT's NDE and NDA systems can examine gamma emission sources, some dense TRU waste drums are poor gamma emitters. A semi-trailer assay system called Active Passive Neutron Examination Assay (APNEA) has been built by Lockheed Martin Specialty Components (LMSC) in Largo, FL. APNEA was originally developed by Oak Ridge. APNEA can measure transuranic fissionable isotopes even in the presence of dense matrices. In addition to imaging capabilities, APNEA makes both geometry and matrix corrections for heterogeneous waste. The first WIT-APNEA data fusion results are shown in Figure 8, where WIT volume rendered X-ray CT data of a sludge phantom drum is shown fused to APNEA data with one gallon volume elements. The gray scale number given to the APNEA volume elements is proportional to the ^{239}Pu gms in that volume.

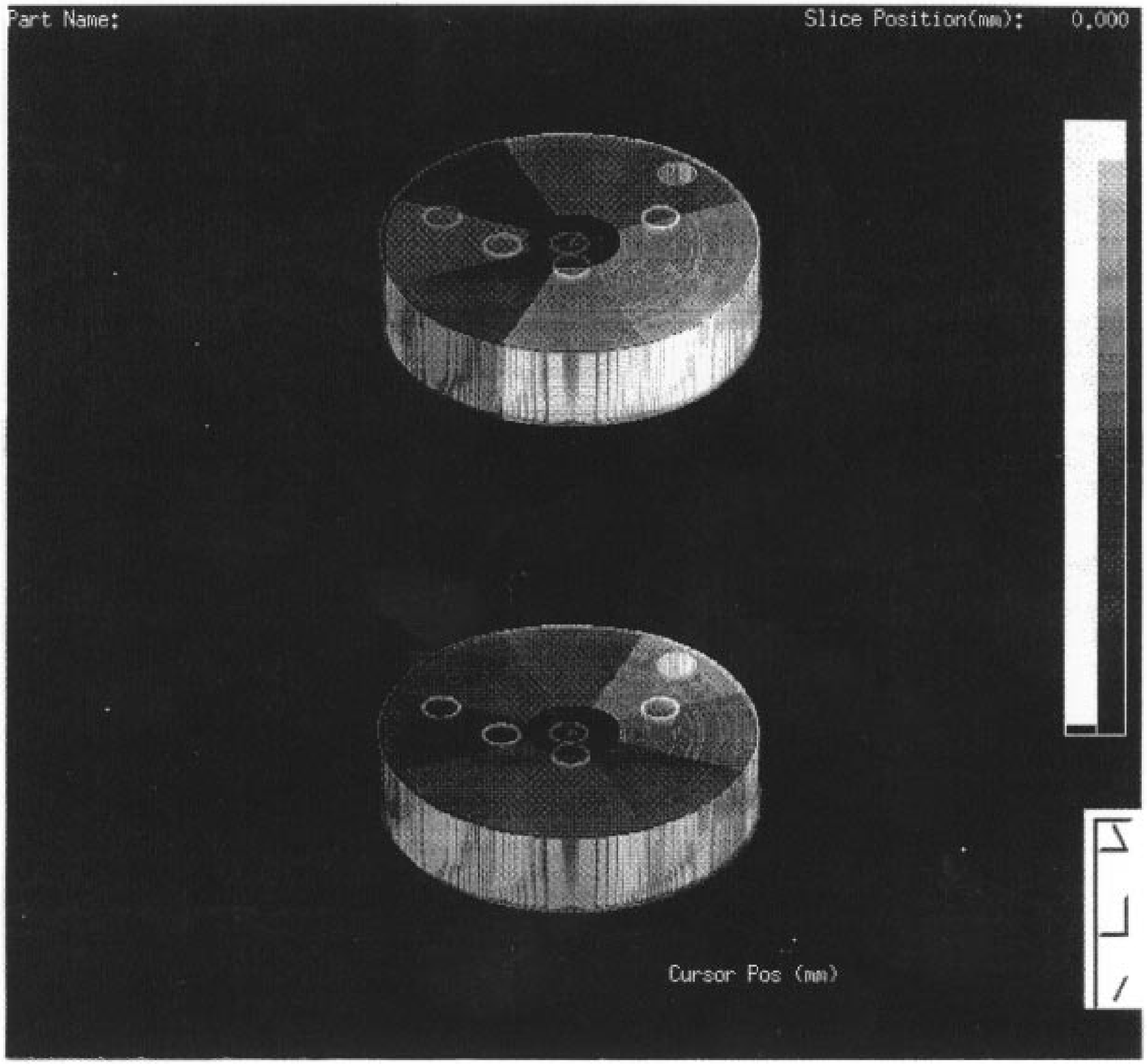

Figure 8 - WIT CT volume rendering of a phantom sludge drum of TRU waste fused to course (pie shaped) volume elements of APNEA data. The gray scale of each large volume element number is proportional to the total grams of ^{239}Pu in the drum.

Table 1. Summary of the Mobile WIT Trailer Initial PRDA Phase 2 Field Test Results for 65 Drums at Four Sites over Seven Months as of 7/25/96 with Nearly 10,000 Miles Travelled

Chronological Order for Field Test Sites[l]	Drum No.	(well-known gram load) 55 gal. Drum CID #	NDE WIT 2 MeV DR/CT (@ 70 rads/min./meter) for Matrix Identification	WIT Gamma-SPECT Emission Localization	NDA ^{239}Pu Mass (grams)		
					WIT CGS[g]	WIT A&PCT[e] No-/5:1 septa	Site SGS/PAN[i]
LLNL:	1	cold BIR mock waste	mixed[f] with liquids	—	—	—	—
(two scan months) B-612 yard	2	SGS calibration (19.6 g ^{239}Pu)	combustibles/metal	yes, 1 seen	—	12.9[a]/17.1	20
12/95 - 02/96 at Livermore, California	3	LLNL mock waste w/PIDIE (~0.775 g ^{239}Pu)[1] = 1,102 nCi/g	mixed[f]	yes, 4/5 seen	—	0.963/0.42[b]	—
	3	PIDIE Top (0.176g) 440 nCi/g	combustibles	yes, 1 seen	—	0.200/0.110[b]	—
	3	PIDIE Mid (0.131g) 210 nCi/g	cements	yes, 1 seen	—	0.181/0.107[b]	—
	3	PIDIE Low (0.468g) 380 nCi/g	metals	yes, 2/3 seen[h]	—	0.582/0.243[b]	—
	4	323 TRU[c]	cemented/combustibles	yes, 1 seen	—	2.3/—	20
	5	519 TRU[c]	grouts/combustibles	yes, multiple	—	1.44/—	3
	6	1187 TRU[c]/MW	combustibles/lead	yes, multiple	—	11.1/—	2.5
	7	11414 LLW	combustibles	none seen	—	—	0
Commercial (non-DOE) (three scan days) 03/96, East Coast, Virginia (BIR-supported)	1-45	37 waste drums, 8 phantom drums	2 DRs and 90 CT slices per drum[k]	—	—	—	—
BIR: 06/96 (1 scan day) Lincolnshire, Illinois	1	LMSC sludge phantom	sludge (INEL formula) with two cement layers	yes, 1 seen[j]	—	—	—
	2	BIR phantom	combustibles/mixed[f]	yes, 1 seen[j]	—	—	—
RFETS:	1	cold, stainless liner	combustibles/metals	—	—	—	—
(nine scan days)	2	D68680[d] TRU	combustibles	yes, multiple	7.3±0.2	—/14.9	12
B-663 yard	3	D67752[d] TRU	combustibles	yes, multiple	3.4±0.2	—/6.97	8
07/96 at	4	D74739[d] TRU	combustibles	yes, 1 source	5.2±0.15	—/8.16	5
Rocky Flats, Colorado	5	D68871 TRU	combustibles	yes, multiple	0.76±0.10	—	1
	6	D66740 LLW	pre-filters	none seen	—	—	0
	7	D74821 TRU	combustibles	—	—	—	—
	8	D64920 TRU	filters (CT only)	—	—	—	—
	9	D64364 TRU	filters	—	—	—	—
	10	D68546 TRU	combustibles	—	—	—	—
	11	D68652	filters	yes, multiple	—	—	—

Note: Drum weights varied between 80 lbs. for combustibles, up to 600 lbs. net weight for sludge.

Revision 1, 9/6/96

— means, no data acquired

* No septa corresponds to 2.5:1 detector collimator aperture aspect ratio; septa evaluated at LLNL.

a Suspected interference effects in attenuation data.

1 Plutonium Isotopics Determination Intercomparison Exercise (PIDIE) sources are well-characterized radioisotopic sources.

b Low statistics data.

c These are highly attenuating non-homogeneous matrices, therefore, the LLNL SGS results are questionable.

d These are low attenuating combustible matrices; SGS should perform well for these drums.

e A&PCT uses 1 HPGe, Ho^{166m} @ 1.4 mCi, UCSF codes, LLNL background subtraction, no lump corrections, and isotopic determinations.

f Mixed matrix includes: combustibles, metals, and cement at different drum heights.

g CGS was not operational at LLNL; the WIT CGS technique consists of 18 collimated slices, similar to SGS, and developed at RFETS by LLNL.

h Two sources appeared as one; both were below resolution of gamma cameras.

i Site supplied SGS/PAN results with baseline techniques.

j 250 μCi of Ba-133-1 oz. liquid.

k Reporting matrix identification is pending B&W approval for public release.

l Additionally, with BIR support, WIT was displayed at Argonne National Laboratory in Illinois on 07/95, a Mixed Waste Symposium in Baltimore, Maryland on 08/95, a TRU Steering Committee Meeting in San Antonio, Texas on 11/95, and at *WM '96* in Tucson, Arizona on 02/96. Total WIT travel adds up to nearly 10,000 miles as of INEL arrival on 7/25/96.

Acknowledgments

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NOTE: Other WIT funding sources have been a second PRDA DE- AC21 -96MC33 127 and an RCI cooperative agreement 96-RCI-09, also managed by METC

BIR plans to commercialize WIT and plans to offer drum scanning/characterization services to DOE and other sites requiring mobile characterization capabilities.