WIPP Certification of the Retrieval Box Assay System at the Advanced Mixed Waste Treatment Plant, Idaho - 16241

Alan Simpson *, Jim Seamans *, Jacob Stirler *, Keith Gainer *, Doug Dinneen [#], Steve Turner [#]
* Pajarito Scientific Corporation, 2976 Rodeo Park Drive East, Santa Fe, NM 87505, USA
asimpson@pscnda.com, jseamans@pscnda.com, jstirler@pscnda.com, kgainer@pscnda.com
[#] Idaho Treatment Group LLC, 850 Energy Drive, Suite 100, Idaho Falls, ID 83401, USA
Doug.Dinneen@amwtp.inl.gov , Steven.Turner@amwtp.inl.gov

ABSTRACT

The Retrieval Box Assay System (RBAS) at the Advanced Mixed Waste Treatment Plant (AMWTP) is an Imaging Passive Active Neutron system supplemented with a High Purity Germanium (HPGe) gamma system for the quantification of Pu-239 Fissile Gram Equivalent (FGE) and transuranic (TRU) alpha activity of waste containers of various sizes up to 249 cm x 149 cm x 198cm (Length x Width x Height). The system was originally calibrated in 2002 (with a range of surrogate matrices and radioactive sources in a 213 cm x 122 cm x 122 cm FRP box) and has been operational for over a decade. As of August 2015, the RBAS has measured approximately 18,000 boxes (50,000 m^3 of waste) which has subsequently been fed into the facility's treatment process. Its success, and the wide envelope of waste that it can characterize, has led AMWTP to extend the RBAS mission to include WIPP certification.

As part of this new project, the instrument must be capable of meeting WIPP's Waste Acceptance Criteria (WAC) which include reporting activities and masses of the 10 WIPP-tracked radionuclides. The system will be required to assay sludge and debris waste streams, shredded waste and large metal items. The container size includes Standard Waste Box (SWBs), Fiberglass Reinforced Plywood (FRPs) and large Shredder Boxes. Sludge matrices will be loaded into 210-liter (55-gallon) drums and placed inside an SWB. After assay, boxes will be over-packed into SLB-II's for shipment to WIPP.

The target waste streams will contain mixtures of Weapons Grade plutonium, Heat Source plutonium (high in Pu-238 content) and Mixed Oxide (MOX). The activity of the waste is expected to encompass a wide dynamic range of activity from low-level waste (LLW) to TRU with up to several hundred grams of plutonium. Some packages will have high gamma activity associated with fission and activation products such as Cs-137 and Co-60.

The existing RBAS hardware (detectors, electronics, assay chamber etc.) was retained for this project. Two lead filters were provided and installed on the existing filter wheels to attenuate the gamma ray flux from the highest activity boxes to avoid overload of the HPGe detectors.

The new software suite includes PC-FRAM (Version 5), which is used for the isotopic analysis of the gamma spectra. Integration of FRAM and neutron results is performed using a software package known as RBAS WIPP Analysis Reporting Software (RWARS). This package also performs matrix dependent background adjustments. Other upgrades provided include automated tests that identify when assay parameters fall outside a predetermined range and a new Quality Checking (QC) application.

Minimum Detectable Activity (MDA) values were determined for the active and passive neutron modes as a function of measured matrix correction indices. The resulting Minimum Detectable Concentration (MDC) has been demonstrated to be less than 3700 Bq/g alpha activity (100 nCi/g). Modifications were performed to update the system TMU parameters to accommodate assay of non-standard size boxes and a wider range of matrix materials.

A series of calibration confirmation, measurements were performed on site in 2014 using a representative range of surrogate boxes and radioactive sources including Pu. The WIPP WAC performance criteria were successfully demonstrated up to 157g Pu and the system passed its first Performance Demonstration Program (PDP) cycle in the Spring of 2015.

INTRODUCTION

The Advanced Mixed Waste Treatment Plant (AMWTP) Retrieval Box Assay Systems (RBAS) shown in Figure 1 is an imaging passive/active neutron system supplemented with a High Purity Germanium (HPGe) gamma system for the quantification of Pu-239 Fissile Gram Equivalent (FGE) and transuranic (TRU) alpha activity of waste boxes of various sizes.

Fig. 1 Retrieval Box Assay System

The system was originally calibrated in 2002 and has been operational for over a decade. As of August 2015, the RBAS has measured approximately 18,000 boxes (50,000 m^3 of waste) which has subsequently been fed into the facility's treatment process. Its success, and the wide envelope of waste that it can characterize, led AMWTP to extend the RBAS mission to include Waste Isolation Pilot Plant (WIPP) certification [1]. Pajarito Scientific Corporation (the original system supplier) were sub-contracted to support AMWTP in delivery of this project, supplying a new upgraded software suite and performing expert data analysis activities including calibration confirmation.

The upgraded instrument must comply with WIPP's Waste Acceptance Criteria (WAC) which include reporting activities and masses of the 10 WIPP-tracked radionuclides. The system is required to assay sludge and debris waste streams, shredded waste and large metal items. The container size includes Standard Waste Box (SWBs), Fiberglass Reinforced Plywood (FRPs) and large Shredder Boxes. Sludge matrices will be loaded into 210-liter (55-gallon) drums and placed inside an SWB. After assay, boxes will be over-packed into SLB-II's for shipment to WIPP.

The system must be capable of analyzing Weapons Grade and Heat Source plutonium (high in Pu-238 content) as well Mixed Oxide (MOX). The activity of the waste is expected to encompass a wide dynamic range of activity from low-level waste (LLW) to TRU with up to several hundred grams of plutonium. Some packages will have high gamma activity associated with fission and activation products such as Cs-137 and Co-60.

To meet the isotopic requirements, the new software incorporates PC-FRAM [2] for analysis of the gamma spectra. Integration of FRAM results and RBAS neutron results is performed using software known as RBAS WIPP Analysis Reporting Software for Expert Analysis (RWARS-EA) The existing RBAS hardware (detectors, electronics, assay chamber etc.) was retained for this project. Two lead filters were provided and installed on the existing filter wheels to attenuate the gamma ray flux from the highest activity boxes to avoid overload of the HPGe detectors.

A series of calibration confirmation, Total Measurement Uncertainty (TMU), Minimum Detectable Activity (MDA) and Quality Control (QC) measurements were performed at AMWTP with surrogate boxes and radioactive sources including Pu.

CALIBRATION CONFIRMATION METHOD

The RBAS has been previously calibrated with a range of surrogate matrices and radioactive sources in a 213 cm x 122 cm x 122 cm (Length x Width x Height) Fiberglass Reinforced Plywood (FRP) box. The existing calibration is robust for a wide range of box sizes with diverse matrix contents. The key dimensional parameter affecting performance is the box length (width and height are of lesser importance). It was demonstrated that the maximum permissible box size is 249 cm x 149 cm x 198 cm (Length x Width x Height) and the minimum is 61 cm x 61 cm x 51 cm. The software calculates TMU terms to account for various effects including matrix and box size effects and includes specific uncertainty terms for boxes that are less than a minimum value or greater than a maximum in length.

Calibration confirmation measurements were undertaken with measurements using Pu standards loaded into various sizes of surrogate boxes containing surrogate matrix materials over a range that is representative of waste planned for measurement by the system.

The WIPP WAC [1] acceptance criteria will be used for calibration confirmation. The WAC provides specific criteria for non-interfering matrices. For interfering matrices, the WIPP Performance Demonstration Program criteria for accuracy (bias) were used. The percentage Relative Standard Deviation (%RSD) for interfering matrices shall not exceed 16% over the 6 replicates. The criteria are described in Appendix 3.

Background measurements were performed on site (gamma, active neutron and passive neutron) with an empty measurement chamber.

The MDA for the system was evaluated as a function of matrix type by performing a series of blank (no Pu) measurements on each of the representative surrogate boxes / matrix types. The MDA measurement and calculation methods are required to comply with the WIPP WAC Data Quality Objectives (DQOs) such that the Lower Limit of Detection (TRU α-activity concentration) shall be 3700 Bq/g (100 nCi/g) or less.

The TMU for the system was evaluated by analysis of on-site measurements with the surrogates. The confidence interval for each measurement was evaluated against the known tag values to determine any appropriate adjustment of the existing system TMU parameters.

QC parameters (2 sigma and 3 sigma equivalent measurement control limits) were determined from a series of measurements with background and standardization / check box sources. Tolerance ranges for the required Weekly Interfering Matrix (WIM) Tests were determined from evaluation of the Calibration Confirmation data. The new software suite included an application for QC, background and WIM tracking.

SURROGATE MATRIX BOXES

Standard Waste Boxes (SWBs) with dimensions of 180 cm x 138 cm x 94 cm (Length x Width x Height) with 24 source insert tubes (see Figure 2) were configured with the following surrogate matrices (two letter code for each is given in parenthesis): Empty (EM) Dry combustibles (DC) and Light metals (LM). In addition an SWB was prepared with 4 sludge drums, of 210-liter (55-gallon) volume each.

Shredder Boxes with dimensions of 244 cm x 122 cm x 122 cm (Length x Width x Height) containing 33 source insert tubes (8 x 4 array with one central tube) were filled simulated shredded debris (a random mixture of metals and wood). Shredder box #1 (SB1) contained simulated debris plus a simulated steel item. Shredder Box #2 (SB2) was filled with simulated debris only.

FRP Boxes containing 29 source insert tubes (7 x 4 array with one center tube) were configured with the following surrogate matrices: Matrix #1 (Empty), Matrix #2 (115 kg Polyethylene + 249 kg Vermiculite), Matrix #10 (76 kg Salt + 229 kg Polyethylene + 208 kg Vermiculite) and Matrix #15 (38 kg Salt + 267 kg Vermiculite).

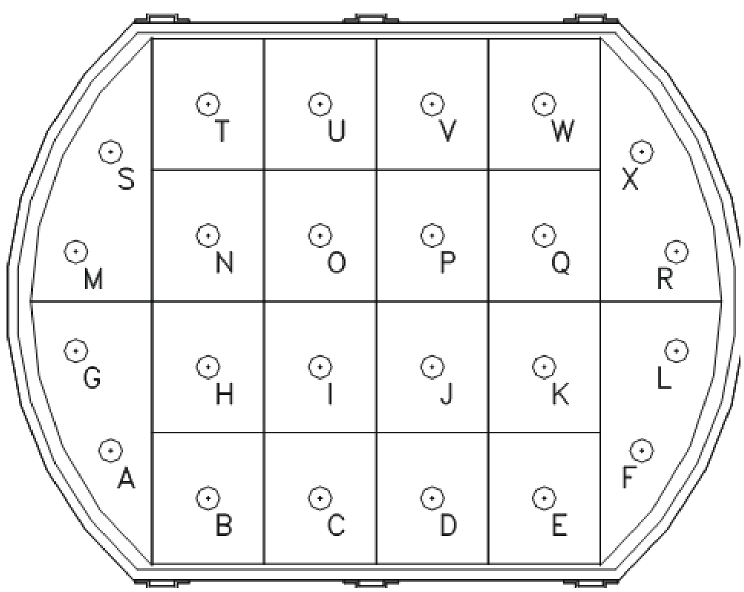

Fig. 2 Arrangement of Source Insert Tubes in Standard Waste Box.

A summary of the matrices is given in Table I. The matrix correction indices known as “ABS”, “MOD” and “ABSMOD” are listed for each matrix. These indices are used in the system software in passive and active mode to select the appropriate calibration matrix. FRP M1 was not used in calibration confirmation due to its similar dimensions and similar matrix correction indices to the SWB empty box.

TABLE I. Summary of Surrogate Matrices

Size	Matrix	Matrix Code	ABS	MOD	ABSMOD	Gross Wt (kg)	Tare Wt (kg)	Net Wt (kg)
FRP	FRP #1 (Empty)	M1	2.283	1.186	2.105	252.42	231.82	20.60
FRP	FRP #2	M2	5.884	5.631	5.039	597.74	231.82	365.92
FRP	FRP #10	M10	10.263	8.347	9.117	745.04	231.82	513.22
FRP	FRP #15	M15	6.330	2.503	5.955	538.55	231.82	306.73
SWB	SWB Empty	EM	1.889	0.872	1.758	391.25	291.00	100.25
SWB	4x55G Sludge	SL	3.049	1.681	2.797	1160.82	291.00	869.82
SWB	Dry Comb	DC	3.568	2.212	3.236	649.88	291.00	358.88
SWB	Light Metals	LM	3.645	1.349	3.443	999.57	291.00	708.57
Shredder	SB Large Item	SB1	13.879	2.433	13.514	3446.63	742.50	2704.13
Shredder	SB Random	SB2	18.258	6.488	17.285	3542.43	742.50	2799.93

CALIBRATION UPDATES

The system calibration from 2002 was used as the basis for the WIPP certified system. This calibration was performed using National Institute of Standards and Technology (NIST) traceable standards.

The calibration was amended by including two additional matrices to the active imaging library (AMX file) in order to accommodate analysis of containers with ABSMOD index up to 19.06. The new AMX file is summarized in Table II. The applicable range of the new active matrix calibration is ABSMOD index from 1.82 to 19.06 (this is equivalent to 0.91 to 9.53 for SWBs). For the matrices indicated with (*) the ABSMOD index has been adjusted slightly from the original calibration AMX file based on the measured surrogate matrix correction parameters.

TABLE II. New RBAS Active Calibration Library Summary (AMX)

Matrix #	Standard ABSMOD	SWB ABSMOD RANGE	Creation Date
M1	2.02	0.91 ≤ ABSMOD ≤1 .71	10/3/2002
M2	4.80*	1.71 < ABSMOD ≤ 2.64	10/3/2002
M3	5.74	2.64 < ABSMOD ≤ 3.13	10/3/2002
M8	6.78	3.13 < ABSMOD ≤ 3.52	10/3/2002
M14	7.30*	3.52 < ABSMOD ≤ 3.73	10/3/2002
M11	7.61	3.73 < ABSMOD ≤ 3.93	10/3/2002
M7	8.10	3.93 < ABSMOD ≤ 4.35	10/3/2002
M6	9.30*	4.35 < ABSMOD ≤ 4.71	10/3/2002
M9	9.53	4.71 < ABSMOD ≤ 5.36	10/3/2002
M12	11.91	5.36 < ABSMOD ≤ 6.49	10/3/2002
M21	14.06	6.49 < ABSMOD ≤ 8.28	11/1/2014
M22	19.06	8.28 < ABSMOD ≤ 9.53	11/1/2014

No adjustment is necessary for the Passive Matrix library (summarized in Table III) which has an applicable MOD index range from 1.07 to 12.48.

TABLE III. RBAS Passive Calibration Library Summary (PMX)

Matrix #	Standard MOD	Creation Date
M1	1.19	10/3/2002
M2	5.17	10/3/2002
M3	8.25	10/3/2002
M8	9.38	10/3/2002
M14	12.48	10/3/2002

The threshold for active / passive mode was set at 10 g Pu-239 effective. If the Imaged Active Mass result is greater than or equal to this value then passive mode is used. This threshold represents a trade-off between self-shielding (which affects the active result at high mass values) and coincidence count rate statistical precision (which affects the passive mass at low mass values). For sludge waste analysis, a higher active / passive threshold (35 g Pu-239 effective) is recommended due to the fact that large plutonium lumps are unlikely to occur in sludge [3]. In practice, the sludge threshold may be implemented by manual selection.

BACKGROUNDS

A series of background measurements (no sources loaded and an empty chamber) was performed over the period 11/05/2014 through 12/22/2014. This is a special sequence that acquires background gamma, active neutron and passive neutron data.

The RWARS-EA software determined the Background Adjusted Passive Coincidence Mass M_{PM}^{BA} using Equation 1.

$$M_{PM}^{BA} = \frac{M_{PM}(R_{CCRAW} - R_{CCRAW}^{ADJBKG})}{(R_{CCRAW} - R_{CCRAW}^{PMXBKG})} \quad \text{(Eq. 1)}$$

where M_{PM} is the Passive Coincidence Mass calculated by the RBAS software (i.e. using the PMX background), R_{CCRAW} is the Raw Coincidence Count Rate for the assay, R_{CCRAW}^{PMXBKG} is the Raw Coincidence Count Rate from the PMX file, and R_{CCRAW}^{ADJBKG} is the Background Adjusted Raw Coincidence Count Rate which is calculated below:

$$R_{CCRAW}^{ADJBKG} = \frac{X_3^p R_{CCRAW}^{QCBKG}}{X_0^p + X_1^p MOD + X_2^p MOD^2} + X_4^p R_{CCRAW}^{PMXBKG} + X_5^p Wt_{gross} \quad \text{(Eq. 2)}$$

where MOD is the measured MOD index, Wt_{gross} is the gross weight of the container, (in kilograms), R_{CCRAW}^{QCBKG} is the QC Background (Empty Chamber) Raw Coincidence Count Rate. The constants X_0^p, X_1^p etc. were determined from measurements with surrogate (blank) containers. These were defined for several background physics models (denoted by *p*) depending on whether significant matrix mass is present such that a cosmic spallation correction and/or MOD index correction is required. These constants are given in Table IV. The final parameter for the weight model was determined by linear regression of net coincidence rate with the surrogate gross weight.

TABLE IV. Background Physics Model Library Parameters

Physics Model Name	p	X_0^p	X_1^p	X_2^p	X_3^p	X_4^p	X_5^p
Linear	0	1.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Weight	1	1.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	1.66E-03
PMX	2	1.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00

Analysis of the blank (no source added) MDA replicate measurements with the surrogate matrix boxes described demonstrates that the backgrounds fall into two categories (i) light containers (below 872 kg gross weight) where the mean background for the blanks is approximately equal to the QC background with empty chamber (here the “linear model” is applicable), (ii) heavy containers (equal to or greater than 872 kg) where a dependence on weight is observed between the Net Coincidence Count Rate and gross weight (here the “Weight” model is applicable). The “PMX” model is included for backward compatibility with legacy data sets.

For the evaluated matrices there was no statistically significant relationship observed between background rate and MOD index and therefore the MOD index correction part of Equation 2 was set to unity.

MINIMUM DETECTABLE ACTIVITY

Using the Currie method [4], the MDA is defined as that level of radioactivity that, if present, yields a measured value greater than the critical level with a 95% probability, where the critical level is defined as that value which measurements of the background will exceed with 5% probability. The MDA also accounts for interferences from different matrix conditions or radiation backgrounds that occur in the waste.

The MDA is determined using Equation 3.

$$MDA = 2.71 + 4.65\sigma \qquad \text{(Eq. 3)}$$

where σ is the standard deviation of the background rate over 6 replicate ‘blanks’, i.e. background measurements of a surrogate matrix containing no source, acquired on site in typical operational conditions. Note that, for this MDA analysis, it is assumed the background measurement time will be the same as the assay count time.

A series of replicate measurements were performed using the RBAS with the various surrogate matrices over the period 11/06/2014 to 12/22/2014. Table V provides a summary of the mean and standard deviation in the Imaged Active Mass (g Pu-239 effective) and Passive Coincidence Mass (g Pu-240 effective) respectively. The standard deviations in the 6 replicates were used to determine estimates of MDA for both active neutron mode and passive neutron mode.

TABLE V. Summary of results from MDA blank measurements at AMWTP

Surrogate Description		Summary of 6 Replicate Blanks (no source)			
Size	Matrix	St Dev (g Pu239e)	Act MDA (g Pu239e)	St Dev (g Pu240e)	Pas MDA (g Pu240e)
FRP	FRP M2	0.006	0.026	0.083	0.388
FRP	FRP M10	0.052	0.240	0.085	0.397
FRP	FRP M15	0.009	0.041	0.016	0.076
SWB	SWB Empty	0.007	0.034	0.119	0.552
SWB	4x55G Sludge	0.116	0.539	0.319	1.484
SWB	Dry Comb	0.020	0.091	0.049	0.229
SWB	Light Metals	0.018	0.082	0.044	0.205
Shredder	SB1 Large Item	0.014	0.067	0.047	0.219
Shredder	SB2 Random	0.036	0.168	0.058	0.269

Functional forms of the MDA have been determined using the data in Table V and are given in Equation 4 (which defines active mode MDA_A) and Equation 5 (passive mode MDA_P).

$$MDA_A = \alpha_A e^{\beta_A ABSMOD} \quad \text{(Eq. 4)}$$

$$MDA_P = \alpha_P e^{\beta_P MOD} \quad \text{(Eq. 5)}$$

where α_A, β_A, α_P and β_P are constants. The values for these constants were determined from analysis of blank surrogate replicate measurements as 0.02, 0.30, 0.16 and 0.14 respectively.

The Minimum Detectable Concentration (MDC) is determined on a real-time basis, by using the measured (or default) isotopic fractions, container net weight and the active mode MDA. Based on the Pu default isotopic fractions the MDC values for the surrogate matrices vary from 15.5 nCi/g (from SWB Light Metals) to 88.7 nCi/g (for Shredder Box SB2).

Figure 3 shows the relationship between ABSMOD, net weight and MDC. The solid red line indicates the threshold of 100 nCi/g (3700 Bq/g) above which Low Level Waste (LLW) /TRU sorting can be performed with the RBAS. The points on the plot indicate the position of the surrogate matrices (all above the line).

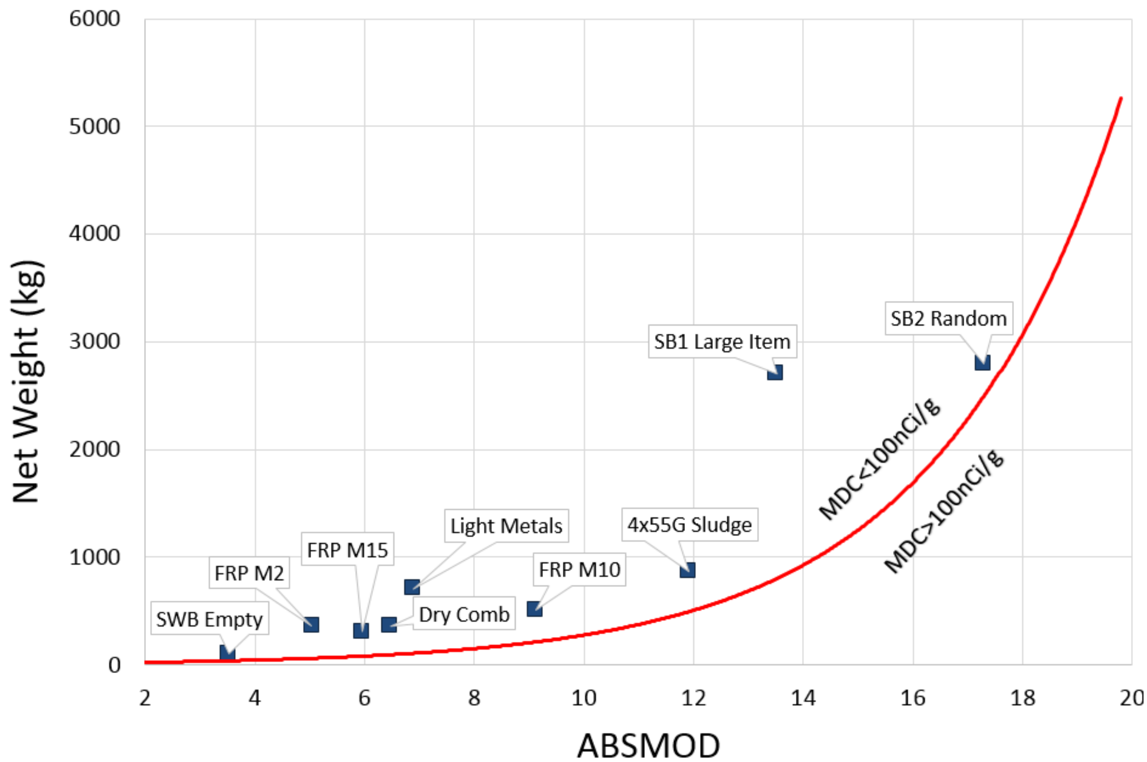

Fig. 3 LLW/TRU sorting threshold as a function of Net Weight and ABSMOD

CALIBRATION CONFIRMATION

Calibration confirmation runs were performed over the period 11/05/2014 through 12/22/2014. A set of six “routine assay” replicate measurements (gamma, active neutron, passive neutron) were performed with each box at each loading. A summary of results is given in Table VI. In this table %R is defined as the ratio of the mean of measured results for each loading to the known value expressed as a percentage. The %RSD is the standard deviation of the measured results as a ratio of the known value. The average “number of sigmas” residuals for each of these nuclides is also given here.

TABLE VI. Summary of Calibration Confirmation Results

Barcode ID	Matrix	Pu Mass (g)	Mode	%R	%RSD	%R P/F	%RSD P/F	Avg Num Sigmas
BCAL1003	M2	0.9	ACT	85.0%	0.88%	**PASS**	**PASS**	0.58
BCAL1004	M10	0.9	ACT	84.9%	3.79%	**PASS**	**PASS**	0.58
BCAL1005	M15	0.9	ACT	83.7%	2.03%	**PASS**	**PASS**	0.64
BCAL1025	EM	0.9	ACT	93.6%	2.06%	**PASS**	**PASS**	0.02
BCAL1006	DC	0.9	ACT	78.9%	3.01%	**PASS**	**PASS**	0.06
BCAL1007	LM	0.9	ACT	80.7%	2.79%	**PASS**	**PASS**	0.06
BCAL1040	SB1	2.9	ACT	95.6%	2.70%	**PASS**	**PASS**	0.11
BCAL1041	SB2	2.9	ACT	88.8%	15.80%	**PASS**	**PASS**	0.46
BCAL1051	SL	2.9	ACT	91.2%	7.75%	**PASS**	**PASS**	0.02
BCAL1011	M2	8.9	ACT	75.9%	0.11%	**PASS**	**PASS**	1.05
BCAL1012	M10	8.9	ACT	66.4%	0.59%	**PASS**	**PASS**	1.66
BCAL1013	M15	8.9	ACT	64.8%	0.57%	**PASS**	**PASS**	1.79
BCAL1026	EM	8.9	ACT	75.0%	0.47%	**PASS**	**PASS**	0.08
BCAL1014	DC	8.9	ACT	67.0%	0.88%	**PASS**	**PASS**	0.11
BCAL1015	LM	8.9	ACT	77.1%	0.88%	**PASS**	**PASS**	0.07
BCAL1009	SB1	8.9	PAS	132.8%	9.20%	**PASS**	**PASS**	0.67
BCAL1010	SB2	8.9	ACT	58.6%	4.21%	**PASS**	**PASS**	1.65
BCAL1016	SL	8.9	ACT	53.9%	2.81%	**PASS**	**PASS**	0.20
BCAL1038	SB1	74.7	PAS	99.1%	5.62%	**PASS**	**PASS**	0.11
BCAL1039	SB2	74.7	PAS	153.1%	4.53%	**PASS**	**PASS**	0.99
BCAL1037	SL	74.7	PAS	71.4%	13.95%	**PASS**	**PASS**	0.88
BCAL1019	M2	157.1	PAS	120.6%	3.20%	**PASS**	**PASS**	1.00
BCAL1020	M10	157.1	PAS	135.4%	3.91%	**PASS**	**PASS**	1.52
BCAL1021	M15	157.1	PAS	118.0%	4.30%	**PASS**	**PASS**	0.89
BCAL1027	EM	157.1	PAS	108.3%	5.92%	**PASS**	**PASS**	0.16
BCAL1022	DC	157.1	PAS	58.1%	3.41%	**PASS**	**PASS**	1.52
BCAL1023	LM	157.1	PAS	110.5%	6.24%	**PASS**	**PASS**	0.19
BCAL1017	SB1	157.1	PAS	150.9%	8.44%	**PASS**	**PASS**	0.96
BCAL1018	SB2	157.1	PAS	154.4%	3.54%	**PASS**	**PASS**	1.00
BCAL1024	SL	157.1	PAS	122.4%	14.24%	**PASS**	**PASS**	0.36

PC-FRAM / AK ISOTOPIC ANALYSIS

The RWARS-EA software uses a combination of neutron assay results, PC-FRAM analysis of the gamma spectra and Acceptable Knowledge to determine the WIPP reportable results for each container. The FRAM analysis will generally produce good statistics for mass loadings above 10g Pu. Below this value the RWARS-EA software will usually select AK for analysis based on the rules defined in the software.

The RBAS has two Broad Energy Germanium (BEGE) detectors arranged on opposite sides of the assay chamber for isotopic analysis. FRAM parameter sets have been configured for isotopic analysis of Pu-238, Pu-239, Pu-240, Pu-241, Pu-242 (by correlation) and Am-241. The following additional nuclides (suspected to be present in the AMWTP waste streams with detectable gamma emissions) are included in the parameter sets: U-232, U-233, U-235, U-238 (via Pa-234m daughter), Ra-226, Th-232, Np-237, Am-243, Cm-243, Cm-244, Cf-249, Co-60, Cs-134 and Cs-137.

Four FRAM parameter sets were created for routine analysis of gamma spectra acquired with the RBAS :

- **pu_cx_120-1300-rbas** - optimized for analysis of Pu over the range of 5% Pu-240 up to 14% Pu-240 mass fraction. The analysis covers the region 120 – 1300 keV. Diagnostic messages are evoked when the FRAM results indicate heterogeneous Pu or possible presence of MOX.
- **het_pu_cx_120-1300-rbas** - optimized for analysis of heterogeneous Pu/Am over the range of 5% Pu-240 up to 14% Pu-240 mass fraction. The analysis covers the region 120 – 1300 keV. The Am-241 uses a secondary efficiency function with the assumption that Am-241 is not co-located with the Pu. A systematic uncertainty term of 10% (1 sigma) is included for Am-241. FRAM combines the systematic uncertainty with the statistical terms in quadrature.
- **mox_cx_120-1300-rbas** - optimized for analysis of Mixed Oxide (MOX) containing U-235 and Pu. The analysis covers the region 120 – 1300 keV.
- **hs_pu_cx_145_1300-rbas** - optimized for analysis of Heat Source (HS) Pu (up to 80% Pu-238 mass fraction). The analysis covers the region 145 – 1300 keV.

Default isotopic fractions are stored in software for Weapons Grade and Heat Source Pu. The Am-241 default mass fractions were calculated using an assumed chemical separation date and applying the formula for the Am-241 mass fraction (as a function of elapsed time and Pu-241 mass fraction) given in the FRAM manual [2]. U-234 and Cs-137 are both determined by scaling factors.

TABLE VII. Summary of FRAM Results

			Avg Replicate % Mass Frac.			Number of Sigma Residuals			Neutron>Alpha Conversion		
Barcode ID	Matrix	Pu Mass (g)	Pu239 (g/g-Pu)	Pu240 (g/g-Pu)	Am241 (g/g-Pu)	Pu239	Pu240	Am241	Mode	%R iso	%RSD iso
BCAL1011	M2	8.9	92.9%	6.9%	4.3%	0.4	0.4	2.1	ACT	100.7%	1.3%
BCAL1012	M10	8.9	93.4%	6.4%	3.7%	0.2	0.2	1.3	ACT	100.0%	0.0%
BCAL1013	M15	8.9	93.5%	6.3%	4.3%	0.2	0.2	2.4	ACT	100.4%	0.8%
BCAL1026	EM	8.9	93.8%	6.0%	4.1%	0.0	0.0	0.7	ACT	100.0%	0.0%
BCAL1014	DC	8.9	92.8%	7.0%	4.0%	0.5	0.5	0.5	ACT	100.0%	0.0%
BCAL1015	LM	8.9	91.2%	8.5%	4.3%	0.6	0.8	1.1	ACT	100.4%	0.9%
BCAL1009	SB1	8.9	N/A	N/A	N/A	N/A	N/A	N/A	PAS	100.0%	0.0%
BCAL1010	SB2	8.9	N/A	N/A	N/A	N/A	N/A	N/A	ACT	100.0%	0.0%
BCAL1016	SL	8.9	90.0%	9.7%	3.3%	1.0	1.1	1.4	ACT	100.0%	0.0%
Tag Isotopics			93.9%	6.0%	3.9%						
BCAL1038	SB1	74.7	91.9%	7.9%	0.48%	0.5	0.6	2.5	PAS	100.0%	0.0%
BCAL1039	SB2	74.7	N/A	N/A	0.29%	N/A	N/A	0.7	PAS	100.0%	0.0%
BCAL1037	Sludge	74.7	79.9%	19.7%	0.46%	1.6	3.3	1.0	PAS	100.0%	0.0%
Tag Isotopics			93.7%	6.1%	0.36%						
BCAL1019	M2	157.1	93.8%	6.0%	0.38%	0.3	0.3	1.2	PAS	99.2%	1.8%
BCAL1020	M10	157.1	93.5%	6.3%	0.41%	0.2	0.2	0.5	PAS	100.5%	1.2%
BCAL1021	M15	157.1	93.4%	6.5%	0.41%	0.6	0.6	0.7	PAS	95.6%	5.0%
BCAL1027	EM	157.1	93.1%	6.7%	0.42%	0.8	1.0	0.3	PAS	99.2%	2.8%
BCAL1022	DC	157.1	94.1%	5.7%	0.36%	0.6	0.5	1.7	PAS	102.4%	5.8%
BCAL1023	LM	157.1	93.4%	6.4%	0.43%	0.2	0.3	0.1	PAS	100.1%	0.1%
BCAL1017	SB1	157.1	94.0%	5.9%	0.33%	0.6	0.5	2.4	PAS	100.0%	0.0%
BCAL1018	SB2	157.1	89.4%	10.4%	0.36%	0.9	1.0	1.1	PAS	100.0%	0.0%
BCAL1024	SL	157.1	94.4%	5.4%	0.27%	0.9	0.8	3.5	PAS	111.8%	13.0%
Tag Isotopics			93.7%	6.2%	0.44%						

Analysis of the FRAM results for the 8.9g, 74.7g and 157.1g Pu loadings was performed and compared to the known average isotopics of each respective loading. A summary of the FRAM analysis study is given in Table VII. The average % mass fraction for the key nuclides Pu-239, Pu-240 and Am-241 is given.

For each replicate, the rules used by RWARS-EA were applied to select use of the FRAM mass fraction or AK mass fraction for Pu isotopes and Am-241. Thus the FRAM results with poor statistics have been treated in the same manner as would be applied by the RWARS-EA software.

The final two columns in Table VIII, give the %R and %RSD for the “key” isotopic ratios which are used by RWARS-EA to combine neutron results with FRAM to determine total TRU alpha activity, total FGE and other WIPP reported parameters.

TOTAL MEASUREMENT UNCERTAINTY

The system TMU was been characterized previously during the original calibration. Based upon analysis of the calibration confirmation results, the following adjustments were made to the TMU parameters (summarized in Table VIII) in accordance with WIPP TMU guidance methods [5]:

- The ABSMOD index range has been extended from 11.91 to a new upper limit of 19.06. It has been demonstrated that there is linear relationship between the active calibration matrix correction factor and the ABSMOD index over the higher range. The active matrix fractional uncertainty has been changed from 18.8% to 37.6% and the active source distribution fractional uncertainty has been changed from 23.0% to 46.0%.
- A new TMU constant (known as “lambda”) is the one sigma relative uncertainty in the MOD index used in the Background Adjusted Coincidence Rate Error. Based on analysis of the calibration confirmation results, the appropriate value for lambda is 1% over the qualified range.
- The uncertainty term for the large box sizes (applicable for boxes that are more than 90 inches in length) has been set to 60% for both active and passive mode. Analysis of the calibration confirmation runs with the shredder boxes has indicated that the previous uncertainty terms (207.4% for active and 184.7% for passive) are overly conservative. The largest observed “number of sigmas” residual for the shredder boxes is 1.65 sigma where the new 60% term is used for large box uncertainty. This provides confirmation that the revised term provides an adequate bound of the large box uncertainty term within a 95% confidence interval (1.96 sigma).

In order to validate the new TMU parameters, the absolute difference between the Imaged Active Mass (IAM) (measured Pu-239 effective) and the total tag Pu-239 effective mass has been divided by the reported IAM TMU in each replicate to determine the “number of sigmas” residuals for each replicate for all the calibration confirmation runs where active mode was selected. The same process was used for the Passive Coincidence mass where passive mode was selected.

The statistical expectation is that the number of residuals in each case should be less than 1.96 for 95% of test cases. Since there are 9 surrogate box tests at 0.9 - 2.9 g, 9 tests at 8.9g, 3 tests at 74.7g and 9 tests at 157.1g, the total number of cases is 30. Therefore the expectation is that no more than 1 case shall exceed 1.96 sigma residual. From the final column of Table VII, it can be seen that 0 cases out of 30 exceed 1.96 sigma residual. Therefore, this test is considered to have passed and the TMU has been demonstrated to be validated.

TABLE VIII. RBAS TMU parameters

Uncertainty Component	RBAS TMU
Passive Matrix Uncertainty	20.3%
Passive Source Distribution Uncertainty	24.5%
Passive Calibration Uncertainty	8.3%
Active Matrix Uncertainty	37.6%
Active Source Distribution Uncertainty	46.0%
Active Calibration Uncertainty	4.1%
Large Box Active Uncertainty	60.0%
Large Box Passive Uncertainty	60.0%
Small Box Active Uncertainty	853.5%
Small Box Passive Uncertainty	87.3%
Lambda (One sigma relative uncertainty in the MOD index)	1.0%

CONCLUSIONS

The RBAS has been upgraded for WIPP certification over an extended range of matrix contents, isotopics and box sizes. Calibration Confirmation was successfully performed on site using a representative range of container sizes and waste matrices. The WIPP WAC performance criteria for accuracy and precision have been successfully demonstrated over a Pu mass range from the MDA up to 157.1g Pu.

The system's original calibration range has been extended to accommodate a wider range of matrix correction index. Additional AMX file matrix correction library entries have been generated to extend the upper limit of ABSMOD allowing analysis of heavy waste matrices including shredder boxes with large metal items and debris waste (metal and combustible). The system can also analyze sludge waste in 210-liter (55-gallon) drums inside SWBs.

The new software suite provided by Pajarito Scientific Corporation combines the neutron assay results with FRAM isotopic analysis using AK ratios and scaling factors where appropriate. The software deploys AK mass fractions where the FRAM counting precision is below a predefined threshold. Above this level, it has been demonstrated that the measured Pu isotopics and Am-241 mass fractions are statistically consistent with the known isotopics of the standards.

MDA values have been determined for the active and passive neutron modes as a function of measured matrix correction indices using the Currie method. The MDC for all surrogate matrices has been demonstrated to be less than 100 nCi/g (3700 Bq/g). The system TMU parameters have been updated for the new range of input waste streams.

The system passed its first Performance Demonstration Program (PDP) [6] cycle in the Spring of 2015.

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