Radiological Performance of an Automated HPGe Assay System for Bulk Containers of Decommissioning Waste Intended for Free Release

Timothy R. Twomey, Ronald M. Keyser, and Davide Sacchi
ORTEC
801 South Illinois Avenue
Oak Ridge, TN, 37831 USA
Email: ron.keyser@ametek.com, tim.twomey@ametek.com, davide.sacchi@ametek.com

Giuseppe Merlino and Paolo Grignani
EL-SE S.r.l.
Via Pier della Francesca 26,
20090 Trezzano sul Naviglio (MI)
Italy
Email: giuseppe.merlino@el-se.com, paolo.grignani@el-se.com

Gianluigi Migliore, Nunzia Radatti and Sabrina Romani
Sogin S.p.A.
Via Torino, 6
00184 Roma
Italy
Email: migliore@sogin.it, radatti@sogin.it, romani@sogin.it

ABSTRACT

The decommissioning of a nuclear power plant is an immense engineering effort requiring an array of specialist tools and techniques. The decommissioning activities generate large quantities of low-activity waste. For economic disposal, it is desirable to certify the waste as suitable for free release. Every container must be assayed to a sufficient degree of accuracy and sensitivity so that it may be certified as "free release". The more reliable the analysis, the lower the total cost of decommissioning because of the high cost of radioactive waste disposal. Since the waste quantities are large, a suitable measurement system must be highly automated, reliable, and sensitive enough to reliably demonstrate that the free release criteria have been met. The automated system is required to measure a variety of sample sizes and forms: bags, boxes, and B25 containers, with densities approximately in the range 100 kg/m^3 to 2000 kg/m^3. This paper gives the radiological performance (detection limits) of a commercial system designed for this application, installed at the SOGIN decommissioning sites at Caorso, Trino and Latina, Italy. The assay systems were developed by El.Se. Srl (ITALY) in collaboration with ORTEC. Each system uses four ORTEC Interchangeable Detector Module (IDM) mechanically cooled HPGe spectrometers. The IDMs simplify the mechanical design and improve the serviceability. Analysis of spectra is performed using the ORTEC ISOPlus waste assay software under control of a user interface developed using National Instruments LabView. A new "average MDA" algorithm has been developed and implemented. The system will be fully described and performance data will be presented.
Keywords: Waste assay, box counters, HPGe, Germanium detectors, MDA, Free release

INTRODUCTION

Free release of Nuclear Waste, such as is produced in large quantities during dismantling and decommissioning activities in redundant nuclear facilities, is controlled by regulatory bodies. For free release the contents of a waste container must be certifiably below the specific activity limits in Bq/g or equivalent prescribed in the regulations. There is a severe cost penalty in disposing of waste which cannot be certified as “below clearance limit” (CL) or “free release”. This paper describes the joint development of a container assay system, capable of handling large waste containers and determining their suitability for free release.

The system was developed by El-SE s.r.l. in conjunction with ORTEC, who provided spectroscopic components, for the Italian company Sogin S.p.A. which manages the decommissioning of Italy’s nuclear power plants. Sogin has deployed three examples of this system at the decommissioning sites in Caorso, Trino, and Latina.

OVERVIEW

The system is highly automated for measurement of a variety of samples sizes and forms: bags, boxes, and B25 containers, with densities approximately in the range 100 kg/m^3 to 2000 kg/m^3, generally loaded by the use of a fork lift or overhead crane.

The system hardware comprises the following major sub-systems:

- Mechanical Hardware: Container conveyor and Detector Support and positioning mechanism.
- System control: Operator Console, personal computer, and PLC
- Germanium Detectors: 4 ORTEC IDMs (Interchangeable Detector Modules)

A computer-controlled automatic Cart-On-Track (Rail) conveyor capable of handling weights of up to 6000 kg moves the container past the four HPGe detector systems in two “tower” structures positioned on either side of the container (Fig 1). An automatic weigh scale with a resolution of 1 kg is integrated within the conveyor.

The vertical positioning of the detectors is also carried out under computer control with a resolution of +/- 1 mm to handle different container sizes, while detector-to-container distance can be adjusted manually. All machinery movements are implemented and controlled locally by a PLC and are managed remotely by a System Control Computer which is a PC providing the system operator interface.

Electrical hardware control, with the exception of the spectroscopy system electronics, is provided by means of a PLC from the operator console. The PLC firmware supports a local MMI (Man Machine Interface) and an ethernet interface allowing remote control of the system from the system control computer. A touch-screen LCD, mounted on the operator console allows system set-up and calibration (for example, test of the scale accuracy), plus manual positioning of the container platform and pre-calibration of detector positions. For calibration/setup purposes, each detector may be moved to the desired position by the operator console and then the system software can read the position information and save it for future use as part of a “learning” process. As part of this process the software warns the user if the computed detector coordinates are out of range or would lead to a detector collision when in operation.

The local interface is locked when the PLC is executing remote procedures, in order to avoid conflicts between automatic and manual operations. The PLC firmware also manages all the system safety features (light barriers, anti-collision sensors, etc), immediately stopping any running motor if a security input is triggered. Diagnostic messages are issued and archived by the PLC whenever anomaly conditions occur.

HPGe Detectors

The spectroscopy system hardware is implemented using a fundamental gamma-ray detection “building block,” the ORTEC IDM. The IDM consists of an 85 mm x 30 mm HPGe Detector, Stirling cooler, DSP MCA, high voltage supply, and high speed USB communication. It uses standard, low-current mains power.

Figure 2 Interchangeable Detector Module (IDM)

The large diameter detector gives excellent efficiency in the range ~40 to ~3000 keV, contributing to low MDAs and short count times. Standardized detector crystal dimensions mean that all IDMs will perform similarly. Relative efficiency is approximately 55%. A complete description is given in [1]. Digital filtering techniques reduce the effect of low frequency noise from mechanical vibration [2].

Each IDM is provided with a 10 cm deep lead rectangular shield which provides cylindrical collimation. The minimum lateral wall thickness is 10 cm. Each collimator is provided with a 1mm thick copper liner along the internal curved surfaces. The collimator depth is variable between 0.5 cm and 3 cm to vary the field of view for different containers.

Software description

In routine operation, the system is controlled by the operator through the system control PC. The underlying activity calculations are performed by ORTEC Isotopic-32 version 4.1 [3, 4] operating in "container mode" under a user interface program, written be EL-SE in National Instruments LabVIEW which provides hardware control, analysis set-up, and measurement process management. Operator and password protected setup modes are provided.

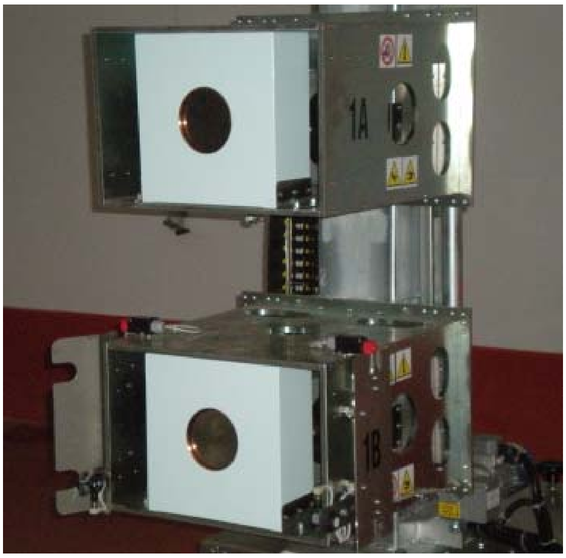


Figure 3 Collimator Detail

Calibration

Each detector (IDM) is first characterized by a single point source measurement and knowledge of detector crystal dimensions and dead-layer, and the end cap thickness.

This primary calibration, which can be traceable if a traceable standard is used, is then extrapolated to match the physical situation of the sample: container geometry, material, and matrix composition. The entire measurement problem is broken down into multiple source/matrix voxels and their contribution to the composite spectrum are calculated and summed.

No special separate measurements are needed to characterize the detector other than the above point-source calibration. The container or item is modeled, based on its physical dimensions, material, and the average density of the waste matrix. The method amounts to an "efficiency transfer" method in which an efficiency measured with a standard in one (calibration) geometry is transformed by calculation to the efficiency which would be measured in a second (sample) configuration.

Under control of the automatic process, the item is moved to the first pre-programmed counting position. Each selected detector (usually all four) counts to the chosen preset time and then the item is moved to the second position and counted. This process repeats until all measurements in all counting positions have been made. For a 3 m^3 container, typically 3 sets of measurements are made each of 4 spectra, one from each detector. Twelve results are obtained for the total activity which can be examined individually or as the average. When all spectra have been counted, analysis takes place and final reports are generated.

Averaged MDAs are also available according to the NUREG 4.16 which can be extended, in the case of four similar detectors to:

$$MDA_{SUM} = \frac{2.71 + 4.66 \cdot \sqrt{\sigma_{B1}^2 + \sigma_{B2}^2 + \sigma_{B3}^2 + \sigma_{B4}^2}}{\gamma \cdot (LT_1 + LT_2 + LT_3 + LT_4) \cdot \bar{\epsilon}_c}$$

Where: σ_{Bi} is the uncertainty in the background in peak area *i*
γ is the branching ratio or gamma-ray yield
LT_i is the live time of the spectrum from detector *i*
$\bar{\epsilon}_c$ is the corrected average efficiency (absorption and geometry)

If the background term $4.66 \cdot \sqrt{\sigma_{B1}^2 + \sigma_{B2}^2 + \sigma_{B3}^2 + \sigma_{B4}^2}$ is much larger than 2.71, then for identical detectors and backgrounds this reduces to:

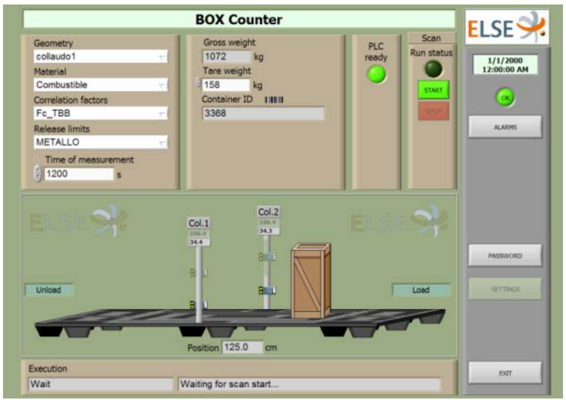
$$MDA_{SUM} = \frac{MDA_1}{\sqrt{d}} = \frac{MDA_1}{2}$$

Where MDA_1 is the MDA for a single detector.

Tabulated scaling factors are used to calculate the activities of non gamma-emitters or very weak emitters, including correction for the different half-lives of the vector and correlated nuclides.

Tables of release limits are used to compute percentage of limit for individual nuclides.

Operator process



BOX Counter

Geometry: collaudo1
Material: Combustible
Correlation factors: Fc_TBB
Release limits: METALLO
Time of measurement: 1200 s
Gross weight: 1072 kg
Tare weight: 158 kg
Container ID: 3368
Position: 125.0 cm
Execution: Wait — Waiting for scan start...

Figure 4 Main Operator Screen

The main operator screen is show in Figure 3. Extensive use is made of LabVIEW Graphics in order to make the system user friendly. The setup process is similarly graphical and is used to pre-define container type measurement parameters, such as horizontal and vertical measurement positions, container data (materials, thicknesses, and dimensions), and to build data tables such as release limits and scaling factor tables. Any subset of the available four detectors can be programmed to be used for a measurement.

After Setup, only five choices are required for an operator to start a routine scan:

- The measurement geometry (defines the container type and the measurement positions)
- The material in the container (chosen from a dropdown list of database materials)
- The correlation factor table (which may vary depending on the waste material type and origin)
- The concentration limit table (which may vary depending on the material type (e.g., metal, concrete)
- The preset time for the spectrometric measurement in each position

After these data are entered, the system proceeds to automatically take data at the pre-programmed positions and preset times, and then performs an activity analysis of each spectrum. After the initial analysis by ISOTOPIC, the operator program generates reports, including activities, MDAs and “release index” reports showing the percentage of maximum allowed release activities for specific nuclides.

Testing and Performance Results

On site testing was carried out at Latina, Trino and Caorso Nuclear Power Plants by Sogin personnel to demonstrate compliance with EU directive 96/29 EURATOM and EC Recommendation: Radiation Protection RP89, RP113, RP122.

MDA Testing

In order to determine the MDA of the system for the nuclides specified, a long background run was made (typically 58000 seconds over night), then a representative “blank” container and matrix was counted. The MDAs were then calculated from the spectrum after correction for background peaks. The measured MDAs were compared with the Sogin performance specification requirements and the with the clearance limits in references [5-7]. These are presented in Tables I and II.

Table I MDA on single spectrum

	MDA low density Bq/g		MDA high density materials Bq/g			Clearance Limit Bq/g		
Radionuclide	Required 0.3 g/cc 40 min	Measured[a] 0.4 g/cc 40 min	Required 2 g/cc 4hr	Measured[b] 1.5 g/cc 4hr	Measured[c] 1.8 g/cc 4hr	RP 89 [5]	RP 113 [6]	RP 122 [7]
Mn-54	0.05	0.0030	0.005	0.0008	0.0004	1.0	0.1	0.1
Co-60	0.05	0.0019	0.005	0.0006	0.0003	1.0	0.1	0.1
Sb-125	0.05	0.0102	0.010	0.0038	0.0013	10.0	1.0	1.0
Cs-134	0.05	0.0032	0.005	0.0009	0.0005	1.0	0.1	0.1
Cs-137	0.05	0.0037	0.005	0.0011	0.0005	1.0	1.0	1.0
Eu-152	0.05	0.0131	0.010	0.0040	0.0019	1.0	0.1	0.1
Eu-154	0.05	0.0080	0.010	0.0021	0.0013	1.0	0.1	0.1
Am-241	1.00	0.0655	0.500	0.0203	0.0066	1.0	0.1	0.1

[a] Trino NPP $1m^3$ container, 1mm wall. 4 detectors fixed position Matrix: LECA

[b] Trino NPP $1m^3$ container, 1mm wall. 4 detectors fixed position. Matrix: gravel

[c] Caorso NPP $1m^{3,}$ NO container. 2 detectors fixed position Matrix: concrete block

Table II MDA averaged on multiple spectra

Radionuclide	MDA low density Bq/g		MDA high density materials Bq/g			Clearance Limit Bq/g		
	Required 0.3 g/cc 40 min	Measured[a] 0.4 g/cc 40 min	Required 2 g/cc 4hr	Measured[b] 1.5 g/cc 4hr	Measured[c] 1.8 g/cc 4hr	RP 89 [5]	RP 113 [6]	RP 122 [7]
Mn-54	0.01	0.0011	0.001	0.0003	0.0003	1.0	0.1	0.1
Co-60	0.01	0.0007	0.001	0.0002	0.0002	1.0	0.1	0.1
Sb-125	0.01	0.0039	0.002	0.0012	0.0009	10.0	1.0	1.0
Cs-134	0.01	0.0013	0.001	0.0004	0.0003	1.0	0.1	0.1
Cs-137	0.01	0.0014	0.001	0.0004	0.0004	1.0	1.0	1.0
Eu-152	0.01	0.0049	0.002	0.0015	0.0013	1.0	0.1	0.1
Eu-154	0.01	0.0028	0.002	0.0008	0.0007	1.0	0.1	0.1
Am-241	0.50	0.0270	0.100	0.0097	0.0037	1.0	0.1	0.1

[a] Trino NPP 1m^3 container, 1mm wall. 4 detectors fixed position Matrix: LECA

[b] Trino NPP 1m^3 container, 1mm wall. 4 detectors fixed position. Matrix: gravel

[c] Caorso NPP 1m^{3,} NO container. 2 detectors fixed position Matrix: concrete block

Accuracy Testing

Accuracy tests were carried out using 1 m x 1 m x 1 m steel containers filled with matrix and with plastic source tubes aligned along the container diagonals; uniform source distributions were simulated by regularly spaced point sources along the diagonal sample tubes. The hot spot was simulated by placing all sources at the extreme end on one diagonal.

Fig 5 Accuracy test containers

Tables III and IV provide the results of the tests of uniform source distributions and Table V provides the results of non-uniform ("hot spot") testing.

UNIFORM SOURCE DISTRIBUTIONS:

Table III Accuracy test 1: Measured at Caorso NPP - volume = 1 m^3. 2 detectors.
Matrix: paper, plastic 0.3 g/cc, 2400 sec live time (2-sigma uncertainty)

Nuclide (number of sources)	**Reference Source Activity (kBq)**	**Averaged Measured Activity Values (kBq)**	**Δ %**
.			
Co-60 (4)	720.2	689,5±19,6%	-4,2
Eu-152 (4)	1102.7	1185,0±19,6%	-7,5
Cs-137 (4)	1351.2	1354,0±20,0%	-0,2

Table IV Accuracy test 2: Measured at Trino. NPP volume = 1 m^3. 4 detectors. Matrices: LECA Lightweight aggregate 0.4 g/cc and gravel 1.5 g/cc, 1200 sec live time (1-sigma uncertainty)

Nuclide (number of sources)	**Reference Source Activity (kBq)**	**0.4 g/cc Averaged Measured Activity (kBq)**	**Δ %**	**1.5 g/cc Averaged Measured Activity (kBq)**	**Δ %**
Eu-152 (5)	1022.8	1178,0±7,3%	+13,2	991,3±7,3%	-3

Non-UNIFORM SOURCE (Hot spot) DISTRIBUTIONS:

Table V Accuracy Test 3: Measured at Latina NPP volume = 0.5 m^3. 4 detectors.
Matrices: paper 0.5 g/cc 4500 sec live time and gravel 1.5 g/cc 2000 sec live time (1-sigma uncertainty)

Nuclide (number of sources)	**Total Reference Source Activity (kBq)**	**0.5 g/cc Measured Activity Values (kBq)**	**Δ %**	**1.5 g/cc Measured Activity Values (kBq)**	**Δ %**
Eu-152 (6)	1224 kBq	959±7.8%	-21.8	1390±11.8%	+13.5

Susceptibility to vibration and electrical noise:

The ORTEC IDM incorporates digital filtering to minimize resolution degradation due to low frequency noise. In addition, the system was designed to minimize the electrical noise generated by the motors and the associated drivers through the study of the layout, the use of shielded cables and ferrite and EMC filters. Tests were performed to assess the level of immunity of the spectroscopy acquisition system. The measured results of the FWHM and background measurements, carried out in different operating conditions of the machine (Static mode, Conveyor in operation, Detector moving), show the high level of electrical noise immunity reached.

Table VI FWHM (keV) Measurements using Eu-152 reference source

Reference Conditions	Real Time (s)	Live Time (s)	Dead Time %	FWHM @ 121.78 keV	FWHM @ 344.28 keV	FWHM @ 778.9 keV	FWHM @ 1112.11 keV	FWHM @ 1408 keV	Integral Total Counts
Static	300	206.1	31.27	1.12	1.28	1.58	1.79	1.95	2.18E+06
Conveyor in motion	300	205.6	31.45	1.12	1.28	1.59	1.78	1.97	2.17E+06
Detector Housing in motion	300	208.8	31.71	1.11	1.27	1.56	1.73	2.04	2.13E+06

Discussion and Conclusions

The test data show that the automated measurement system is capable of meeting below clearance limit or “free release” requirements for the nuclides under consideration as required by the system specification. It also demonstrates compliance with the cited EU recommendations.

The average MDA calculation reduces the container MDA by approximately a factor of two when all four detectors are used instead of a single detector. Testing has shown reasonable accuracy for uniform and non-uniform source distributions. The spectroscopic performance has been shown to be unaffected by operation of the heavy electromechanical systems associated with movement of the items to be measured.

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