Innovative Technology
Summary Report

DOE/EM-0470

Nondestructive Waste Assay Using Gamma-Ray Active & Passive Computed Tomography

Mixed Waste Focus Area

Prepared for
U.S. Department of Energy
Office of Environmental Management
Office of Science and Technology

September 1999

INNOVATIVE TECHNOLOGY
Summary Report

Nondestructive Waste Assay Using Gamma-Ray Active & Passive Computed Tomography

OST Reference #2123

Mixed Waste Focus Area

Demonstrated at
Nevada Test Site
Mercury, Nevada

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://OST.em.doe.gov under "Publications."

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SUMMARY

Technology Summary

This project was supported by the Mixed Waste Focus Area (MWFA) and the Federal Environmental Technology Center (FETC) to develop an improved nondestructive assay (NDA) capability that uses gamma-ray computed tomography and gamma-energy spectral analysis techniques to perform waste assay measurements. It was the intent of the Gamma-Ray Active & Passive Computed Tomography (A&PCT) development and demonstration project to enhance the overall utility of waste assay through the implementation of techniques that can accommodate known measurement complications, e.g., waste matrix and radioactive material distribution heterogeneities. This technology can measure the radionuclide content in all types of waste regardless of their classification as low level (LLW), transuranic (TRU) or mixed (MLLW or MTRU).

The nondestructive waste assay capability needed to support Department of Energy (DOE) mixed waste characterization needs is necessarily a function of the waste form configurations in inventory. These waste form configurations exhibit a number of variables impacting assay system response that must be accounted for to ensure valid measurement data. Such variables include: matrix density, matrix elemental composition, matrix density distribution, radioactive material radionuclidic/isotopic composition, radioactive material physical/chemical form, and physical distribution in the waste matrix. Existing nondestructive assay technologies have identified capability limits with respect to these variables. Certain combinations of these variables result in waste configurations within the capability of one or more of the existing systems. Other combinations that are prevalent in the inventory are outside of the capability of such systems.

The A&PCT technology uses two separate gamma-ray measurements during operation to accommodate measurement complications. The first is an active density mapping of the waste drum matrix by an external radioactive source(s) and the second is a passive measurement of the gamma-emitting radioactive source(s) within the drum. The matrix and radioactive material spatial information determined from the computed tomography (CT) reconstruction process is used to arrive at an gamma attenuation corrected assay. The gamma-ray A&PCT method involves: (1) data acquisition; (2) image reconstruction; and (3) gamma-ray spectral analysis. Accurate and quantitative radioactivity values can be obtained for radionuclides present in quantities above the detection limit of the system.

Two A&PCT systems have been developed through this project: Isotope Measurements by Passive and Active Computed Tomography (IMPACT), and Waste Inspection Tomography/Active and Passive Computed Tomography (WIT/A&PCT). The IMPACT system is located at Lawrence Livermore National Laboratory (LLNL) and its primary purpose was to research the A&PCT technology and to develop and verify its concepts. It was not developed to assay real waste on a production basis; however, some real waste has been assayed at LLNL for research purposes. Also, the system did officially participate in the third cycle of the National TRU Program's (NTP) Performance Demonstration Program (PDP) examination.

The WIT project is a collaborative effort between LLNL and Bio-Imaging Research (BIR), Inc., to integrate the A&PCT technology into a mobile trailer. This effort was primarily funded through FETC with support from the MWFA. The WIT system was developed to perform demonstrations of the A&PCT technology and to become a certified production-mode assay system.

Phase 1 development consisted of development and demonstration of both the IMPACT and WIT/A&PCT systems. These systems were configured with a single high purity germanium (HPGe) detector. As part of the Phase 1 project scope of work, a multidetector A&PCT system was designed. The multidetector system will have the same capabilities as the IMPACT and WIT/A&PCT systems, but with a higher throughput (reducing average measurement time from 20 hours to 1 hour per drum). Phase 2, the multidetector system development and demonstration, is funded through FETC in FY-98. Work will be completed in FY-99.

A summary of the Phase 1 Gamma-Ray Active & Passive Computed Tomography system demonstrated capabilities and the issues that will affect its implementation by a DOE site is provided in this report to support end users and other interested parties in technology selection. A second ITSR is planned to be issued in FY-99 to summarize the results of the multidetector A&PCT development effort.

Demonstration Summary

Numerous tests have been carried out with the A&PCT technology on surrogate and real alpha contaminated mixed waste drums. In general, simpler mock-waste drums with known radioactive sources were used to carry out initial A&PCT development and testing. Testing next moved to "calibration" drums that had been used to calibrate LLNL's segmented gamma scanner, and then on to use of the PDP matrix drums and PDP radioactive standards when they became available. Surrogate waste tests include the following:

- Developmental testing at the LLNL, using both the IMPACT and WIT systems. Numerous tests were completed to support the A&PCT development effort. These measurements were used to check/verify: (1) active and passive computed tomography (CT) data acquisition, (2) gamma-ray spectral analysis, and (3) image reconstruction for NDA determination.
- Demonstration of the IMPACT system informally in the PDP Cycle 2 demonstration and formally in the PDP Cycle 3 demonstration.
- Participation of the WIT system formally in the PDP Cycle 4 demonstration.

The real waste tests include the following:

- Developmental testing at the LLNL using both the IMPACT and WIT systems. Much of this waste consisted of 208-L (55-gal) drums containing multiple 19-L (5-gal) containers of solidified chemical wastes.
- Demonstration of the WIT system at the Rocky Flats Environmental Technology Site (RFETS). The RFETS wastes were low-density combustible type matrices.
- Demonstration of the WIT system through the Rapid Commercialization Initiative (RCI) and the Capability Evaluation Project (CEP) programs at the Idaho National Engineering and Environmental Laboratory (INEEL). The wastes at the INEEL included both lead-lined and normal drums containing waste matrices of graphite, glass, metals, wet and dry combustibles, and sludge.
- Current participation of the WIT system in the Carlsbad Area Office's (CAO) mobile system certification program at the Nevada Test Site (NTS).

Key Results

The key results from the A&PCT project are listed below:

- Two systems, fixed and mobile, were developed and demonstrated.
- A multidetector system was designed and fabricated. Demonstration of this system will be completed in FY-99.
- It was concluded that the under sampling protocol, which uses one quarter the passive data acquisition time, can be used to assay a drum. This was verified experimentally.
- Through simulation studies it was found that there is a tradeoff between spatial resolution and signal-to-noise in A&PCT.
- Participated in PDP, CEP, and RCI test programs, which yielded objective data on satisfactory system performance with respect to National TRU Program quality assurance objectives.
- The A&PCT technique does not require matrix dependent calibrations (traditionally time-consuming) as it directly measures and corrects for all known bias elements. This is a advantage with respect to other commonly employed waste NDA methods.
- The A&PCT technology has demonstrated that it can localize, quantify, and identify TRU isotopes, and that this quantification can be done independent of the type of waste matrix.
- The technology has been successfully transferred from the R&D realm to an industrial partner. The partner has begun the commercialization of this technology and demonstrated that it can be incorporated into a mobile laboratory.

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SECTION 2

TECHNOLOGY DESCRIPTION

During the course of this project two systems have been developed based on the A&PCT technology: IMPACT and WIT/A&PCT. This project consisted of both hardware and software development and optimization. A description of the hardware and software is given below. Included in this section is a description of the two systems constructed during this project.

Overall Process Definition

The A&PCT system uses three techniques to perform an assay: active CT, passive CT, and image reconstruction.

The A&PCT technology employs a scanner that uses a HPGe detector and the associated electronics. It differs from conventional CT scanners in that it discriminates between photons of different energies. The quantity that is reconstructed in active CT is the attenuation value for some volume element, or voxel, at location *x*, *y*, and *z* within a drum. The voxel size and clarity are defined by scan and image reconstruction parameters. The reconstruction algorithms require line integrals, also called ray sums, for the many ray paths through the object. (A CT ray sum acquired at a single energy is analogous to a simple gamma-ray transmission gauge.) The algorithm results are a discrete quantitative measurement of the linear attenuation coefficient at each energy measured, i.e., there has been no integration over the energy spectrum. Such scanners provide active CT images with pixels that represent the absolute measurement of attenuation at specific energies. The linear attenuation coefficient (μ) is the parameter determined by image reconstruction of the active CT measurements. For a waste drum, the attenuation due to its contents is accurately measured in three dimensions and displayed as a sequence of two dimensional images at different *z* planes (or elevations) of the drum. (Active CT does not identify any isotope or measure the source strength or activity within a waste drum.)

Passive CT is used to measure and determine the location, identity, and strength of radioisotope sources within a drum. The ray sum for passive or single-photon-emitted CT (sometimes called SPECT) imaging is the counts measured in disintegrations (*d*) per unit volume per unit time of the passive source within a waste drum. Therefore, a single-photon-emitted ray sum is the integrated radioisotope activity, modified by one or a multiple of exponential attenuations, along the path from a source position within a drum to the detector. The function that is imaged for passive CT is the measured gamma-ray activity at one or more energies of all detectable radioisotopes within a drum. The spectrometry detection equipment collects the entire energy spectrum for each integration point and the radioisotopes are identified by their characteristic peaks within the energy spectrum.

Image reconstruction is key to addressing a central difficulty in NDA in that an accurate absolute assay is impossible unless the emitted radiation can be corrected for the attenuation it suffers within its container. This correction requires knowledge of the spatial distribution and density of both emitters and absorbers throughout the volume. An accurate assay will necessarily involve a complete determination of the three dimensional (3-D) structure of all radioisotopes present even though the original problem posed by the regulations requires only one number, the total radioactivity quoted as Pu-effective grams, contained within a waste drum.

In order to assay the 3-D structure of a waste drum, it is divided into a set of 3-D volume elements or voxels. The number of counts for all detectable radioisotopes is determined for each voxel. The sum of the counts in each voxel determines the NDA of the drum. The emitted radiation is measured at a series of detector positions, which constitutes the ray sums in a passive CT scan. The system matrix represents and incorporates the effects of the system's geometry and the attenuation map determined from the active CT scan.

The A&PCT code uses an iterative method for reconstruction. For example, given an accurate description of the system, including the nonlinear effects, minimizing the squared difference between the predicted and observed data will result in an accurate reconstruction. Several numerical algorithms exist for least squares minimization. Most proceed by moving down the gradient of the objective function, the sum of squared differences, for example, by steepest descent, by conjugate directions, or by successive projections. Alternatively, the data may be obtained as the result of a stochastic process based on a Poisson probability distribution. For any given model of the source, there is a certain probability of actually obtaining the measured data. The source may then be reconstructed by varying the model to maximize the probability of obtaining the measured data. Such algorithms go by the name of Maximum Likelihood-Expectation Maximization. Another optimization technique, Constrained Conjugate Gradient (CCG), includes both the peak and background and thus a better solution can be achieved. CCG allows for a maximum likelihood function to be created that correctly relates the background and peak signals. CCG is also not a pure steepest descent algorithm, which allows it to converge to a solution faster.

The A&PCT assay is determined from the reconstructed image of the matrix and radioactive material. Attenuation corrections are applied as a function of position for one isotope, usually ^{239}Pu. The total mass of ^{239}Pu is arrived at by summing the attenuated corrected gamma emission over all volume elements. Gamma-ray spectra acquired on each ray sum are used to establish the mass ratios of the important radioactive material constituents, with respect to the ^{239}Pu isotope. This information is then used to determine the masses of the associated Pu isotopes and related nuclides. These assay data are used to calculate the thermal power, total alpha activity, and fissile gram equivalent necessary for the characterization of the waste.

Technology Descriptions

IMPACT System

The IMPACT scanner consists of two towers constructed of aluminum interlocking space-frame tubing (see Figure 1). One tower supports a ^{166m}Ho isotope source that is used for the active CT mode. The ^{166m}Ho source produces gamma rays at 184-, 280-, 365-, 411-, 530-, 712-, and 810-keV, and provides crucial, energy-specific, attenuation information for a range of items that reside within the waste matrix. The other tower supports a single well-collimated 90% efficient [relative to a 3 in. x 3 in. NaI(Tl) detector at 1.33 MeV] HPGe detector. The detector has a collimator with an aperture size of 50.8 mm in the horizontal and vertical dimension. The collimator also has an aspect ratio of 5:1. It has been verified through experiments that this aspect ratio provides an accurate assay.

The towers were designed to be versatile so that additional sources and detectors could be added to the scanner in the future. Between the two supporting towers, there is a three-axis staging system for drum manipulation. The staging system is capable of translating and elevating a 1,000-pound waste drum 50 inches. In addition, the stage is capable of rotating the drum 360 degrees. The drum manipulator was designed to be robust with safety features that are necessary for handling TRU waste in a seismically active area. Engineering safety notes were developed for the entire IMPACT scanning system for seismic assurance.

A 1-ton jib crane is located at one end of the IMPACT scanner and provides easy and safe loading of the heavy drums. The crane is interlocked in a home position away from the drum manipulator to ensure that the waste drum cannot be driven into the jib crane during system operation.

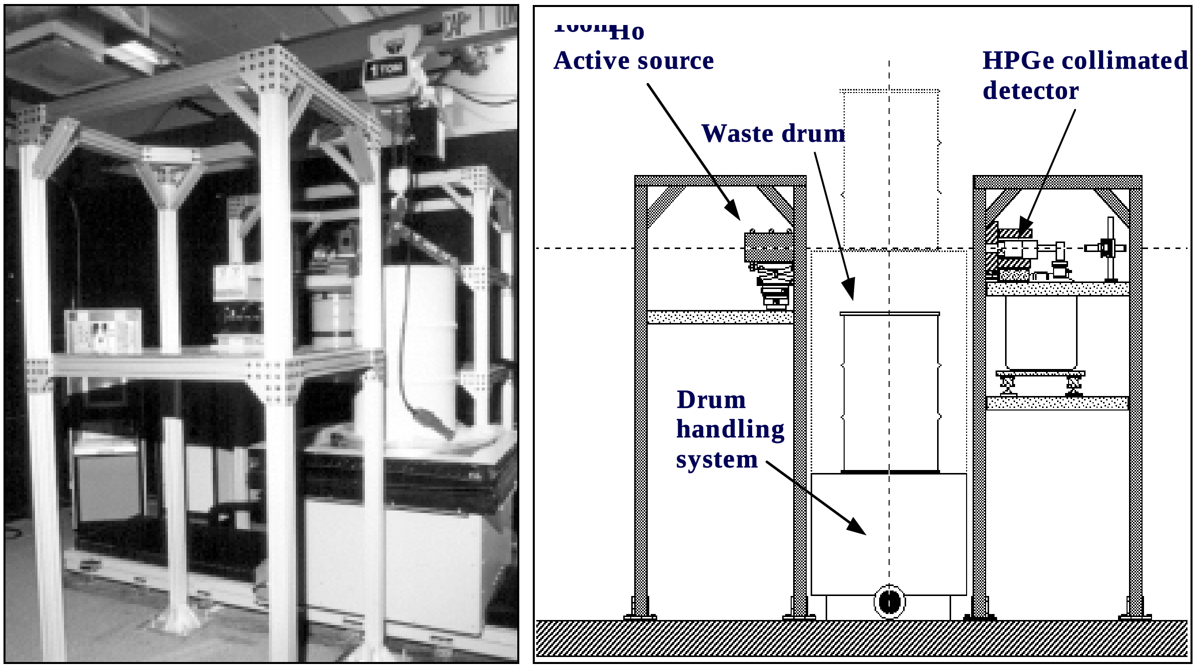

Figure 1. Photograph and schematic of the IMPACT scanner.

The IMPACT scanner uses a personal computer (PC) for system control and data acquisition. During both active and passive operations, the PC control computer discretely positions the drum for data acquisition. After positioning, the control computer communicates with a multichannel analyzer (MCA) that acquires data from the HPGe energy-discriminating detector. The detector integration time is variable and depends on the amount of activity within the drum and the attenuating waste matrix. When the integration time is completed for each ray sum, the control computer downloads the MCA's data and stores selected energy regions of interest and/or the entire spectra onto a system disk. After the data are stored, the control computer and manipulator move the drum to the next ray sum to perform another integration. The PC again acquires data from the MCA and HPGe detector system.

For the active mode, the IMPACT scanner translates the drum in 50.8-mm increments after each integration point. A 208-L (55-gal) drum is translated 14 times over a distance of 711.2 mm and then rotated approximately 8.5 degrees. Each set of 14 ray sums make up a projection. After the rotation, the next projection of 14 integration points is acquired with a 50.8-mm translation after each ray sum. This process is repeated for 21 rotations (or projections) before the drum is elevated 50.8 mm and the process is repeated for the next level or slice plane.

For the passive mode, the drum is translated only seven times over a distance of 711.2 mm and then rotated approximately 17 degrees. There are only 10 projections acquired over 360 degrees for each slice in the passive mode. The drum is correctly sampled in the passive mode with fewer ray sums and projections because of the large acceptance angle of the detector. The acceptance angle of the detector is larger in the passive mode than in the active mode. IMPACT acquires 18 slice planes for a 208-L (55-gal) drum.

The data acquired from IMPACT are processed, reconstructed, and analyzed on a UNIX based workstation. A UNIX file system is mounted by the PC and data are transferred over an ethernet cable. Both the energy regions of interest (EROI) and/or the spectra that represents each individual ray sum are transferred.

The EROI data are simply the integrated photon counts within an energy peak of interest where the background is subtracted to produce a net value of activity for some specified integration time. The EROI is set before the assay on the known energy peaks of the active or passive sources. The EROI data are processed and reconstructed without any need for further isotopic analysis. The disadvantage of using the EROI data for the A&PCT reconstruction is that the type of emission sources that are being evaluated within the drum must be known before the assay. This may not be the case for all waste drums being assayed; therefore, there is an option to save the spectra acquired for each ray sum. The accumulated gamma-ray spectra are used to determine the isotopics of the waste drum before reconstruction. The EROI, required for image reconstruction, are extracted from each ray sum's spectrum after the isotopes have been identified.

WIT/A&PCT

Work has been performed as a subcontractor to Bio-Imaging Research (BIR), Inc., to integrate the A&PCT technology into a mobile trailer. The trailer contains two additional nondestructive evaluation (NDE) technologies. When combined they provide a complete x- and gamma-ray WIT capability. The three NDE/A measurement technologies were installed into a semitrailer, which will allow inspection of waste containers to be carried out at many waste-drum storage sites. These NDE/A technologies help characterize waste drums up to 416 L (110 gal) with weights up to 725 kg (1,600 lb), and containers up to 92 cm (3 ft) diameter and 122 cm (4 ft) tall. Figure 2 (top) shows a photograph of the semitrailer, while the lower portion shows a schematic layout for placement of equipment within the trailer. The 60-ft-long by 8.5-ft-wide trailer is divided into four areas.

The rear area provides space for two 160-L (42-gal) liquid nitrogen containers, calibration and phantom drums, a 60-k BTU heating and air conditioning unit, and storage lockers. The next room is dedicated to drum inspection and contains a 2-MeV linear accelerator for transmission computed tomography (TCT) and/or digital radiography (DR). This accelerator is supported by 896 cadmium-tungstate, solid-state detectors mounted in an array on individual photodiodes with septa between each detector to minimize cross talk, inplane scatter, and blooming. To measure emitted gamma rays, there are two large, collimated, sodium-iodide [NaI(Tl)] detectors similar to Anger cameras used in nuclear medicine for single photon emission CT or SPECT. To identify gamma-ray isotopics there is a highly collimated HPGe detector. A collimated ^{166m}Ho radioactive source is also available to obtain energy specific attenuation data in the active A&PCT mode. The third area is an equipment room and entry/exit to the trailer. The most forward area contains all of the supporting electronics and a control room where waste inspection personnel use several computer terminals to operate the NDE/A measurement technologies.

The WIT/A&PCT system is similar to the LLNL IMPACT system with some minor variations. The staging system of the IMPACT scanner manipulates the drum only during data acquisition; however, the WIT scanner staging system rotates and elevates the drum, but translates the source and detector pair instead of the drum. There is no difference in the data that are stored when translating the source/detector pair instead of the drum.

The required collimator length for a 5:1 aspect ratio exceeds the space available in the WIT trailer system; however, septa was used to reduce the collimator length, yet retain the effective 5:1 aspect ratio. Septa are highly attenuating, dividing-plates that run the length of the collimator. These plates help collimate the gamma-ray beam, providing an effective aspect ratio that is better than that provided by the aperture size alone. All other parameters of the WIT scanner are the same as those used for the IMPACT scanner.

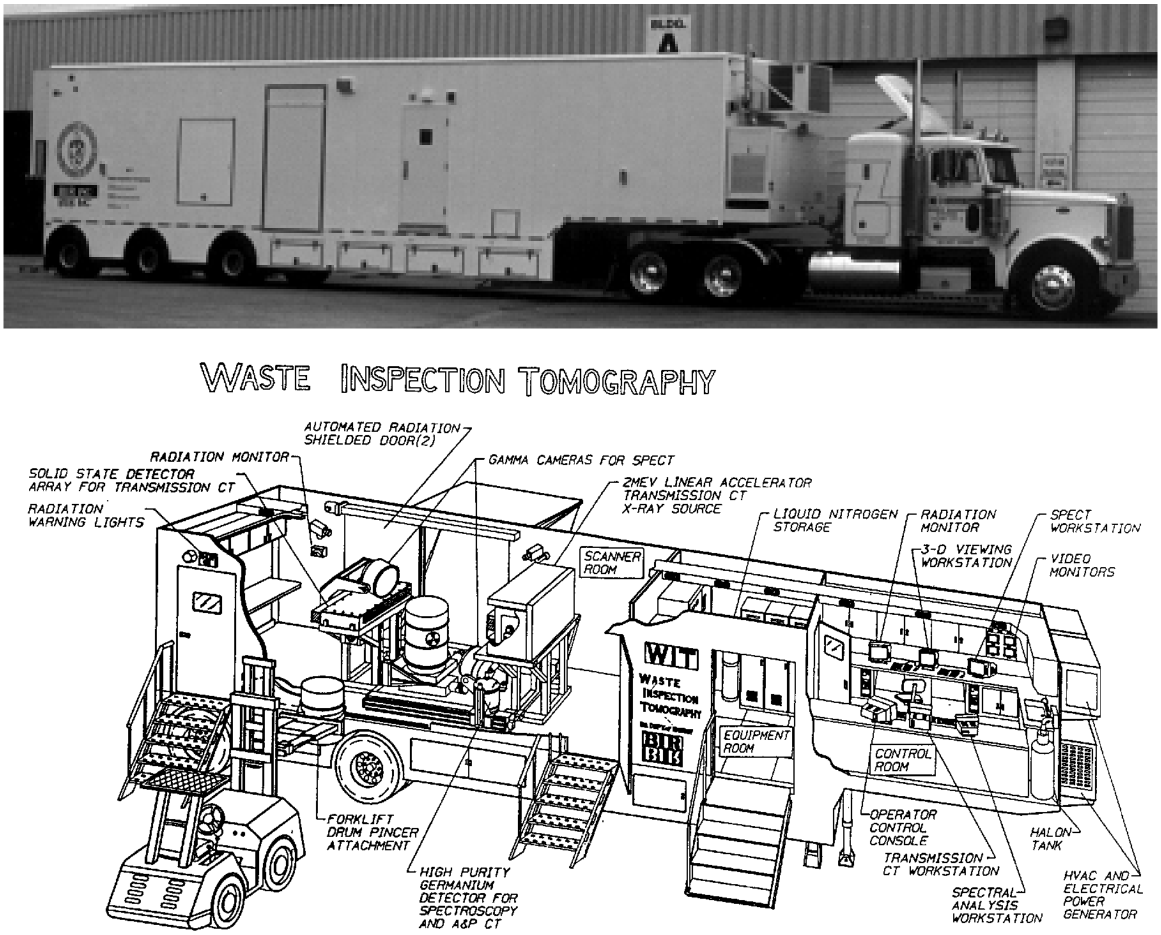

Figure 2. Photograph of BIR's mobile waste inspection trailer and the equipment layout.

SECTION 3

PERFORMANCE

A series of experiments were completed to demonstrate the performance of the A&PCT method for characterizing radioactive waste drums. The first experiments focused on the ability to correct passively measured data with an ACT (active) attenuation map. These experiments included a reference PCT scan acquired with only a passive CT source, i.e., no drum or waste items were present; hence, there was no attenuation of the source. Then, passive CT measurements were taken using a 208-L (55-gal) drum filled with one or more mock-waste matrices and their results were compared to the bare-source PCT reference scans. These preliminary measurements were necessary to determine how well the system was able to correct for attenuation from the drum and the various mock-waste matrices. This was determined by comparing the corrected PCT images to the reference scans.

Additional sets of measurements were obtained to study the A&PCT reconstruction algorithm(s) and their ability to yield an absolute measurement. These measurements were performed on several waste matrices: calibrated passive sources (e.g., ^{133}Ba) and no waste matrix (corrected with null matrix), simple uniform attenuators (e.g., aluminum cylinders), or mock-waste drums with complicated waste matrices. Measurements acquired using the PDP drums were used to provide a final validation of the A&PCT technique.

The experimental design focused on three key development areas: (1) active and passive CT data acquisition, (2) gamma-ray spectral analysis, and (3) image reconstruction for nondestructive assay determination. The test plan includes the following measurements:

HPGe detector baseline:

- Point source at a fixed distance – to identify energy resolution and detector efficiency as a function of energy

A&PCT system baseline:

- Empty drum – to determine background fields
- Point source with no attenuators – to perform a simple assay check
- Point source with a heterogeneous attenuator – to perform a rotational verification and assay check with nonuniform attenuation
- Point source with a uniform Al attenuator – to perform an assay check with uniform, low attenuation
- Point source with a uniform sand matrix – to perform an assay check with uniform, high attenuation.

These measurements were used to check/verify the data acquisition hardware and software, gamma-ray spectral analysis routine, and image reconstruction for NDA determinations. Once these were shown to be correct, A&PCT assays of mock-waste drums were investigated. In general, the approach was to initially perform simple tests and gradually move on to more difficult matrices. The test progression was the following:

- use of simpler mock-waste drums with known radioactive sources to carry out initial A&PCT scans,
- use of the “calibration” drums that were used to calibrate LLNL’s SGS system.

Once completed, none of the above experiments must be performed on a continuous basis unless the IMPACT system hardware or software goes through a major change, or unless a different data acquisition protocol is chosen or required. Changes to the gamma-ray spectral analysis software or image reconstruction software will not require reacquisition of data from the above experiments. The existing data are simply rerun through any new software developed.

The next step in the development/demonstration process was to make formal surrogate waste measurements and real waste measurements using both the IMPACT and WIT systems. The A&PCT technology participated in three formal demonstrations: PDP, RCI, and CEP. The remainder of this report will focus on these more formal demonstrations of the technology.

Nondestructive waste assay system utility is defined in terms of its ability to comply with the requirements and quality assurance objectives for nondestructive assay as delineated in the TRU Waste Characterization Quality Assurance Program Plan (QAPP, U.S. DOE 1995). The QAPP identifies the quality of data necessary to meet the specific data quality objectives associated with the DOE's Waste Isolation Pilot Plant (WIPP) TRU waste characterization program. Two primary parameters describing the waste must be determined; the total alpha activity and the activity of the individual isotopes present. The quality assurance objectives (QAOs) for precision (% relative standard deviation), accuracy (% recovery), minimum detectable concentration (MDC), completeness, and total bias are stated in the QAPP. These parameters must be demonstrated over the spectrum of waste form configurations for which the assay system is intended to characterize.

The QAPP also requires that facilities intending to use NDA methods to generate data in support of WIPP certification participate in a PDP. The PDP program is designed as an independent quality assurance test to provide data that supports the overall QAPP compliance assessment process. The PDP program parameters, criteria and scoring formalism is used in the following sections to document the IMPACT and WIT/A&PCT performance where applicable. Additionally, the RCI and CEP performance tests used criteria and scoring formalism founded in the PDP criteria but are slightly different as described below. These performance evaluation test programs are purposely derived from the primary QAPP compliance requirements to support a direct interpretation of IMPACT and WIT/A&PCT performance results. Thus, the IMPACT and WIT/A&PCT performance measures can be readily interpreted relative to the QAPP requirements. The criteria of these various programs are listed next.

National TRU Program Quality Assurance Program Plan

The performance assessment parameters and evaluation criteria as found in the QAPP, Section 9.0, Interim Change are presented in Table 1. All measurement series that were acquired per this guidance are evaluated via the applicable criteria within this table.

Table 1. Quality assurance objectives for nondestructive assay.

Waste Activity alpha-Ci range[a]	Nominal[b] Compliance Point, *alpha-Ci* (g WG Pu)	Precision[c] (%RSD)	Accuracy[d] (%R)	Total Bias[e] (%)
>0.002 –- 0.02	*0.008* (0.1)	$\leq$20	75 – 125	low 25 high 400
>0.02 – 0.2	*0.08* (1.0)	$\leq$15	50 – 150	low 35 high 300
>0.2 – 2.0	*0.8* (10)	$\leq$10	75 – 125	low 67 high 150
>2.0	*12.5* (160)	$\leq$5	75 – 125	low 67 high 150
Minimum Detectable Concentration (nCi/g) ---- 60				

[a] Applicable range of TRU activity in a 208-L (55-gal) drum to which the QAOs apply, units are curies of alpha-emitting TRU isotopes with half-lives greater than 20 years.
[b] The nominal activity (weight of Pu) in the 208-L (55 gal) drum used to demonstrate that QAOs can be achieved for the corresponding range in column 1, values in parentheses are the approximate equivalent weights of weapons grade plutonium (WG Pu), 15 years after purification: for purposes of demonstrating QAOs, "nominal" means $\pm$ 10 percent.
[c] Plus or minus one standard deviation based on 15 replicate measurements of a noninterfering matrix.
[d] Ratio of measured to known values based on the average of 15 replicate measurement of a noninterfering matrix.
[e] 95 percent confidence bounds for system bias established by studies to determine contributions to total uncertainty from all significant sources. Units are confidence bounds divided by true value, expressed as a percent. Requirement for the QAO for total uncertainty is to determine and document, but no system-wide values are established.

Performance Demonstration Program

The NDA PDP is designed to help ensure compliance with the QAPP QAOs. The PDP consists of periodic assay tests conducted on waste matrices of increasing matrix and source complexities. These tests are used to evaluate the capability of a technology to properly characterize TRU wastes. Each test is termed a PDP cycle. These evaluation cycles are blind tests that provide an independent objective measure of the reliability and performance of NDA systems. The PDP consists of a set of 208-L (55-gal) drums configured to allow for the installation and fastening of a matrix in place, and external introduction and precise positioning of radioactive standards sources within the drum. The PDP requires six replicate measurements and removal of the drum between replicates.

Presently there are three drum matrices: (1) air (no matrix), (2) combustibles, and (3) glass. Aluminum source insert fixtures are provided for each of three insert tube radii: Center or 0R, 0.5R and 0.8R, where R is the drum radius. Radioactive standard(s) are positioned at desired vertical locations within the three insert fixtures. Several versions of radioactive standards are used in the program. The initial standards for the first four cycles were weapons-grade (WG) plutonium dioxide (PuO_2) uniformly mixed in diatomaceous earth and then encapsulated in a dual stainless steel cylinder configuration (*o.d.*: 5 cm, *l*:23 cm). Each assembled PDP drum for every official cycle included a tamper indicating seal. Currently, four cycles have been completed. The A&PCT technology has participated in and passed Cycle 2 informally and formally in Cycles 3 and 4. All measurement series that were acquired per the PDP are evaluated via the applicable criteria within Table 2.

Table 2. Summary of PDP criteria.

Range of Waste Activity (α-Curies)	Nominal Compliance Point α-Curies (g WG Pu)	Relative Precision (R_p)	Accuracy Noninterfering Matrix (% R)	Bias Interfering Matrix (% R)
>0–0.04	0.008 (0.1)	40	75–125 (25)	Low 40% High 175%
>0.04–0.4	0.08 (1.0)	30	50–-150 (50)	Low 30% High 200%
>0.4–4.0	0.8 (10)	20	50–150 (50)	Low 30% High 200%
>4.0	12.8 (160)	10	75–125 (25)	Low 50% High 150%

Capability Evaluation Project

As part of the MWFA characterization development strategy, a method to objectively evaluate the utility of waste assay system technologies was implemented in conjunction with the Characterization Monitoring and Sensor Technology (CMST) crosscut area program. This evaluation was designed to support nondestructive waste assay system technology capability and deficiency determinations and to facilitate resource allocation to areas requiring development. The evaluation will also generate information and data to end-user EM-30 Waste Management programs to support appropriate selection and application of a given NDA technology to the various waste streams.

The CEP evaluation project was specified such that information could be gathered to substantiate NDA capability and utility statements as a function of waste type and/or characteristic (CEP Test Plan 1997). The waste types of interest were those contaminated with TRU elements. The evaluation program was conducted at the INEEL's Radioactive Waste Management Complex (RWMC), using actual waste forms currently in storage and appropriate surrogates. To the extent RWMC waste form attributes approximate other site waste inventories, statements can also be made regarding system utility per the site of interest. The capability evaluation test plan addressed the acquisition, compilation, and reporting of performance data, thereby allowing an objective evaluation of the participating waste NDA systems. The evaluation was structured such that a statement regarding select INEEL RWMC waste forms can be composed relative to compliance potential relative to applicable NTP requirements and criteria.

Criteria used to evaluate assay system capability are founded in the NTP QAPP, Section 9.0, Interim Change version, the PDP Plan for NDA for the TRU Waste Characterization Program, and the Transuranic Packaging Transporter Transportation Requirements. Applicable criteria can be readily applied to the surrogate type test samples in that the alpha activity emplaced in the surrogate matrix is well known. This allows the accepted scoring formalism of the NDA PDP program to be used in the CEP performance evaluation process with minor modifications, thus simplifying interpretation and the derivation of compliance/performance statements. The actual waste type test samples are the unique aspect of the CEP in that performance is assessed with respect to actual waste forms and their associated configurations.

The precision and bias QAOs used for the surrogate type test sample and the precision QAOs for the actual RFETS type sample are based on the NDA PDP Program QAOs. Modification to the NDA PDP QAOs has been performed to account for the number of replicates (eight) used per sample in the CEP project. The NDA PDP noninterfering and interfering matrix QAOs for precision are tabulated in Table 3. The Table 3 precision criteria apply to both the surrogate and actual RFETS test samples. The noninterfering and interfering matrix QAOs for bias used in the CEP are taken directly from the PDP (Table 2) and are tabulated in Table 4.

Table 3. Measured relative precision requirement adjusted for eight replicates used in the CEP.

Activity Range in "-Curies	**Maximum Allowable Precision (95% CB of QAPP QAO)**	**Maximum Measured Precision (%RSD) @ 8 replicates (noninterfering)**	**Maximum Measured Precision (%RSD) @ 8 replicates (interfering)**
>0 to 0.02	29.2	≤16.0	≤18.0
>0.02 to 0.2	21.9	≤12.0	≤14.0
>0.2 to 2.0	14.6	≤8.0	≤14.0
>2.0	7.3	≤4.1	≤7.0

Table 4. CEP Bias QAOs taken from PDP.

Activity Range in "-Curies	**Bias QAO Values for $\%R_L$ and $\%R_U$ (noninterfering)**	**Bias QAO values for $\%R_L$ and $\%R_U$ (interfering)**
>0 to 0.02	Low: 75% High: 125%	Low: 40% High: 175%
>0.02 to 0.2	Low: 50% High: 150%	Low: 30% High: 200%
>0.2 to 2.0	Low: 75% High: 125%	Low: 30% High: 200%
>2.0	Low: 75% High: 125%	Low: 50% High: 150%

Rapid Commercialization Initiative Test

BIR is engaged in a Program Research and Development Agreement and a Rapid Commercialization Initiative with the DOE's EM-50. The agreement requires BIR to develop information sufficient to establish compliance with applicable NTP waste characterization requirements and associated quality assurance performance criteria. This effort requires an objective demonstration of the BIR waste characterization system. As with the CEP project, the goal of the RCI test project is to provide a mechanism from which evidence can be derived to substantiate NDA capability and utility statements for the BIR system. The performance evaluation parameters and criteria used in the RCI project are as indicated for the CEP. Similar to the CEP test project, the RCI test used test samples with configurations representative of nominal configurations of large population fraction waste types in inventory at the INEEL RWMC.

Treatment Performance

This section provides a summary of the formal demonstration data for both the IMPACT and WIT systems.

Performance Demonstration Program

The IMPACT system participated officially in Cycle 3, and WIT participated in Cycle 4. Table 5 lists the results of these tests (PDP Scoring Report November 1996 and PDP Scoring Report May 1997).

Table 5. IMPACT results from PDP demonstration.

System/Test Sample ID	Waste IDC	%RSD	Precision QAO (%RSD)	%R Recovery (x/μ)	% Recovery Acceptance Criteria (95% Confidence Bounds)	
					Lower Bias % R	Upper Bias %R
IMPACT PDP-3	Drum 003 (Combustibles)	1.98	6	66.41	52.08	147.92
IMPACT PDP-3	Drum 003 (Combustibles)	1.93	6	70.39	52.08	147.97
WIT PDP-4	Drum 003 (Combustibles)	2.95	12	109.83	33.09	196.91
WIT PDP-4	Drum 001 (Zero)	1.54	3.5	99.06	76.62	123.38

Additional data were collected during the official and unofficial PDP tests. The A&PCT scan data showed that as the integration time decreases, the assay result increases. Increasing amounts of Pu mass attributed to the increasing amounts of noise added as a real signal to the PCT image. The additional mass was due to the fact that the MLEM algorithm does not accept any negative values. Thus, a positive assay bias resulted for signals that approached the noise level of the IMPACT system. Methods applied to account for this bias were not always successful so another method was developed (Goodman 1997). Before the new method longer integration times were needed to provide a signal that was well above the noise. It should be noted that the integration time required is a strong function of the activity of the drum and its attenuating matrix. For example, the bias for the PDP Cycle 3 tests (high activity drums) was not seen due to the short integration times.

The PCT data consisted of a 20 s ray sum integration time. For the drum with the combustible matrix and 71.36 g WG Pu, the measured mean is 47.1 g. The % recovery is 66.0% with a precision of 0.58%. For the drum with the glass matrix and 98.3 g WG Pu, the measured mean is 69.9 g, a % recovery of 71.1% with a precision of 0.84%. The average of the two % recoveries and precisions is 68.5% and 0.7%, respectively. Therefore, the bias of the IMPACT system is ~30% low.

Two additional measurements were made on the glass matrix drum to better understand the system bias at shorter integration times. PCT measurements at 10 and 5 s ray-sum integration times resulted in 69.4 and 69.1 g, respectively. These results agree with the 20 s PCT assay to within 1%. Thus, for signals well above the system noise, assay results are independent of ray-sum integration times.

Under sampling was also evaluated using the PDP Cycle 3 matrix. A 15 replicate study was completed for one of the four QAPP activity ranges. Three PDP standards (3, 0.3 and 0.3 g of WG Pu) were loaded into the combustible matrix drum. The ACT ray sum integration time was 15 s. Results for a complete sampled PCT (ray sum integration time of 25 s) data set and an under sampled PCT data set resulted in a % recovery of 80.4%, with a precision of 2.8%, which meets QAPP requirements. The under sampled data were obtained by computationally removing every other ray and projection from the complete sample data set. This resulted in a 2X to 4X reduction of the complete data set. The under sampled data precision is 3.9% with an accuracy of 79.0%. Since the difference in these two data sets is <2% and both meet QAPP requirements, it was concluded that the under sampling protocol can be used to assay a drum with one quarter the passive data acquisition time. The under sampled results were verified experimentally.

Capability Evaluation Program

The performance results of the WIT trailer for the CEP evaluation are shown in Table 6 (draft report, Becker 1998).

Table 6. BIR WIT Performance Evaluation on Total Alpha Activity Parameter (CEP evaluation).

Test Sample ID	Waste IDC	WIT %RSD	Precision QAO (%RSD)	% Recovery (x/μ)	% Recovery Acceptance Criteria (95% Confidence Bounds)	
					Lower %R	Upper %R
[a]SG6	409 (MSE Salts)	1.1	< 7.0	70.7	50.9	149.1
SG9	442 (raschig ring)	4.2	< 14.0	154.9	33.5	196.5
[b]RF11	003 (organic sludge)	12.8	< 14.0	61.1	40.8	189.2
RF20	480 (metals)	1.2	< 14.0	148.7	31.0	198.9

[a] Surrogate wastes.
[b] RFETS wastes in storage at the INEEL.

Rapid Commercialization Initiative

The performance results of the WIT technology via the RCI test project are tabulated in Table 7.

Table 7. BIR WIT Performance Evaluation on Total Alpha Activity Parameter (RCI Test).

Test Sample ID	Waste IDC	WIT %RSD	Precision QAO (%RSD)	% Recovery (x/μ)	% Recovery Acceptance Criteria(95% Confidence Bounds)	
					Lower %R	Upper %R
1RF[a]	300 (graphite)	7.1	< 7.0	127	57.4	142.6
2RF	336 (moist combustibles)	2.73	< 18.0	Below DL	43.5	171.5
1SG[b]	440 (glass)	3.89	< 14.0	141.4	32.2	197.8
3RF	442 (raschig ring)	2.95	< 14.0	122	33.1	196.9
2SG	330 (dry combustibles)	4.15	< 14.0	162.5	32.5	197.5
4RF	376 (filters/insulation)	1.54	< 7.0	86	51.6	148.4
3SG	480 (metals)	4.15	< 14.0	179.6	33.5	196.5
5RF[c]	001 (inorganic sludge)	2.73	< 7.0	14.9	51.2	148.8

[a] RFETS wastes in storage at the INEEL.
[b] Surrogate wastes.
[c]5RF data not fully evaluated at this time.

To summarize the demonstration results of surrogate tests (PDP, CEP and RCI), Figure 3 shows the system accuracy as a function of percent recovery and test sample mass loading. The vertical bar in the figure represents the allowed error in the accuracy as defined by the QAPP. The ball in each bar represents the mean measured percent recovery for each test. Figure 4 shows the results of precision for these performance measures. The bar represents the allowed error in precision and the ball represents the measured precision as a function of percent relative standard deviation. If the bias (or %R) is plotted as a function of ^{239}Pu mass, the data suggest that the A&PCT systems have a high bias when assaying low mass quantities (less than 10 g, in six out of seven samples) and the IMPACT system has a low bias when assaying high mass quantities (greater than 50 grams). The WIT system appears to have no low bias with high mass quantities. However, the new CCG reconstruction code was developed to reduce these observed biases and will be implemented on the WIT system upgrade in FY-99.

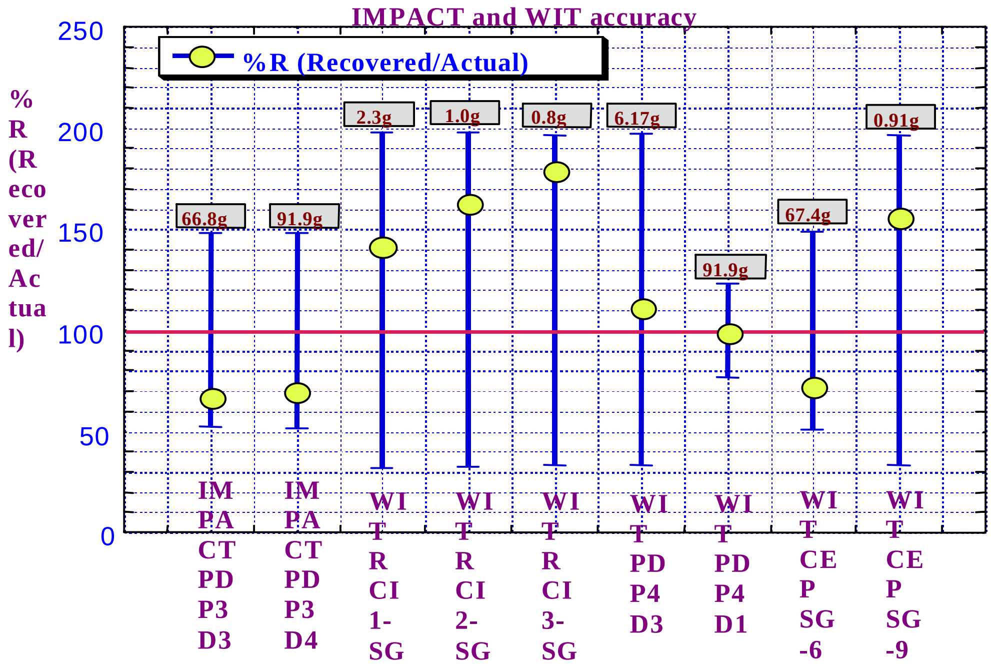

Figure 3. PDP, RCI, and CEP performance measure tests demonstrate bias of the IMPACT and WIT scanners. The vertical bar represents the allowed error in the percent recovery. The ball represents the percent recovery.

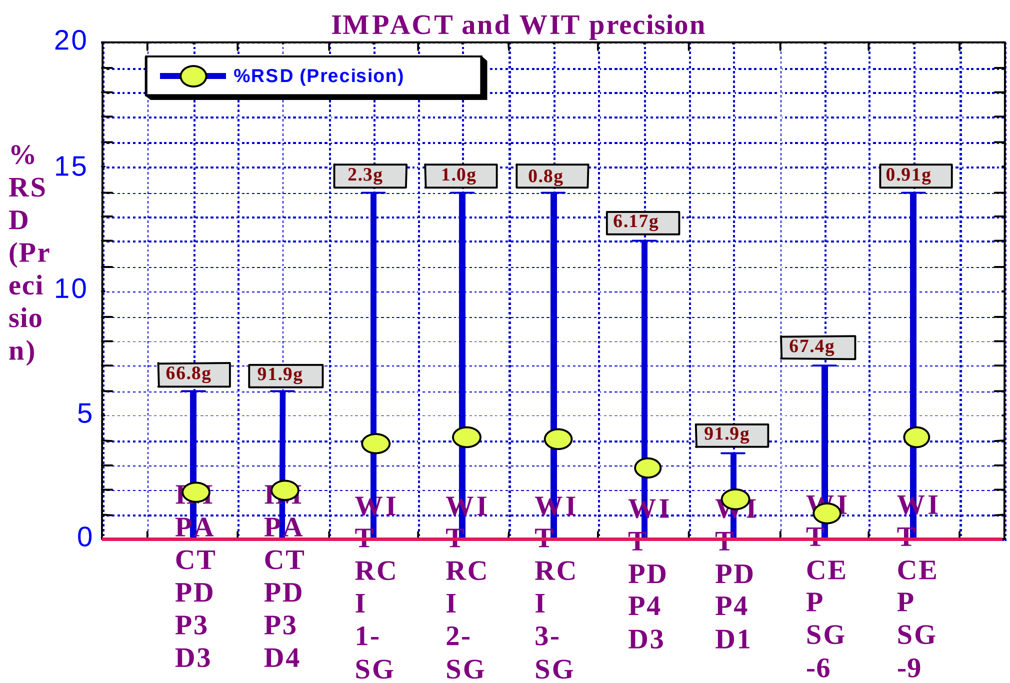

Figure 4. The performance measure tests also demonstrate precision of the IMPACT and WIT scanners. The vertical bar represents the allowed error in the percent RSD (relative standard deviation). The ball represents the measured RSD.

The two A&PCT scanners have been used to assay a wide range of radioactive waste from 1–100 g of Pu within matrices from combustibles to sludge. The preliminary performance of LLNL's IMPACT scanner was determined to have an accuracy of ~70% with a precision less than a few percent for combustible and glass matrices. Additional R&D is required to better understand the negative 30% bias on the IMPACT for good statistical data sets. New image reconstruction and assay codes were completed in FY-98 to reduce the high positive bias for poor statistical data. LLNL has also worked on automating the isotopic analysis and determining the systematic uncertainties, as well as determining IMPACT's MDC and its performance at the other three QAPP activity ranges. The WIT system does not have the negative bias, but did have the same high positive bias for poor statistical data. The new image reconstruction and assay codes developed at LLNL will address this problem. The new codes will be implemented in the WIT system when it is upgraded in FY-99. And finally the total uncertainty applicable to IMPACT or WIT/A&PCT has not been addressed.

Key System Parameters

The WIT/A&PCT technology provides measurement times that can be scaled to the amount of activity and to the drum-fill height found within a drum by the fast survey CGS mode. Thus, A&PCT scan times can be customized to acquire sufficient statistics to ensure that accurate measurements are made and time is not wasted scanning a portion of the drum with no radioactivity. This system has also been designed so that a special calibration is not required as a function of the type of waste matrix, type of gamma-ray radioactive sources within the drum, distribution of the waste matrix, or distribution of the radioactive sources. LLNL's A&PCT technology does not require prior knowledge of, and calibration for, the waste stream that is being assayed. For example, during the PDP cycles, the A&PCT scanners could be calibrated for the drum matrices and source structures that are similar to the PDP drums and attain assay results that are much more accurate. However, something as simple as removing the double steel container used to seal the reference sources (this may be the case in a real waste drum) could make a difference in the final assay results. For that reason, this system assays waste matrices and source structures of all kinds to remove the dependency on calibration procedures. This can be important for assaying waste streams that are unknown or are suspected of containing something other than what is documented on the manifests.

To attain an absolute assay measurement, the A&PCT systems are calibrated once on an absolute detector-efficiency scale by simple measurements of a calibrated radioactive point source. Additional calibrations for different Pu gram-loadings or matrices is not needed because the computed tomography method takes into account the geometry of the source and detector and their collimators. In either the IMPACT or WIT system, the calibration needs to be done once since it only changes if the collimator is changed or if the detector response changes.

Limitations/Potential Problems

Each specific NDE and NDA technology has intrinsic limitations that derive from the physical basis of their measurement process. The A&PCT technology is a gamma-ray based tomographic technique, hence it cannot quantify isotopes that do not emit gamma rays. The CAO requirement to report ^{90}Sr, a pure beta emitter, cannot be measured by this technology. Similarly, the A&PCT technology is not designed to measure either spontaneous or induced neutron emissions from within a waste drum. Thus, the neutron-based NDA technologies can provide information that supplements an assay performed by the A&PCT technology.

Another limitation arises from the very low branching ratios characteristic of many gamma-ray transitions found in TRU isotopes of interest to WIPP. As an example, the isotope of most interest to WIPP, ^{239}Pu, has a branching ratio of $1x10^{-5}$ for its 414-keV gamma-ray transition. Although the 100-keV gamma-ray transitions found in many TRU isotopes of interest do have larger branching ratios, they do not have sufficient energy to escape from a waste matrix and be detected. Long TRU half-lives and low gamma-ray transition branching ratios are the primary reasons that the A&PCT technology is stated to be "physics limited." It is not possible to make a long half-life TRU isotope decay faster nor increase its branching ratio to gives us a counting rate higher than nature allows.

The physics limited aspects of long half-lives and small branching ratios coupled with the required tomographic measurement protocol serve to limit waste drum throughput. This limitation has the greatest impact on those drums having the lowest TRU loadings (0.002 –- 0.02 αCi) and those near the MDC limit. For these drums, measurement times must be longer to obtain better counting statistics, which results in more accurate assays. The best way to overcome the physics and throughput limitations is to increase the number of detectors and thereby increase measurement sensitivity, while still preserving the principles of tomographic imaging and assay.

Another intrinsic limitation and advantage is that the A&PCT technology is a tomographic measurement, which means that the PCT mode locates radioactive sources to within one or more specific small voxels in a waste drum. A single voxel corresponds to a partial drum volume of only six-ten thousandths of a 208-L (55-gal) drum. Unfortunately, this means that many of the passive tomographic ray sum measurements measure nothing, i.e., no source emissions.

Another limitation may be the A&PCT technology's ability to correct for large TRU lumps (or clumps) of material from greater than 0.2 cm in diameter. Even small 1-mm diameter-sized spheres of a TRU isotope are self-absorbing of their own emitted gamma radiations. A 2.54-cm lump may not be properly imaged by the ACT transmission method since it occupies less than 7% of its voxel volume. Thus, the proper quantification of such a sphere of TRU material would derive by combining results from NDE digital radiography and/or tomography with the NDA A&PCT results and perhaps even with NDA neutron based results. This is an excellent example where the fusion of results from one or several NDE modes with results from neutron- and gamma-ray based NDA systems may provide more accurate waste drum characterizations.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

This section addresses in more detail the types of mixed waste streams that the Gamma-Ray A&PCT is most amenable to. The section also compares the A&PCT technology to other competing NDA technologies and defines the status, commercial availability, and maturity of the A&PCT technology.

Competing Technologies

Gamma-ray spectroscopy with high-energy resolution germanium detectors has been successfully used as a quantitative radioactive assay method for many years. The excellent energy resolution associated with the use of HPGe detectors allows for radionuclide identification with high confidence. This resolution also increases the signal to noise for the measurement, thereby enabling very accurate peak areas (or counts) to be extracted from complicated spectra. For point sources, there are several methods available to relate these peak areas to absolute assay values. However, for many sample-detector geometries employed, the point source assumption is not valid and it is difficult to relate peak areas to absolute intensities without calibration sources of the same energy and geometry. This problem arises because of the difficulty in calculating the detector solid angle for extended sources; this is made even more complicated when sample self-absorption is important. For sources that are roughly the same size as the detector there are methods that can relate the extended source efficiency to point source calibration data. However, these methods become less reliable as the source dimensions become much larger than the detector. For 208-L (55-gal) drums measured by 0.2-L detectors, these methods do not apply. Moreover, these conventional gamma-ray spectroscopy methods require the source to be uniformly distributed in a homogeneous attenuating matrix. Real waste drums rarely meet these conditions.

The two commonly used gamma-ray spectroscopy technologies are the segmented gamma-ray spectrometry (SGS) technique and the IQ3, both commercially available. The SGS technique measures spatially averaged gamma-ray intensities in eight or 10 segments, i.e., horizontal slices of the drum. The average matrix attenuation value for each slice is measured by the transmission of an external source. The attenuation value is used to correct each section's average passive gamma-ray emitted intensity. The IQ3 technology uses two sets of three HPGe detectors to complete the data collection. The IQ3 system utilizes several techniques to quantify the fissile content of a waste drum. These include transmission correction to determine the drum matrix density, lump detection using multi energy assays, and non uniformity correction using Canberra's Non Uniformity Correction Software. The IQ3 also utilizes the Multi-Group Analysis (MGA) software to determine the Pu isotopics as well as the U/Pu ratio and the Pu/^{241}Am ratio. MGAU provides uranium isotopics values for materials, which do not contain Pu.

Both systems participated in the CEP. The SGS has been demonstrated at PNNL, LLNL, and RFETS as part of the PDP Cycles 1 through 4, and Canberra demonstrated the SGS as a commercial participant in Cycles 3 and 4. Detailed performance data on both the SGS and the IQ3 systems can be obtained from the PDP final reports and the soon to be published final report on the CEP (PDP Scoring Report November 1996, PDP Scoring Report May 1997, draft report Becker 1998).

Technology Applicability

The WIT/A&PCT technology is applicable to the following:

- drums or items whose volume is equal to or less than a 416-L (110-gal) drum,
- items weighing equal to or less than 1,600 lb each,
- low-level, TRU, and mixed wastes,
- all packaging types including metal drums, lead drum liners, cemented or lead shielding, steel pipe overpacks, metal drum overpacks, poly or fiber board liners, poly drum liners, and poly bags; all matrices including sludge, cement, metals, glass, plastics, etc.;
- TRU specified alpha activity levels (except LLW/TRU threshold).

Technology Status and Maturity

The A&PCT technology can be procured through BIR. Currently, BIR is offering a single, HPGe detector with a drum platform, which is capable of carrying out tomographic scans on waste drums up to 416 liters (110 gallons). This technology can be installed in a permanent facility or operated from a mobile platform. BIR is scheduled to complete demonstration of a multidetector system in FY-99. This improved system should be capable of measuring, on average, one drum per hour.

Patents/Commercialization/Sponsor

A technology transfer effort was initiated in FY-93, with BIR of Lincolnshire, IL. BIR received funding in July 1993, from the FETC's Industrial Programs, to develop a mobile WIT system. A single, HPGe detector with a drum platform, which is capable of carrying out tomographic scans on waste drums up to 416 liters (110 gallons), was deployed to the mobile WIT system.

SECTION 5

COST

Methodology

The cost estimates summarized in this section are at the planning estimate level, and are based on the draft report "*Rapid Commercialization Initiative Final Report for Waste Inspection Tomography,*" Report Number 96-RCI-09 of June 15, 1998. The cost and contingency application methods used in this section follow the Good Practice Guide on Life Cycle Cost and multiple Cost Estimating Guides.

End users should examine the assumptions used in this analysis before applying the cost estimates as their site-specific solution.

Cost Analysis

The referenced report identified these assumptions:
- Drum assay using an A&PCT instrument as part of a mobile assay system will be provided as a service by a technology provider.
- Up to 22,500 drums will be assayed over a period of 60 months.
- Performance will be based on gamma scanning an average of 16 to 20 drums per day.
- Multiple shifts and Friday work days are expected
- Standby charges per day or hour are required for a lack of drum delivery and site shutdowns
- Mobilization and demobilization charges are also required

The referenced report then collected detailed cost data on:
- Transportation and set-up costs for mobile system.
- Site documentation costs.
- Site readiness review costs.
- Mobile system operation costs (including site support).
- Mobile system maintenance costs.
- Tear-down and transportation costs for mobile system.

Some data were based on the testing during the development and demonstration phases; other data were based on past mobile equipment system costs.

Conclusions

Drum assay costs, using the A&PCT technology as part of a mobile assay system provided by a technology vendor, are estimated at between $400 to $1200 per drum based on the total throughput and batch sizes committed. These costs include data generator validation (2nd technical review), data generator QA check, and data generator management approval of batched data packages.

SECTION 6

REGULATORY AND POLICY ISSUES

This section presents current and anticipated regulatory requirements that an end user of a NDA technology would have to meet site and disposal facilities characterization requirements. The specific regulatory requirements and their associated issues that pertained to the A&PCT development effort are also described.

This section also presents an analysis performed by the MWFA that assesses the various risks involved with deployment of the A&PCT and pertinent stakeholder responses to the technologies application.

Regulatory Considerations

The objective of using a WIT/A&PCT system is to characterize all radioisotopes within a mixed waste container nondestructively (without opening the container). Major regulatory requirements, including permit/license requirements, for implementation of this technology are expected to include:

- National Environmental Policy Act (NEPA) review for implementation at federal facilities. At DOE facilities, this includes an initial environmental checklist that is used to assist in determining if a more detailed environmental assessment or environmental impact statement is required.
- A radioactive material license from the Nuclear Regulatory Commission (NRC) or its applicable agreement state for non-DOE facilities and for DOE facilities regulated by NRC or the agreement state.

The regulatory activities conducted for the WIT/A&PCT system demonstration at the INEEL included an NRC license to carry isotopic sources that must be registered. A State of Illinois license, approved by the NRC, was also required for each sealed isotopic source up to 15 mCi in activity. Only one source of this type was associated with the WIT system: a ^{166m}Ho source with an activity of less than 1.5 mCi. In addition, BIR would be required to register the WIT 2 MV x ray source with the State of Illinois if title and ownership of the WIT system were transferred to a non-DOE entity. If the system were operated at a non-DOE or non-Federal site while still owned by DOE, each state that the unit is to be operated in would be notified in advance that the mobile 2MV x ray source is planned to be operated on a temporary basis on a specific date or for a given period of time at a specific location in that state.

Regulatory Issues

The RCI demonstration experienced no unusual regulatory issues. State and federal regulators participated on the WIT Project Team. A copy of the demonstration plan was provided to each team member for review and comment. Each regulator was invited to actively contribute during each phase of the demonstration process. There were no regulatory issues raised.

Safety, Risks, Benefits, and Community Reaction

Eight risk areas were evaluated and assessed independently. These risk values for MWFA developed technologies have been derived from the eight top-level requirements defined in the MWFA Systems Requirements Document (INEL 1997). The eight areas evaluated for level of risk are: (1) ease of permitting, (2) technical correctness, (3) level of safe operability, (4) technical completeness (i.e., ready to use), (5) timely to meet treatment schedules, (6) acceptability to stakeholders, (7) cost-effectiveness to use, and (8) committed sponsorship. A complete description of the methodology and a detailed definition of each risk element, the event scenario, and the basis for assigning consequences and probability factors are included in Appendix C.

Permitable: The risk category is rated as low and improbable that a permit application will be rejected. This is not a treatment process, therefore a permit to operate is not required. A DOE site must certify an instrument to use in characterizing TRU waste. The vendor for this technology, BIR, is currently participating in the NTP's PDP to certify the technology.

Complete: The risk category is rated as low and improbable that additional engineering is required to allow the instrument to be incorporated into a system. The A&PCT system has been engineered, by the private sector vendor, to operate on a mobile trailer. The IMPACT system at LLNL would require engineering modifications to be used in a characterization facility.

Acceptable: The risk category for acceptable is rated as low and improbable that a Native American Tribe or public interest group would resist implementation of the A&PCT technology at a DOE site.

Timely: The risk category is rated as low and improbable that the technology will not be available by Site Treatment Plan or Consent Order dates. The A&PCT system is commercially available to make real waste measurements through BIR.

Cost: The risk category is rated as medium and improbable that the operational costs will be higher than expected. The cost analysis is based on the characterization of a large volume of waste. Even a minor difference in cost could affect a site if large quantities of waste were targeted.

Sponsored: This category is listed as low and unlikely that no end user or commercial entity selects the technology for implementation. A commercial company, BIR, is marketing the technology. The system has been licensed by the NTS to characterize their waste.

Correct: This category is listed as medium and improbable that the technology will not be applicable to the target waste. Multiple waste types were measured using this instrument to identify the applicable target streams.

Safe: This category is listed as low and improbable that system failure will adversely impact the health and/or safety of a collocated worker, the environment, or a member of the public. No hazardous materials will be added or generated during the measurement. Radiological hazards should be no different than commonly accepted medical techniques, i.e., cat scans.

The MWFA Tribal and Public Involvement Resource Team reviewed stakeholder issues and concerns related to characterization of mixed wastes. The risk to the community is very low. In general, the public has limited familiarity with NDA systems such as the A&PCT, but would be expected to support it as an improvement. The issues of concern to the public are discussed:

Community Safety

- There is no adverse safety impact to the community.

Potential Socioeconomic Impacts and Community Perceptions

- No socioeconomic impacts are anticipated.
- No adverse public or tribal input regarding the A&PCT technology was received.
- Community reaction to the A&PCT technology is anticipated to be favorable, since the technology will not adversely impact quality of life issues.
- Comparisons of this technology to x ray systems currently in use (such as those in dentists offices or hospitals) may also reduce the anxieties associated with the sources.

Benefits

- The improved accuracy and reliability of the system can provide the public with increased confidence in assay data.
- There will be no potential to release contaminants to the environment.

SECTION 7

LESSONS LEARNED

Implementation Considerations

Owners of mixed waste and potential technology end users have several choices for waste characterization. These choices include the A&PCT technology, the SGS, or any other gamma or neutron based NDA system. It is recognized that an end user may need to use a suite of technologies to address their waste assay needs. Factors that should be considered when evaluating the use of this or any NDA technology include:

- System assay times – Technology operations should not affect site schedules.
- Operator knowledge – Particularly of concern when a site contracts outside services. Operators should demonstrate a very good working knowledge of all the trailer infrastructure systems as well as the assay system hardware and software operation.
- Adherence to Environment, Safety, and Health (ES&H) – Particularly of concern when a site contracts outside services. The vendor's onsite operators must adhere to site ES&H requirements.
- Preparation time to start assay – Technology operations should not affect site schedules.
- Trailer/assay system working condition – Safety related components/systems in good shape and no equipment or software items require repair.
- Troubleshooting capability – The vendor has demonstrated capability in troubleshooting and maintenance of their system.
- Time to obtain data reports from vendors – Characterization process should not affect site schedules.
- Coordination/communication – Evaluate how well the vendor management team coordinates and communicates with the customer (overall hassle factor).
- Ease of operation/maintenance – Simplicity of operation and ease of maintainability, e.g., time required for infrastructure system setup and takedown (stairways, shielding, utility/data connections, etc.), number of operators, systems simple to operate, etc.

Design Issues

The technology currently uses a single HPGe detector during waste measurement. This requires a lengthy data acquisition period, which may impact a site's operational schedule. FETC has funded the development and demonstration of a multidetector system, which would reduce this time significantly. Demonstration data will be collected in FY-98 and FY-99 to determine this system's capability. A second ITSR is planned to summarize the multidetector demonstration project.

Technology Limitations and Needs for Future Development

It is expected that this technology will enable the characterization of wastes for WIPP (or other facility), that formerly could not be certified to meet the TRUPACT-II requirements or the WIPP Waste Acceptance Criteria (WAC). However, there are several development areas associated with the A&PCT technology that have just been completed or require further development to overcome the limitations described in Section 3. They include a multiple detector system, "smart" scan techniques to shorten drum scan times, further optimization of the automated isotopic analysis program, continued testing of lump correction techniques, and the fusion of other NDE and NDA modalities that could lead to more accurate assay values and more complete waste characterizations. Many of these development areas were recently completed and implemented in the software at LLNL. However the improved software has not been implemented on the WIT system. The new software will be implemented during the WIT system upgrade in FY-99. This upgrade will include modifying the WIT system from a single to a multi-detector unit. Once installed the improved software and hardware will be tested and ready for implementation in FY-99. The activities required to further enhance the WIT/A&PCT technology includes the following:

- Reducing the scan time required to assay a drum. Methods to reduce data acquisition scan times in the ACT and PCT modes without compromising the accuracy of the assay are being evaluated. These methods include the upgrade of the WIT A&PCT scanner to incorporate multiple detectors and a continuous motion scanning mode. This should reduce the counting time by a factor of 10 for the long integration times currently required to assay low waste activity and to perhaps as much as a factor of 100 for high waste radioactivities.

- Increasing the throughput of the A&PCT technology. This could be accomplished by implementing scan geometries that differ from traditional computed tomography: or "smart" scans. The type of scan geometry used would depend on the drum matrix or other factors identified by other means. For example a sludge drum may be found to be homogeneous by NDE methods and therefore scanned differently from other non-homogenous drums. Using the smart scan method for particular classes of drums could increase the throughput of a system by a large factor.

- An automated isotopic analysis program was developed for TRU waste. This program is designed to be flexible so that it can be tailored to expected waste streams. However, through experience in evaluating real waste drums in the field, there may be a need in the future to add enhancements or optimize the isotopic code. These enhancements may include the addition of isotopes that were not initially expected in the TRU waste streams, and optimization for isotopes that occur more than originally expected. Incorporating these and other future experiences will lead to a more robust operation of the code.

- Including an improved lump correction in the system. A lump correction is required when the size of the material lump being assayed is massive enough to self-attenuate its own gamma-ray emissions. Although a method was developed to correct for the self-attenuation expected from certain size lumps of Pu, it may be possible to improve this technique by other methods. Only recently (August 1998) have well characterized sources that exhibit problems associated with self-absorption become available to the DOE community. These PDP sources should be used to reveal what methods are most promising to solve the lump correction problem.

- Incorporating a data fusion methodology into the software. This is the process of integrating the results from both NDE and NDA characterization techniques to achieve a more accurate assay or to increase the confidence of an assay. The integration of A&PCT quantitative data and NDE high spatial resolution data may solve problems related to: lump corrections and homogeneity of a drum (that in turn can be used to determine the optimum A&PCT scan geometry that should be used to obtain maximum throughput). The integration of other NDA assay data with A&PCT data sets will provide increased accuracy and confidence.

APPENDIX A

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APPENDIX C

RISK ASSESSMENT METHODOLOGY

Risk has been measured for eight of the system requirements as defined in the MWFA Systems Requirements Document.

Technically Correct (**Correct**)
The MWFA shall deliver treatment technologies that are technically correct. Operable treatment systems shall be able to: (1) treat target waste streams identified in Federal Facility Compliance Act (FFCA) Site Treatment Plans (STPs) and (2) treat wastes to meet EPA treatment standards (and TSCA or state-regulated treatment standards, where applicable) and comply with the disposal facility Waste Acceptance Criteria.

Technically Complete (**Complete**)
Treatment technologies delivered by the MWFA shall be demonstrated to function as described, and shall be described in sufficient detail so that they may be incorporated into a detailed system design of a mixed low-level or mixed transuranic waste treatment system without further development.

Acceptable to Stakeholders (**Acceptable**)
The MWFA shall deliver mixed waste treatment technologies that are acceptable to the stakeholders.

> Note: The term "stakeholders" means all those who have an interest in the outcome of the MWFA program except the DOE and DOE contractors who have a direct and immediate interest or involvement in the MWFA. Stakeholders include: tribal governments, members of the public, federal, state, and local agencies, universities, and industry.

Acceptable to an End User (**Sponsored**)
The MWFA shall deliver mixed waste treatment technologies to users committed to pursuing the use of those treatment technologies in mixed waste treatment systems.

Permittable
The MWFA shall deliver mixed waste treatment technologies along with sufficient data to show that there are no probable technical reasons to prevent receiving a permit to implement the technology in an operational treatment system. The permit process will be facilitated by involvement with national regulatory organizations such as NTW on Mixed Waste Treatment and Interstate Technology and Regulatory Cooperation Subgroup (ITRC). This will include working with the regulators to improve technologies and/or a facility's ability to obtain a permit.

Safe
The MWFA shall deliver mixed waste treatment technologies that can be incorporated into a treatment system and safely operated.

Timely
The MWFA shall deliver mixed waste treatment technologies to enable treatment systems to be designed, built, and operated in time to meet treatment schedules in the FFCA STPs and negotiated in Consent Orders.

Cost
The “delta” refers to the cost of implementation by an end user when compared to the cost analysis included in the Technology Performance Report (TPR). The more closely the cost of implementation compares with cost as reported in the TPRs, the smaller the consequence to the end user of the technology.

Each of the eight system requirements will be addressed independently. Events that can lead to negative consequences relative to implementation of a technology will be identified and assigned to each system requirement. These events will be referred to as “risk factors.” Each technology will be evaluated independently and relative values for consequences and probability will be assigned to each of the events.

Criteria have been defined for each risk category to allow the user to, as quantitatively as possible, determine the probability and consequence measures to be applied for determination of risk.

Permittable

Permit application is rejected based on regulations that became effective after development of the technology.

The consequences of this scenario will be:

Low if	Treatment process is simple.
Medium if	Treatment process is complex.
High if	Treatment process is highly complex.

The probability of this scenario occurring will be:

Improbable if	An applicable permit has been received.
Unlikely if	Regulators have maintained interaction with developers on this technology during development and demonstration.
Likely if	A permit application has already been rejected for this technology.

Complete

Technology is insufficiently mature to incorporate into a system without additional engineering data.

The consequences of this scenario will be:

Low if	Technology can be deployed without the need for additional testing.
Medium if	Technology can be deployed with limited additional testing and documentation.
High if	Technology requires significant additional development and/or testing to deploy.

The probability of this scenario occurring will be:

Improbable if	Technology successfully meets Stage 5 requirements for full system functionality and has successfully conducted a treatability study.
Unlikely if	Technology successfully meets Stage 5 requirements for full system functionality and has conducted successful demonstration(s) with surrogate wastes.
Likely if	Technology successfully meets Stage 5 requirements for full system functionality but demonstration/testing program is incomplete.

Acceptable

Native American Tribes and/or public interest groups resist implementation of the technology at DOE sites.

The consequences of this scenario will be:

Low if	Concerns can be addressed by providing additional information about the technology's performance.
Medium if	Concerns center on the performance of the technology; relatively minor modifications to the technology can address the needs and concerns.

High if Major modifications to the technology are required to address concerns about the performance and ability to solve the problem.

The probability of this scenario will be:

Improbable if The affected Tribes and public perceive implementation of the technology as resolving an important problem at their site with minimal or no impact to their quality of life, or have not expressed any concerns.

Unlikely if The affected Tribes and public perceive implementation of the technology as solving an important problem but having a negative impact on the quality of life.

Likely if The affected Tribes and public perceive implementation of the technology will not solve an important problem at the site and is perceived to have significant negative impact on the quality of life.

Timely
The technology is not available for implementation by the STP or Consent Order date.

The consequences of this scenario will be:

Low if Delay in the availability of the technology will not result in missing a milestone in a Consent Order.

Medium if Need dates for the Consent Order can be renegotiated to accommodate the delay in availability of the technology.

High if Unavailability of the technology results in missing key milestones in Consent Orders at multiple sites.

The probability of this scenario will be:

Improbable if Technology development/implementation activities are completed within end-user schedules.

Unlikely if Need dates identified accommodate any minor delays in technology development activities.

Likely if Technology does not meet end-user schedules.

Cost
Operational costs are higher than projected.

The consequences of this scenario will be:

Low if Volume of the targeted waste is low.

Medium if Volume of the targeted waste is fairly small.

High if Volume of the targeted waste is very large.

The probability of this scenario will be:

Improbable if Projections of the technology's cost is based on data from multiple campaigns.

Unlikely if Projections of the technology's cost is based on data from only one campaign.

Likely if No actual cost data for the technology on the targeted waste exists.

Sponsored
No end-user or commercial entity selects the technology for implementation.

The consequences of this scenario will be:

Low if	Multiple data sets detailing the technology's performance on targeted waste are available.
Medium if	Only limited data are available detailing the technology's performance on targeted waste.
High if	Data are not available detailing the technology's performance on the targeted waste.

The probability of this scenario will be:

Improbable if	Multiple licensing agreements or financial commitments have been made.
Unlikely if	A single licensing agreement or financial commitment for the technology has been made.
Likely if	No commitments have been made or interest shown in the use of the technology.

Correct
Operable treatment systems, which incorporate this technology, are not applicable to target wastes.

The consequences of this scenario will be:

Low if	Volume of targeted waste to be treated is low.
Medium if	Volume of targeted waste to be treated is fairly small.
High if	Volume of targeted waste to be treated is very large.

The probability of this scenario will be:

Improbable if	Technology developed was tested against multiple waste types.
Unlikely if	Technology developed was tested against only one waste type.
Likely if	Technology developed was not tested against targeted waste type.

Safe
System failure adversely impacts the health and/or safety of a collocated worker, the environment, or a member of the public.

The consequences of this scenario will be:

Low if	Hazardous constituents added or generated by the system are less than the reportable quantities shown in 40 CFR 302.4 and 40 CFR 355, Appendix A.
Medium if	Nominal reportable quantities of hazardous constituents shown in 40 CFR 302.4 and 40 CFR 355, Appendix A, are added or generated by the system.
High if	Hazardous constituents in quantities 10 times or greater than those listed in 40 CFR 302.4 and 40 CFR 355, Appendix A, are added or generated by the system.

The probability of this scenario will be:

Improbable if	System is a benign process, difficult to combust with no natural gas or fuel sources present.
Unlikely if	System is a moderately energetic process with natural gas or fuel sources present.

Likely if	System is an energetic system (high temperature and/or pressure); large amounts of flammables or pyrophorics.

APPENDIX D

ACRONYMS

A&PCT	Active & Passive Computed Tomography
BIR	Bio-Imaging Research, Inc.
CAO	Carlsbad Area Office
CCG	Constrained Conjugate Gradient
CEP	Capability Evaluation Program
CMST	Characterization Monitoring and Sensor Technology
CT	computed tomography
DOE	Department of Energy
DR	digital radiography
EM	Environmental Management
EPA	Environmental Protection Agency
EROI	energy regions of interest
ES&H	Environment, Safety, and Health
FETC	Federal Environmental Technology Center
FFCA	Federal Facility Compliance Act
FY	Fiscal Year
HPGe	high-purity germanium detector
IMPACT	Isotope Measurements by Passive and Active Computed Tomography
INEEL	Idaho National Engineering and Environmental Laboratory
ITRC	Interstate Technology and Regulatory Cooperation Subgroup
ITSR	Innovative Technology Summary Report
LLNL	Lawrence Livermore National Laboratory
LLW	low-level waste
LMITCO	Lockheed Martin Idaho Technology Company
MCA	multichannel analyzer
MDC	minimum detectable concentration
MLLW	mixed low-level waste
MTRU	mixed transuranic waste
MWFA	Mixed Waste Focus Area
NDA	nondestructive assay
NDE	nondestructive examination
NEPA	National Environmental Policy Act
NRC	Nuclear Regulatory Commission
NTP	National Transuranic Program
NTW	National Technical Workgroup
PC	personal computer
PDP	Performance Demonstration Program
PNNL	Pacific Northwest National Laboratory
QAO	Quality Assurance Objectives
QAPP	Quality Assurance Program Plan
RCI	Rapid Commercialization Initiative
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
RWMC	Radioactive Waste Management Complex
SGS	segmented gamma-ray spectrometry
SPECT	single-photon-emitted CT
STP	Site Treatment Plan
TGS	Tomographic Gamma Scanner
TRU	transuranic
WAC	Waste Acceptance Criteria
WG	weapons-grade
WIPP	Waste Isolation Pilot Plant
WIT	Waste Inspection Tomography