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Design of Checking Phantom for Metrological Certification Tests of 600 L Rectangular Container Monitoring System

Alojz Slaninka[1,2*], Ondrej Slávik[1] and Vladimír Nečas[2]

[1]*VUJE, Inc., Okružná 5, SK-91864 Trnava, Slovak Republic*
[2]*Slovak University of Technology, Institute of Nuclear and Physical Engineering, Ilkovičova 3, SK-81219 Bratislava, Slovak Republic*

Abstract

New monitoring system for purpose free release of materials into the living environment with a 600 L container counting geometry was designed and developed. Considering that monitoring system is classified as a dedicated measuring instrument the metrological certification is necessary. For purpose of metrological qualification tests the checking verification container (phantom) was proposed and manufactured. The arrangement of the reference sources in the volume of checking container was designed so that it approximates evenly activity distribution considered at efficiency calibration. Description of monitoring system, measurement uncertainty assessment, design of checking container and results of metrological qualification tests are in more detail discussed.

Highlights

- The procedure for metrological certification of the gamma spectrometry monitoring system based on the twin HPGe detectors with 600 L rectangular container counting geometry was proposed.
- The checking container (phantom) containing 24 holes for rod calibration sources evenly mounted through the container in direction of detectors axes was designed and manufactured.
- Proposed arranged of holes for rod sources approximate the homogenous distribution of the activity in container volume that is expected during usual measurement.

Keywords: Container monitoring system; Gamma spectrometry; HPGe full-energy peak efficiency; Metrological certification; Massic activity; Measurement uncertainty

Introduction

Important part of decommissioning project of nuclear power plant A1 in Slovakia is free release of materials into the environment. For purpose of the monitoring capacity increasing during free release of materials, mainly soil and concrete rubble, the monitoring system of 600 L containers was recently developed and delivered. Using counting geometry of 600 L rectangular container that is equipped with self-discharger is able to increase the total monitoring capacity. The monitoring system is able to monitor a material also in standard counting geometry of 200 L drum.

According to the Slovak legislation (Metrological Act Nr. 142/200 Coll.) a metrological certification is required because the monitoring system is considered as dedicated measuring instrument.

Description of the Container Monitoring System

Monitoring system is designed to activity monitoring of radionuclides emitting gamma radiation contained in loose materials for purpose of free release. The two gamma spectrometry chains with electrically cooled HPGe detectors of type GC 3020 are the cores of the monitoring system. Detectors are posited in the reconfigurable rectangular shielding. Horizontally or vertically arrangements of the detectors is used for container or drum monitoring, respectively (Figure 1). The lead shielding of 50 mm thickness and the aperture of shielding collimator ensure that the volume of container or drum only is in view angle of detector during the measurement. Basic technical parameters of counting geometry are noted in the Table 1.

All components of the monitoring system are integrated into the transportable ISO container (5680 × 2330 × 2190 mm; l × w × h) that is divided to measuring and control room. Integrated air condition unit ensures constant environmental conditions. Containers or drums are during measurement placed on the integrated electronic tensometry scale for material weight and density determination (Figure 2). Monitoring of a 600 L container is performed in two steps; firstly one side is monitored and after turning round of container the second side is monitored. Bottom discharger of the container decrease a manipulation time and increase the monitoring productivity. In case of drum monitoring the measurement post is equipped with rotating table ensuring drum rotation during the measurement.

Control PC unit includes spectrometry, evaluation and control SW for acquired spectra evaluation, controlling particular integrated devices and protocol results report. During spectra evaluation the homogenous activity distribution is checked on the basis comparison of the responses form particular detectors.

Full-energy peak (FEP) efficiency was determined by calculation based on detector characterization and designed counting geometry by means of ISOCS calibration software [1-3]. This one is standard calibration method based on MCNP and empirically determined point responses of spherical volume up to distance 500 m from detector. During FEP efficiency calculation the sample and shielding parameters, activity distribution, attenuation coefficients of particular materials

***Corresponding author:** Slaninka A, Slovak University of Technology, Institute of Nuclear and Physical Engineering, Ilkovičova 3, SK-81219 Bratislava, Slovak Republic, Tel: +421 33 5991462; E-mail: slaninka@vuje.sk

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Figure 1: Detectors and shielding arrangement on rack during container measurement .

Parameter	Drum	Container
Collimation angle	53°	53°
Lead shielding thickness	5 cm	5 cm
Distance between axes of detectors	50 cm	60 cm
Distance: detector – vessel envelop	25 cm	30 cm
Weight range	100 ÷ 400 kg	300 ÷ 1000 kg
Vessels dimension	Ø60 × 80 cm	113.5 × 73.5 × 71 cm (l × w × h, inside)

Table 1: Basic technical parameters of counting geometry.

Figure 2: Verification container on the measuring position.

and other relevant factors are taken into the account. Basic metrology features of monitoring system are shown in the Table 2.

Measurement Uncertainty Assessment

Measurement uncertainty of the massic activity (A_m) was assessed by determination of the uncertainties of particular input quantities entering into the A_m calculation according to equation (1).

$$A_m = A/m = N/(m*y*\varepsilon*t) \quad (1)$$

In compliance with standard law of uncertainty propagation the relative standard combined uncertainty of massic activity, $u(A_m)$, can be expressed by equation (2). This approach is more detail descripted in [4]. Meaning of the members of the right side of equations (1) and (2) as components of uncertainty is explained in the Table 3.

$$u(A_m)^2 = u(N)^2+u(m)^2+u(y)^2+u(\varepsilon)^2+u(t)^2 \quad (2)$$

Uncertainty arising from the FEP efficiency determination, $u(\varepsilon)$, as most significant source of uncertainty has been assessed separately. Uncertainty of the used calibration method (ISOCS [1]) as well as the uncertainties of input parameters defining the counting geometry and entering into the FEP efficiency calculation were taken into the account. Most significant components of the FEP efficiency uncertainty are provided in the Table 4.

Curve of relative FEP efficiency in dependence on sample density is shown on the Figure 3. It can be seen that the FEP detection efficiency of low energies is significantly lower. In additionally the sensitivity of the FEP efficiency to sample density change is most significant in low range of density. Consequently the measurable gamma energy range and sample density range was declared according to the Table 2.

Homogenous activity distribution was considered at FEP detection

TaDesignation:	Measurement of massic activity [Bq/kg] of homogenously contaminated soil or concrete debris loaded in 600 L container or 200 L drum.
Declared energy range of measurement :	200 keV - 2 MeV (gamma); RNs emitting gamma ray: ^{137}Cs (dominant contaminant), ^{134}Cs, ^{60}Co, ^{110m}Ag, ^{54}Mn, etc. are being identified
Method of calibration:	Full-energy peak (FEP) detection efficiency has been calculated mathematically, by ISOCS code on the basis ISOCS/LabSOCS characterization of used detectors and parameters of counting geometry [1].
Density range of monitored material:	0.5 – 2.0 g/cm^3 Full-energy peak detection efficiency polynomial curves for various densities and both counting geometries have been determined in advance by step of 0.025 g/cm^3. Proper curve is selected automatically on the basis determined weight (density) of container or drum.
Acquisition time:	10 min (rotating drum), 2 × 10 min (both sides of container are monitored)
Minimum detectable activity:	20 Bq/kg (drum) and 10 Bq/kg (container) of ^{137}Cs at standard acquisition time and at radiation background 0.1 μSv/h background of ^{137}Cs
Expected capacity of monitoring:	10 containers / shift or 20 drums / shift (20 containers / 12 hour working shift)

Table 2: Basic features of monitoring system.

Source of uncertainty, notes	Counting geometry	
	Drum	**Container**
u(m) – uncertainty of weight determination, m; measurement error of scale is ± 0.2 kg	1.0%	1.0%
u(N) – uncertainty of net peak area estimation, N; results from acquisition time and count rate on the free release level 300 Bq/kg of ^{137}Cs	5.0%	5.0%
u(ε) – uncertainty of full-energy peak efficiency, ε; in more detail discussed in the Table 4	10.9%	13.5%
u(t) – uncertainty of the spectra acquisition time, t	neglectable	
u(y) – uncertainty of abundance, y	3.5%	3.5%
$u(A_m)$ – relative standard combined uncertainty of massic activity A_m	11.8%	14.9%

Table 3: Relative standard combined uncertainty of massic activity and its components.

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Source of uncertainty	Counting geometry	
	Drum	Container
$u_{ISOCS}(\varepsilon)$ – uncertainty of calibration method ISOCS; estimated by manufacturer during detector characterization process	6.0%	6.0%
$u_{\rho}(\varepsilon)$ – uncertainty as a consequence of the deviation between real value of density and calibration value of density, results from decelerated energy range and sample density range according to the Table 2	5.0%	5.0%
$u_{mi}(\varepsilon)$ – uncertainty as a consequence of the difference between the real material composition and calibration material composition; soil and concrete rubble is considered only	3.6%	3.5%
$u_{G}(\varepsilon)$ – geometry uncertainty as a consequence of deviation between the real measurement geometry and the calibration geometry; the change in sample position of 3 cm and 2 cm in case of the container and drum, respectively, in various directions was considered	3.5%	3.3%
$u_{Hom}(\varepsilon)$ – uncertainty as a consequence of the inhomogeneous distribution of activity within the volume of drum or container	5.6%	9.9%
$u_{S}(\varepsilon)$ – uncertainty of long-time stability of efficiency	1.0%	1.0%
u(ε) – combined standard uncertainty of full-energy peak efficiency	**10.9%**	**13.5%**

Table 4: Relative standard combined uncertainty of full-energy peak efficiency and its most significant components.

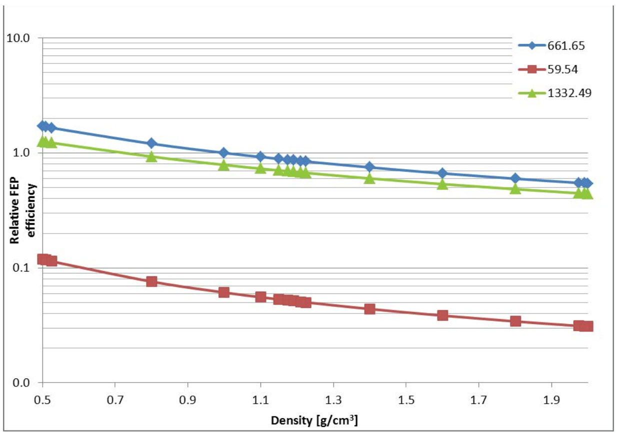

Figure 3: Curve of relative FEP efficiency in dependence on the sample density for gamma rays of various energies in [keV]. 1 on the *y*-axis corresponds to the FEP efficiency of 661.65 keV gamma rays at 1.0 g/cm^3 density of sample at drum counting geometry.

efficiency calculation. Therefore one of important but hard to quantify valuable source of uncertainty is potential inhomogeneous distribution of activity within the volume of container or drum, $u_{Hom(\varepsilon)}$. It is a consequence of uneven detector response distribution from measured volume of sample because the volume of container is too large. Half of the container width (about 35 cm) presents important absorption layer. Therefore, a low inhomogeneity in sample center or close to detectors may significantly affect the measurement results. For this reason the preliminary sorting measurement and both-sides container measurement is established to decrease the uncertainty resulting from inhomogeneous activity distribution. Also container and detectors positions arrangement was proposed so that the dependency of FEP detection efficiency along the container was as even as achievable. Dependency of the FEP detection efficiency along particular directions of the container (length, height and width) is on the Figure 4.

Proposal of Container Monitor Metrological Testing Procedure

Proposal of metrological testing procedure was based on the checking phantom of the container filled by non-active material of the same kind as to be routinely monitored and with reference sources inserted into the container volume. For determination the arrangement of reference sources in the container volume the following requirements were taken into the account:

Minimization of the number of reference sources needed with regard to their price,

Simple way of insertion and removal to/from the container,

Minimization of the deviation of FEP efficiency for phantom container from the FEP efficiency for real container with homogeneous activity distribution.

Using of reference sources of rod shape for easy inserting into the container was proposed. For determination of the direction of the rod sources inserting into the container the distribution of FEP efficiency alongside particular direction of container was taken into the account. From the Figure 4 it can be seen that the change of FEP efficiency is most sensitive in direction of container width, i.e. in the direction of detectors axes due to increasing self-absorption effect. This direction was proposed for the rod sources inserting. Arrangement of the rod sources in direction perpendicular to the detectors axes (along length or height of the container) is inappropriate because small position change of a source in the container volume in the detector vicinity means significant change of FEP efficiency (response of detector. On the contrary, the presence of source in the container middle does not affect the measurement results because the detector response from this source is negligible.

Positions of the rod sources in the container volume were determined so that the container volume was divided to regular segments of the same volume with rod source in the center of all segments. By ISOCS simulation calculation has been shown that for 24 rod sources posited in the container volume (4 columns and 6 rows) according to Figure 5 and for density of material 1.2 g/cm^3 the value of FEP efficiency of 662 keV differs from case of homogeneous distribution less than 5%. This model was selected to the manufacturing. For comparison, model with 60 rod sources (10 columns and 6 rows) means deviation of FEP efficiency from homogeneous distribution on level 1%, but the number of reference rod sources is 3 times higher.

The container phantom was manufactured by modification of the standard container. Into the rod source positions were embedded the plastic tubes (Ø22 mm) with closeable apertures for rod sources inserting. Volume of container was filled by lime stone rubble of fraction 4–8 mm. Density of this material 1.3 g/cm^3 was determined by the phantom container weight measurement.

The standard calibration drums of know density with 6 apertures for reference rod sources inserting were used for metrological certification of drum counting geometry. The distances between the openings and drum axis are designed in such a way as to represent an even activity distribution in the drum volume during its rotation.

Results of Metrological Certification Tests

Metrological certification tests were performed by Slovak Institute of Metrology by help 6 rod sources of ^{137}Cs and ^{152}Eu. During the

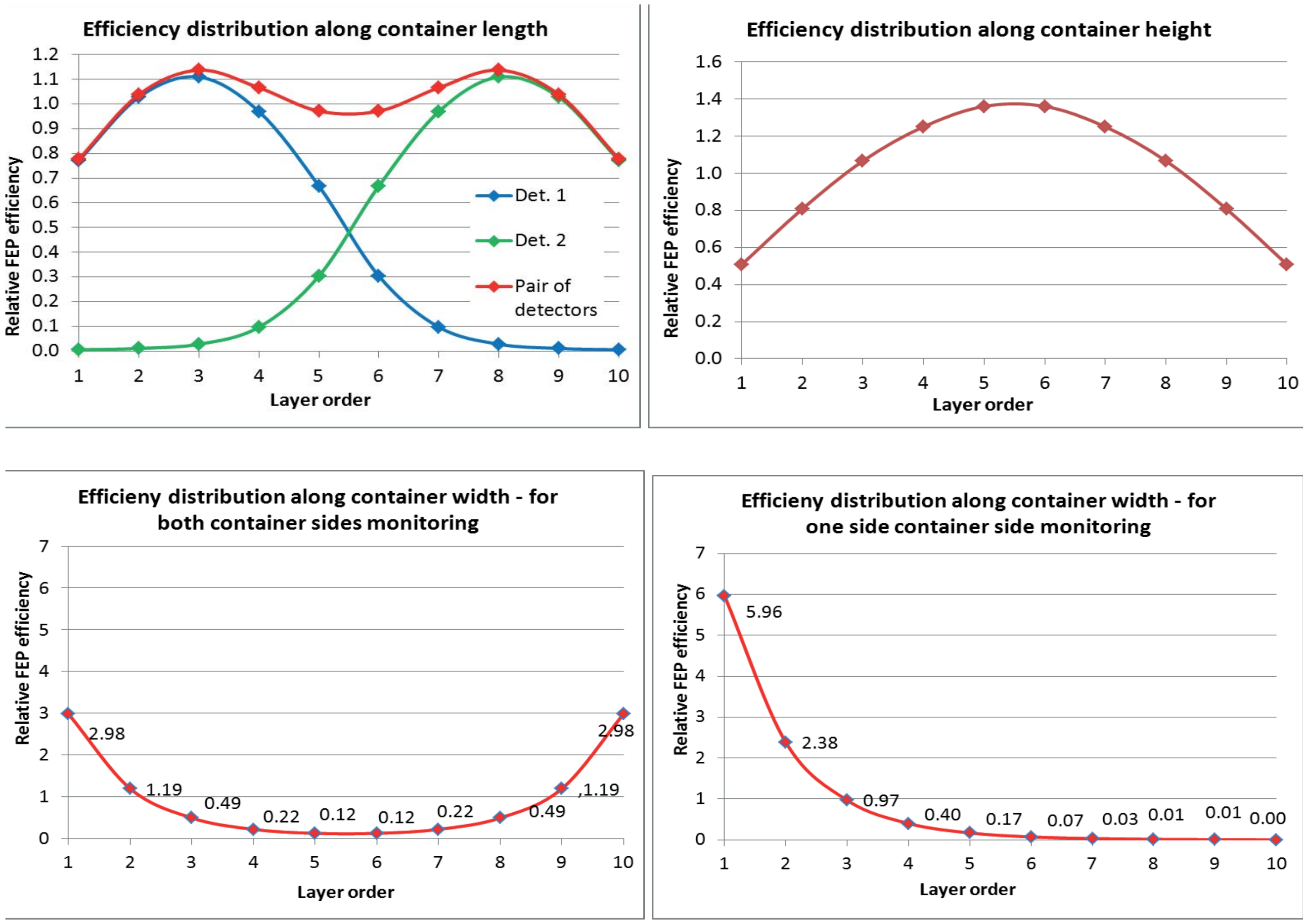

Figure 4: Distribution of the FEP efficiency (661.65 keV) along container length, height and width for one and pair of detectors and for one and both sides monitoring; simulated by dividing the container volume to 10 parallel layers. 1 on the y-axis referring to average FEP efficiency at homogenous distribution of activity in container at 1.0 g/cm^3 density of sample.

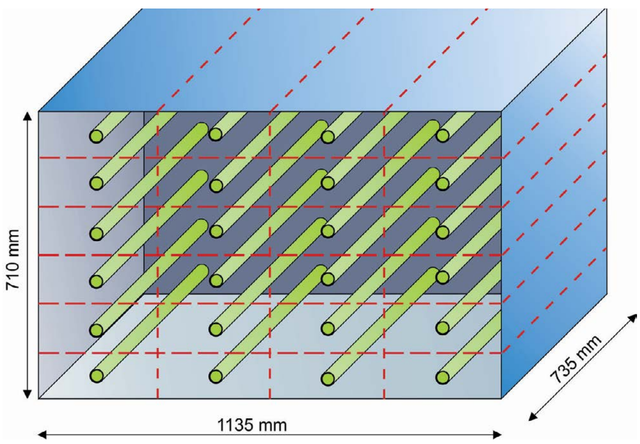

Figure 5: 3D design of the verification container phantom with 24 reference rod sources throught full width of container; container is divided to 24 regular volume segments and the rod sources are posited in the centre of each segment; dimensions of the container are in [mm].

measurement the rod sources were placed into the apertures of one column and sequentially moved into next columns. Counting time for each sources position was the same.

In addition, tests of particular detector response were performed using standard test samples to verify soundness of ISOCS calibration method. An ampoule containing mixture of radionuclides ^{241}Am, ^{85}Sr, and ^{88}Y was placed 13 cm in front of detector head in its axis. In all cases the test results were satisfactory. Results of metrological tests are provided in the Table 5.

Conclusion

For the free release monitoring capacity increasing at NPP A1 in Slovakia the monitoring system using counting geometry of 600 L rectangular container equipped with bottom discharger was developed. Considering the purpose of monitoring the metrological certification was necessary. Due to non-standard counting geometry of rectangular container the special phantom container with pipe openings for reference rod sources inserting and filled up by lime stone gravel was developed and manufactured for metrological certification purpose.

The rod reference sources are posited in direction of detectors axes (along width of container) in regular grid. It has been shown that 24 rod sources is sufficient number for even activity distribution simulation at container dimensions 1135 × 710 mm (length x height). The metrological certification was successfully carried out with the 20% class of accuracy achieved.

RN	Counting geometry	Relative deviation of measured results from the reference value
^{152}Eu	Drum (ρ = 1.5 g/cm^3), 6 rod sources in drum	3.3 %
^{152}Eu	Drum (ρ = 0.8 g/cm^3), 6 rod sources in drum	2.5 %
^{137}Cs	Drum (ρ = 1.5 g/cm^3), 48 ampules merged into 6 rod sources	11.6 %
^{137}Cs	Drum (ρ = 0.8 g/cm^3), 48 ampules merged into 6 rod sources	5.6 %
^{152}Eu	Container (ρ = 1.3 g/cm^3), 48 ampules merged into 6 rod sources	-4.5 %
^{137}Cs	Container (ρ = 1.3 g/cm^3), 48 ampules merged into 6 rod sources	8.3 %
^{85}Sr	Ampule, 1st detector	5.5 %
^{88}Y	Ampule, 1st detector	-2.9 %
^{241}Am	Ampule, 1st detector	-4.1 %
^{85}Sr	Ampule, 2nd detector	8.0 %
^{88}Y	Ampule, 2nd detector	-4.1 %
^{241}Am	Ampule, 2nd detector	-15.3 %

Table 5: Results of metrological qualification tests for particular counting geometry.

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