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Measurement campaign on the JRC Ispra decommissioning site

*JRC-Ispra contribution
to WP3 Deliverable
3.1.6 of MetroDecom
project*

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All images © European Atomic Energy Community 2017, except: [Page 5 *Figure 1(a)* Source: NUVIA Drawings H181-01-S000] 2016, [Page 12 *Figure 7*. Source: NUVIA Drawing H181-01-S000] 2016, [Page 18 *Figure 13(b,d)* Source: NUVIA Drawing H181-01-S000] 2016.

Title *Measurement campaign on the JRC Ispra decommissioning site*

Abstract

This document describes the measurement campaign with the Free Release Measurement Facility at building 41m "Interim Storage Facility" (ISF) of material clearable according to existing licenses as part of the collaborative research project MetroDecom.

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Foreword

In the framework of the European Forum for Science and Industry, the JRC organized on 11 September 2012 a roundtable discussion on "Scientific support for nuclear decommissioning". This meeting, among others events, prompted by Mr. Ristori (then Director General of JRC) to request the JRC institutes of develop research programmes in support to decommissioning.

The JRC G.III.9 and JRC G.II.7 participation to MetroDecom is expected to benefit both JRC G.III.9 and JRC G.II.7 in the sense that JRC G.II.7 would satisfy the request to engage in "support to decommissioning", and JRC G.III.9 with their extensive work programme in decommissioning, would learn about state of the art decommissioning techniques and in particular gain hands-on knowledge and experience with instrumentation for the characterization of waste from decommissioning projects.

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Acknowledgements

We would like to specifically acknowledge for the professional cooperation during the project implementation and the professionalism shown by the NUVIA team during the construction and maintenance of the Free Release Measurement Facility.

The unit G.II.7 recognizes the effort and logistics support from G.III.9 which ensured implementation of all activities, including refurbishment of key infrastructure in ISF. Special thanks to Paulo Peerani, Roberto Franzetti and Heikki Aulamo for its practical implementation in a satisfactory and timely manner.

We truly appreciate the exchange of experience and productive discussion with Vladan Stefula, Dusan Lexa, Philippe Hubert, Diederik Van-Regenmortel, Roberto Accorsi, Giovanni Macchi, Andrea Ravazzani.

Based on the achievements of the measurement campaign in ISF, the unit G.II.7, kindly requests G.III.9 to consider continuing its fruitful cooperation with a possible new project and would like to recommend the further dissemination of the project's results as a best practice and technical reports.

Authors

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Abstract

The purpose of this document is to describe the measurement campaign with the Free Release Measurement Facility (FRMF) at building 41m "Interim Storage Facility" (ISF) of material clearable according to existing licenses as part of the collaborative research project MetroDecom.

The description of the measurement campaign includes the technical requirements and safety implementations necessary for carrying out this project.

The Free Release Measurement Facility (FRMF) was designed as a state of the art facility for measurement of low gamma-ray activity waste packages. Gamma spectrometric method for free release measurement was developed ⁽¹⁾. The complemented with passive neutron counting method⁽²⁾. The both methods are used for different nuclide contents in the waste and are complementary.

For this purpose the instrument incorporates:

- Three passive neutron counters (design of JRC)
- A gamma-ray detection system HPGe Interchangeable Detector Module IDM-200-V (ORTEC)
- NuDET Plastic Scintillation Detectors (design of NUVIA)

Decommissioning unit delivered seventy containers with material clearable according to existing JRC licenses. JRC G.II.7 performed the testing of the free release measurement system. The document contains the overview of that measurement campaign. The detailed measurement protocols, spectra generated by FRMF software are shared with MetroDecom Partners.

⁽¹⁾ MetroDecom deliverable 3.1.4, CMI.

⁽²⁾ Bogucarska T, Pedersen B, Silva Pestana L, Varasano G, " Investigation of the use of neutron counting for segregation of alpha-active decommissioning waste ", Publications Office of the European Union, Luxembourg, 2017, PUBSY No. JRC107756.

1. Introduction

The purpose of the measurements with the Free Release Measurement Facility (FRMF) was to demonstrate the capability to measure radioactivity levels below the limits for free release (clearance levels) of decommissioning waste⁽³⁾.

As part of an earlier joint project (JRP ENV09) a standardized traceable method for free release measurements were developed. The work package (WP)3 of MetroDecom (JRP ENV54) entitled: The purpose of this measurement campaign is implementation of free release measurement facility on a decommissioning site. This concerns installation of an optimized version of the FRMF on the JRC Ispra site for measurements of waste streams considered as material clearable according to existing licenses.

The aim of this document is to describe the measurement campaign, including the technical requirements and safety implementations necessary for carrying out this project.

The contributions from the JRC Ispra site (units G.II.7 and G.III.9) concern the measurement campaign with the FRMF device. All measured waste has not been exposed to any irradiation for past 30 years. It was already measured and officially classified (versus the Italian Authorities). Further in the text, it is called as waste or as material clearable according to existing licenses. The JRC technical report contains the overview of that measurement campaign.

For the purpose of the project, the spectra and relevant measurement protocols are shared only within MetroDecom project consortium and cannot be published or disseminated without agreement of JRC.

The output of those measurements will be summarised in the Good Practise Guide at the end of MetroDecom Project.

⁽³⁾COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013 laying down **basic safety standards** for protection against the dangers arising from exposure.

2. Scope of FRMF measurement campaign at JRC Ispra

The contribution from JRC to MetroDecom project concerns the measurements of real and simulated waste packages with the high performing clearance facility called the Free Release Measurement Facility (FRMF).

NUVIA Czech (ex-ENVINET) and CMI have designed the version of FRMF. NUVIA Czech (ex-ENVINET) has installed it in Interim Storage Facility (ISF) at JRC Ispra. The Czech Metrology Institute (CMI) performed the calibration of gamma measurement system consisting of four high purity germanium detectors.

For the duration of the campaign, Unit G.II.7 of JRC installed three neutron counter modules within the measurement chamber of FRMF. Unit G.II.7 of JRC complemented the free release measurement procedure with passive neutron counting.

The Free Release Measurement Facility (FRMF) was installed successfully on the JRC Ispra site where significant industrial decommissioning activities are underway.

The JRC performed the testing of FRMF under industrial conditions with the waste packages. During the measurement campaign were delivered seventy containers/drums with waste materials from 62 to 627 kg. The total duration of the measurements was more than 250 hours. During all measurement campaign, waste measurements were associated with the daily quality assurance measurements. Those quality assurance measurements included the background measurements and stability checks and the measurements of simulated waste with and without reference radiation standard.

2.1. The FRMF device

Figure 1. Drawing (a) and realisation of the FRMF (b) for measurement campaign in JRC

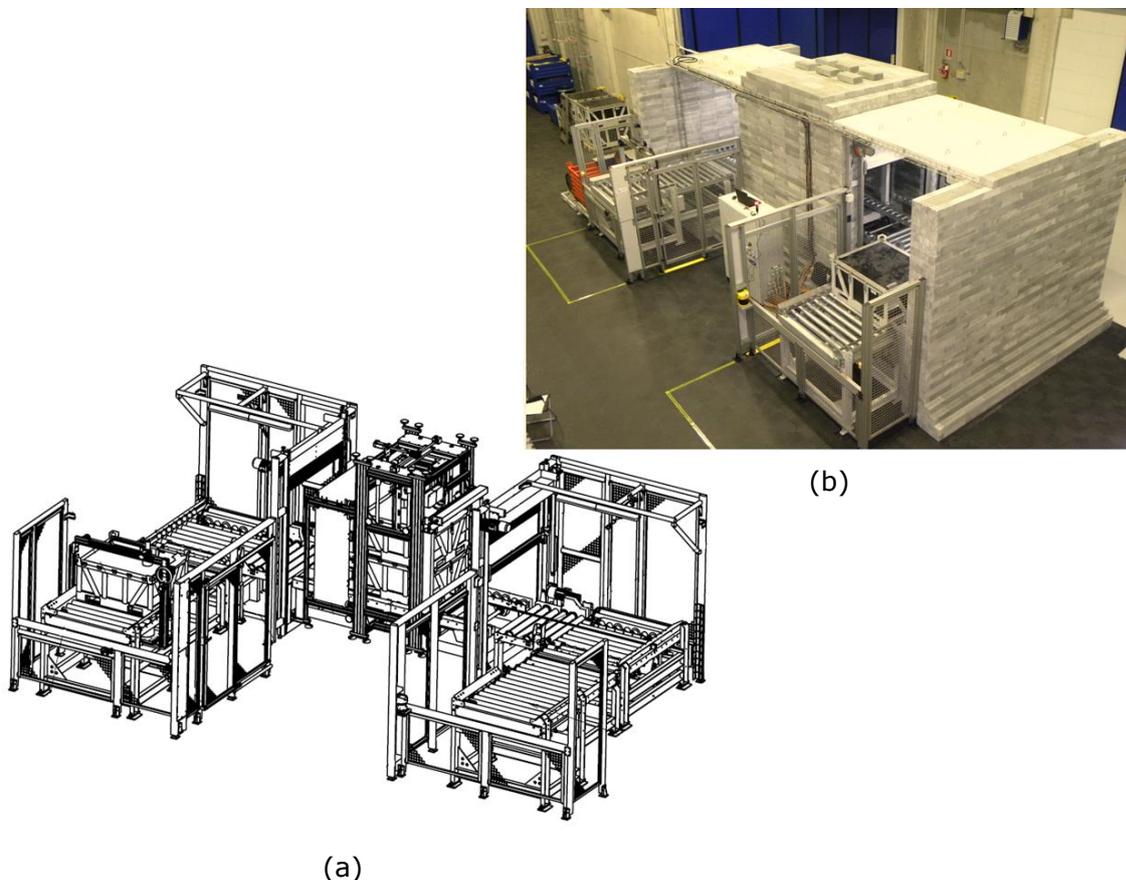


Figure 1(a) Source: NUVIA Drawing H181-01-S000, 2016

Figure 1 shows sketch of the FRMF and its realisation in the Interim Storage Facility on the decommissioning site of JRC. For the purpose of reducing the natural gamma-ray background from radium, thorium and daughter products the FRMF device is equipped with a substantial shield made of concrete bricks. The full dimensions for the FRMF installed in ISF are 9.20 m long, 5.57 m wide and 3.60 m high. The substantial shield on the FRMF makes the complete instrument heavy.

The total weight is subdivided in the following manner:

Concrete shield (total)	82750 kg
Indoor track	1500 kg
Detector frame	900 kg
Outdoor track	2000 kg
Other frame	800 kg
Total	87950 kg

This would imply an average floor load of 2255 kg/m². The floor load requirement for the FRMF was a critical parameter for allocation of the FRMF at the JRC decommissioning site.

2.2. Implementation of a waste clearance station on the JRC Ispra decommissioning site

2.2.1. Preparation of the FRMF campaign at the ISF

A number of issues were addressed before the FRMF campaign ENV54 MetroDecom took place. The JRC was required to validate the research activities to be carried out at JRC under the MetroDecom project by JRC Ispra Specialized Services.

In hindsight the efforts related to the compliance with industrial safety/security standards for work on the nuclear decommissioning site, to ensure the project implementation on the Ispra site is in agreement with existing Italian legislation in health, safety and environment, the JRC project leader must seek agreement, and comply with requirements, from the Ispra site Specialized Services in the so called "consultation procedure". Before implementing the project, all activities must be validated by JRC Ispra Specialized Services concerning aspects of

2.2.1.1. Conventional safety:

1. The installation of FRMF on the Ispra site included installing of a large articulated structure at a static level. Due to the size and complexity of FRMF, it was deemed necessary to elaborate a structural plan by qualified private entity and to appoint an inspector licensed to certify the final construction.

- (a) nomination of the inspector to provide the final verification of the FRMF's construction

2. For issues related to health and safety in the workplace, the JRC on the Ispra site applies Italian legislation. For this reason also foreign company working on the Ispra site need to fulfil the obligations as defined by the Italian legislative decree 81/08 (Consolidated Act on Safety at work), and for the preparation and management of the required safety documentation by the regulations needed at all phases of the activity (a Health & Safety Manager (Responsabile della sicurezza di Prevenzione e Protezione (RSPP), Qualified Expert, competent doctor, etc.).

- (b) Nomination of accredited (by Italian law) Safety Supervisor for the execution phase (CSE) and for the planning phase (CSP). CSE/CSP is responsible for the preparation and follow-up of "Coordination Safety Plan".
 - (c) Nomination of accredited (by Italian law) Health & Safety Manager (Responsabile della sicurezza di Prevenzione e Protezione (RSPP)) for the MetroDecom project partners NUVIA (ex-ENVINET) and CMI. The RSPP is responsible for the preparation and follow-up of "OPERATIONAL SAFETY PLAN".
3. Manipulation of waste containers and shielding bricks by fork lift.
- (d) Nomination of staff authorised by Italian law to operate a forklift, on the nuclear decommissioning site, and licensed to manipulate real and simulated radioactive waste packages (800 kg containers)
4. Preparation of the emergency plan for ISF, building 41m, for activities under the MetroDecom project.

2.2.1.2. Security:

1. Settlement of the responsibility and access control (security) at Interim Storage Facility (ISF) during the execution of MetroDecom project.
2. Coordination, assistance and supervision for access to the decommissioning Ispra site for NUVIA and CMI workers during the construction, dismantling and measurements campaign.

2.2.1.3. Radiation protection safety:

1. Assistance to CMI and NUVIA for the nomination of their qualified expert authorised under Italian law.
2. Assistance to authorisation of CMI and NUVIA to work as B-category classified workers at Ispra decommissioning site:
 - (a) Whole Body counting of the concerned CMI and NUVIA staff,
 - (b) Personal dosimetry of the staff working at Interim Storage Facility,
 - (c) Specific Ispra Site training.
3. Assistance to the JRC Qualified Expert for preparation of the specific procedure:
 - (a) Regarding the use of radioactive sources during the FRMF campaign,
 - (b) Considering aspects related to the classification of Radiation Protection areas,
 - (c) Safe storage and inventory taking of radioactive sources.
4. Communication of local authorities for the arrival and return of radioactive sources to JRC.

2.2.1.4. Licence and Building

1. As the ISF license covers only the interim storage of conditioned low activity waste, an application was issued to the relevant Italian Authorities for the authorisation to temporary store in the ISF the CMI 's sealed radioactive sources in the framework of implementation the FRMF measurement campaign. The authorisation was granted.

2. The load specification of ISF had to be verified prior to the installation of the 88 tons FRMF (Note, the installation of FRMF in the alternative location FARO, building 42, was disallowed due to the load specification of FRMF).
3. The CSP/CSE and “inspector” in charge of verification of FRMF construction, authorized the ISF building to carry the weight of FRMF.
4. Modify electrical installation in ISF to accommodate power requirements of the FRMF facility and in ISF reception hall and control room.
5. Purchase and placement of a protective PVC material on floor of ISF
6. Ensure the surveillance system to manipulate FRMF remotely from the operator room.

Figure 2. The Interim Storage Infrastructure, the picture (a) is central hall and the picture (b) is operator room



(a)



(b)

2.2.2. Installation of FRMF

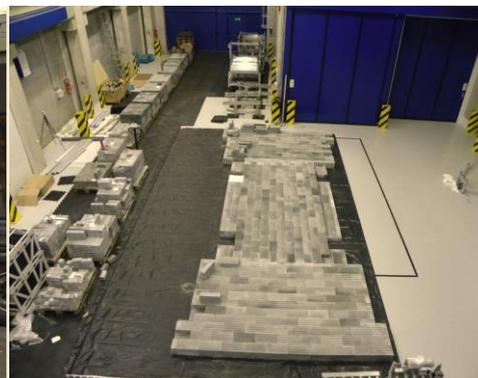
The components of FRMF from NUVIA (Trebic, Czech Republic) to JRC (Ispra, Italy) were delivered by the 4 lorries on 23rd and 24th February 2016.

The 8 workers of Nuvia Czech (ex-Envinet) performed the installation of the free release measurement facility at ISF. The construction of FRMF was completed within 6 weeks, including the mechanical and electrical works. These steps of construction are presented in Figure 3.

Figure 3. Pictures shows the different stages of the construction of the FRMF in ISF



(a)



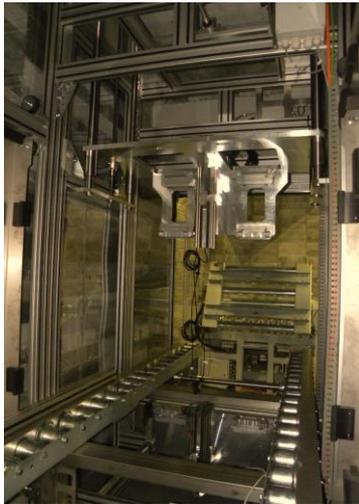
(b)



(c)



(d)



(f)



(g)



On 22nd March 2016, the FRMF construction was validated by the “inspector”.

2.2.3. Execution of measurement campaign

18th April 2016 the JRC Qualified Expert (QE) declared the area of ISF as “controlled area”.

19th April 2016, the sealed radioactive sources were delivered to JRC from CMI (Prague, Czech Republic).

On site calibration of the gamma measurement system was performed by CMI, from 18th to 29th April 2016.

One day training for JRC staff related to operation of the FRMF

On 27th June 2016, the JRC started the measurement campaign of the real waste containers after the uploaded results of the HPGe calibration to FRMF’ software.

The duration of the campaign at JRC Ispra was six months.

During the measurements, the FRMF was operated by two JRC technicians with support of the fork lift driver for loading/unloading of containers.

The procedure and schedule related to the delivery of waste containers was agreed with the Decommissioning unit (G.III.9). The real waste containers were specially prepared for the FRMF. To comply with the weight limitations the materials were weighted before the clearance measurements in ISF. The delivery of containers was scheduled to be four

containers per week. To establish the measurement procedures and to verify the measurement results the same containers were re-measured.

Figure 4. Picture of the FRMF with container loaded



9th January 2017, the return transport to CMI, Prague, of reference radioactive sources was organised.

Figure 5. Return of radioactive materials to CMI



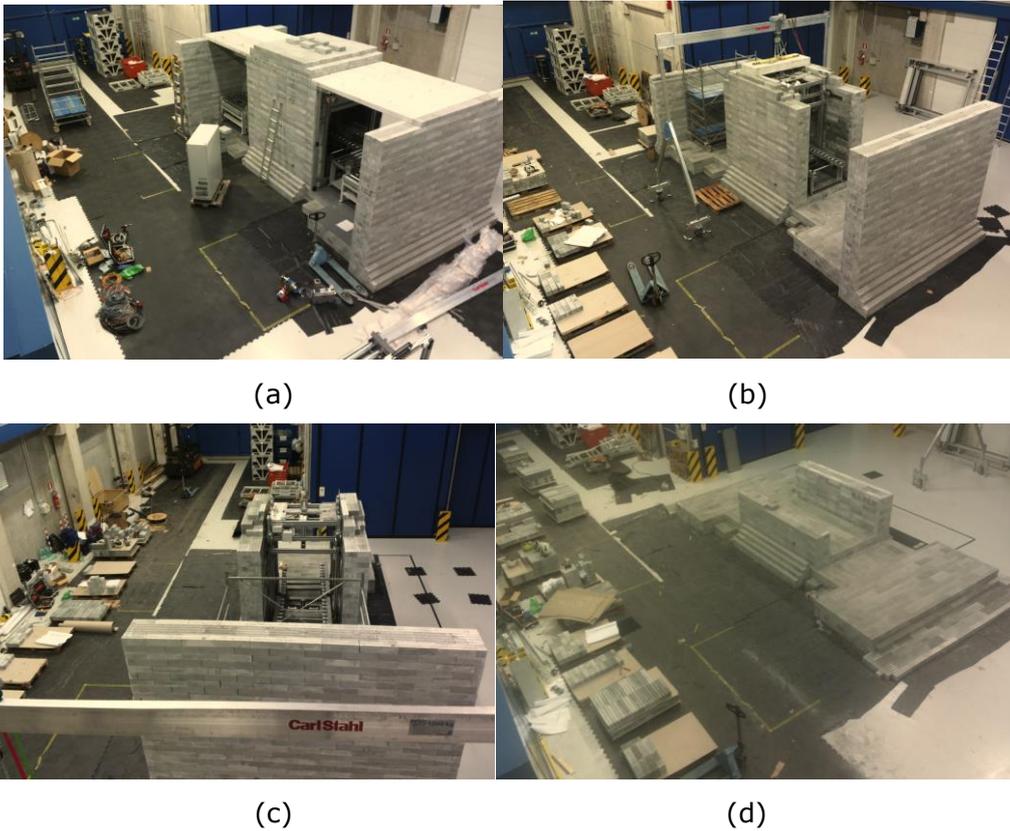
13th January 2017, the JRC QE declassified the area of ISF as “conventional area”.

2.2.4. Dismantling of FRMF

After the conclusion of the measurement campaign, the FRMF was dismantled and removed from the area under responsibility of NUVIA (ex- ENVINET).

On the 16th January 2017, the six NUVIA workers initiated dismantling, which was completed within 2 weeks. The four lorries left the Ispra site with components of FRMF on 24th, 25th and 26th January 2017.

Figure 6. The process of dismantling the FRMF at ISF: (a) 2nd day of dismantling; (b) 3rd day of dismantling; (c) 4th day of dismantling; (d) 5th day of dismantling



3. Materials and methods

The Free Release Measurement Facility (FRMF) was designed as a state of the art facility for measurement of low gamma-ray activity waste packages.

Figure 7 shows the component of the measurement system, with three types of detectors (four HPGe detectors, three neutron slab counters each consisting of five He-3 tubes and four plastic scintillation detectors), mounted around the travel route in the shielding tunnel.

Stirling-cycle cooled gamma spectrometric compact modules (Ortec IDM-200V) are used for free-release measurements. The use of gamma spectrometry for free-release measurement is essential because clearance levels are specified for each released radionuclide. Only spectrometric detectors can be used to direct activity measurement of gamma emitting radionuclides. Gamma spectrometric method for free release measurement was developed [1].

The free release measurements with HPGe detectors were complemented with passive neutron counting method ⁽⁴⁾ [2]. The both methods are used for different nuclide contents in the waste and are complementary.

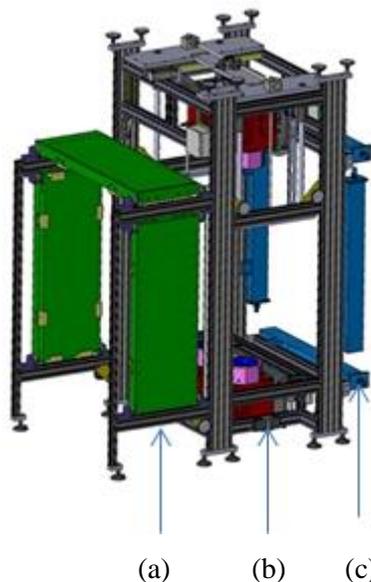
In addition, for some containers were performed the measurements with plastic scintillation detectors. For segregation purposes, four detectors of the NuDET plastic scintillation detectors are used to scan containers in order to check the homogeneity of their radionuclide content as well as to attain high measurement sensitivity.

The three neutron slab counters based on proportional counters filled with He-3 and four plastic scintillation detectors have fixed detector positions.

Threaded bars and laser sensors ensure the horizontal movement of the containers.

Figure 7. The measurement system of the FRMF consisting of

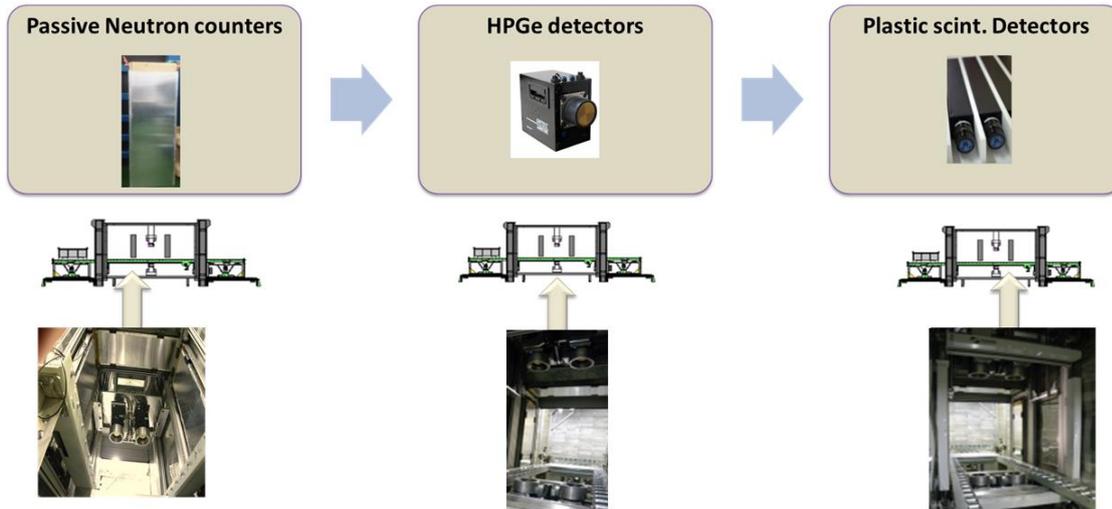
- (a) Three passive neutron counters (design of JRC)
- (b) A gamma-ray detection system HPGe Interchangeable Detector Module IDM-200-V (ORTEC)
- (c) NuDET Plastic Scintillation Detectors (design of NUVIA)



Source: NUVIA Drawing H181-01-S000, 2016

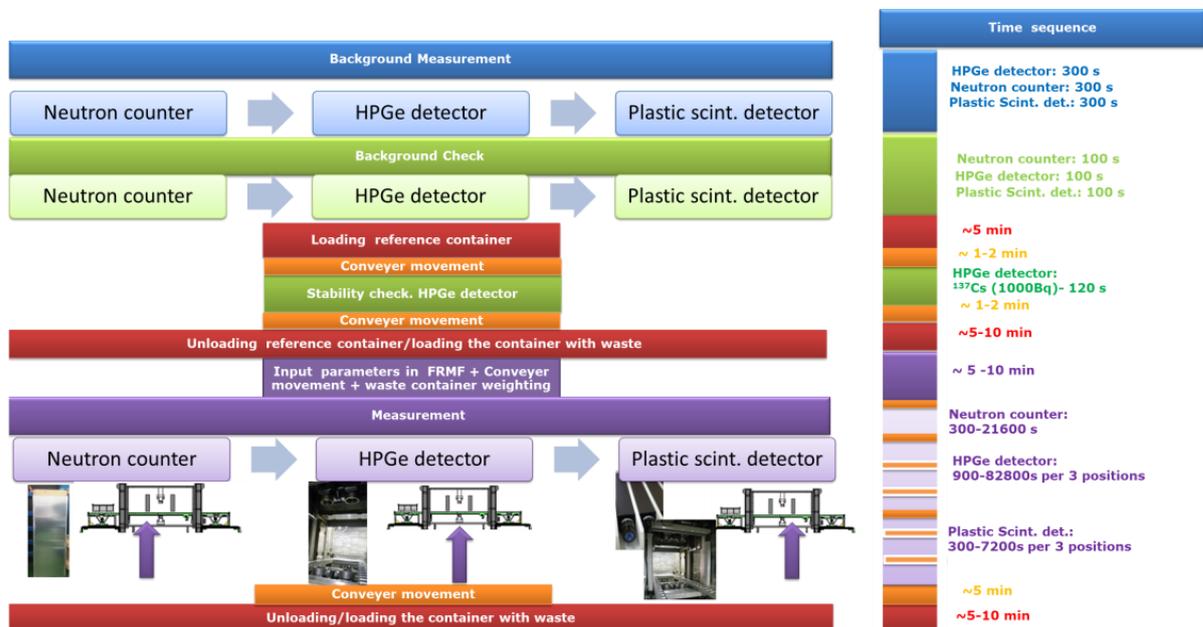
⁽⁴⁾ Bogucarska T, Pedersen B, Silva Pestana L, Varasano G, " Investigation of the use of neutron counting for segregation of alpha-active decommissioning waste ", Publications Office of the European Union, Luxembourg, 2017, PUBSY No. JRC107756.

Figure 8. Simplified diagram of the FRMF measurement system



A conveyer system brings the waste item from the loading station to the measurement chamber. After completing the measurement, the waste item is taken to the unloading station for removal by fork lift. Figure 8 is a sketch of the FRMF measurements. Figure 9 presented the time sequence and the measurement time for the reported waste containers.

Figure 9. The measurement process



3.1. JRC containers to FRMF

A variety of free release waste items which have already been measured and have been officially classified versus JRC licenses for free release are available on the JRC Ispra site.

In particular a large number of waste items in Standard Ispra site containers were delivered and measured at FRMF. Table 1 shows the technical specification of the standard containers for clearance waste used at the JRC Ispra site:

- (d) a "JRC standard orange container CPM530I"
- (e) "JRC modified container CPM530I without walls" used for measurements of cement in so-called big bags
- (f) is 220-litre cylindrical drum.

The FRMF the operators console provides the drop-down list for selection of a box type from the database.

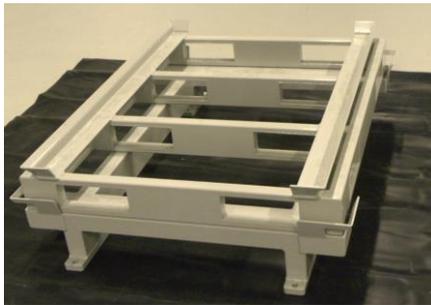
Table 1. Waste packages geometries

Container type	Image	Dimensions	Maximal weight of content [kg]	Volume [m ³]	Weight of container + support [kg]	Number of the measured containers
Orange containers CPM530I		Length: 1000 mm Wide: 800 mm Height: 900 mm	1000 kg	Volume (max.): 0,9 m ³ Volume (utile): ~ 0,6 m ³	158 kg	34 items (Metal, plastic and concrete) 
Big bag		Length: 1000 mm Wide: 800 mm Height: 900 mm	~ 370 kg	Volume (max.): 0.5 m ³ Volume (utile): ~ 0.37 m ³	163 kg	29 items (Concrete)  

Container type	Image	Dimensions	Maximal weight of content [kg]	Volume [m ³]	Weight of container + support [kg]	Number of the measured containers
Drum 220L		Diameter: 590 mm Height: 890 mm	500 kg	Volume (Max.): 243 l Volume (utile): ~ 220 l	76 kg	7 items (Soft tissue) 

To accommodate the standard JRC containers and drums in the FRMF, the special supports were used Figure 10.

Figure 10. Pictures of supports: (a) suited for JRC orange containers and (b) used for 220l drums



(a)

(b)



Figure 10 shows the specially designed supports, which were used during the measurement campaign to manipulate the waste containers on the conveyer.

The FRMF has a conveyer system and a measurement chamber adequate for handling these waste items. Nevertheless, the conveyer had limited of the maximum weight equal to 800 kg (this weight includes the weight of material, the weight of support and the weight of empty container).

3.2. Waste characterization

JRC G.III.9 prepared and organized delivering of the solid waste materials in the standard containers. For the purpose of the MetroDecom project, the FRMF operator received the waste materials have not been exposed to any irradiation for past 30 years. The received material was already measured and officially classified versus the relevant Italian Authorities. The waste or measured material is considered as material clearable according to existing licenses. Furthermore, the Decommissioning Sector of G.III.9, proposed a specific research case on measurement of extremely low levels of ^{235}U (directly) and of ^{238}U (by means of ^{234}Th and $^{234\text{m}}\text{Pa}$). For this purpose were investigated four orange containers (Decom sector) filled with metal, plastic and cement.

The properties of the waste materials are presented in the Table 2.

Table 2. Properties of the measured real waste containers

Material type	Density, [g/cm ³]	Weight, [kg]	Filling, [%]	Number of measured containers
Cement	0.6-0.97	292-463	80%-100%	28
Soft tissue (low density material)	0.06-0.1	12-15	100%	7
Metal	0.57-1.03	215-627	60-100%	30
Cement (Decom sector)	0.95	568	100%	1
Plastic (Decom sector)	0.12	62	80%	1
Metal (Decom sector)	0.7-0.8	266-402	60-80%	2
TOTAL				69

Real waste containers were delivered with the known weight values. The mass of the waste was either automatically measured by the instrument or was inserted manually by the operator. The weight declared by the operational unit and the weight measured by FRMF were compared. The results are presented in Annex 1. During the measurement campaign were delivered seventy containers/drums the weight varies from 62 to 627 kg.

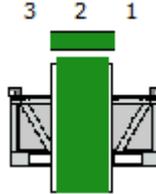
The FRMF' operators console requires the selection of a material type available in the software database. For metals and building materials the options provided were restricted to unique materials i.e. steel for metallic wastes (items or badge materials) and gravel for building material (cement, brick pieces, etc.). For the soft tissue or materials with low density, the provided option in FRMF was fibreglass.

The parameter 'filling' refers to the % waste container volume occupied by material. For the measurements of waste the occupancy of the container was made by direct measurement of the waste material height level inside the container. The material' density is the calculated value based on volume of selected container type and relevant filling.

3.3. Passive neutron measurements

The neutron slab counters were specially designed by JRC to have a high sensitivity of wide energy spectrum neutrons. The passive neutron counters are fixed in the cavity of the FRMF. Passive neutron counting system measurements are performed at position 2/3 and the results are reported as the total counts T (cps) for all three detectors.

Figure 11. The positioning of the containers for the passive neutron counting



The total counts provide a measurement of any alpha decay in the waste because of the (α, n) reactions on light target nuclides in the waste materials. The total count rate T_S due to the measured material alone was calculated based on the equation:

$$T_S = T_t - T_B,$$

where

T_t - the measured total count rate (sample + background),

T_B - the background total rate in the relevant reference material.

The detailed explanations are given in the procedure described in [2]. The FRMF automatically generates the specific neutron measurement report in the TXT format. The overview of the measurements by passive neutron counters is given in Annex 2.

3.4. Plastic scintillation detectors

For segregation purposes, non-spectrometric plastic scintillator detectors employed as high, narrow prisms to allow the optimization of their number and positions are usually sufficient. Four detectors of the same type are usually selected to ensure optimal detection geometry. It makes possible to scan containers in order to check the homogeneity of their radionuclide content and the presence of hot spots as well as to attain high measurement sensitivity.

Figure 12. A photograph of orange container with the definition of the measurement positions



The conveyer stops at three different positions which can be selected by the operator and are at position 1/3, 2/3, 3/3 of container, as shown in Figure 12. The plastic scintillation detectors are fixed in the cavity of FRMF.

The measurement protocol is generated by FRMF in the CSV format. The overview of the generated reports for each measurement by plastic scintillation detectors is given in Annex 3.

3.5. Gamma measurements by HPGe detectors

3.5.1. Definitions of measurement position during measurements

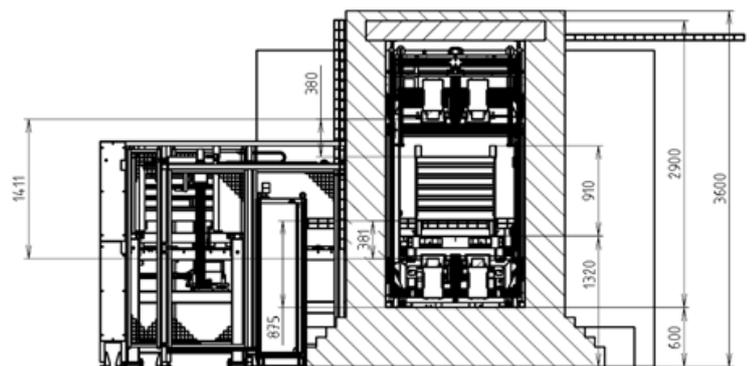
The positioning of the High Purity Germanium detectors in the cavity of the FRMF was adapted to the height of the containers as presented in Figure 13. Two bottom HPGe detectors have a fixed position and the two upper HPGe detectors are supported by a vertically movable platform. The high of the upper detectors adjusted based on the type of the measured containers. Threaded bars and laser sensors ensure the vertical movement of the upper detector positions.

Figure 13. Positioning of the containers in the measurement cavity of the FRMF

Photos of the JRC reference containers: (a) orange container CPM530I, (c) drum, and drawings presenting the positioning of HPGe detectors for: (b) orange container CPM530I, (d) drum



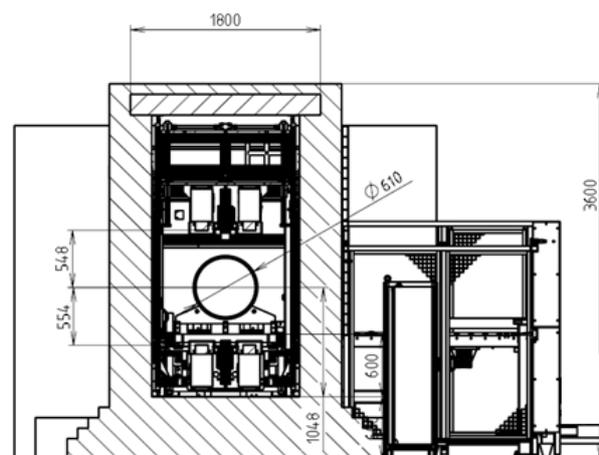
(a)



(b)



(c)



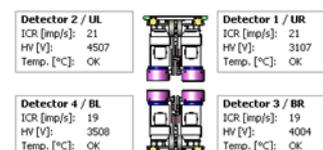
(d)

Figure 13(b,d) Source: NUVIA Drawing H181-01-S000, 2016

The conveyer stops at different positions, which can be selected by the operator and are at position 1/3, 2/3, 3/3 of the container as shown in Figure 11. The spectra acquired correspond to each measurement position and to each of the HPGe detector separately. Each of four detectors acquires one spectrum per position. As result, each container has twelve spectra. The mapping of the spectrum to the measurement position is presented in Table 3. The spectra name corresponds to position of the conveyer and the detectors.

Table 3. Mapping of spectrum with the position of the detector and container

Spectrum name	Measurement point	Position of detector acquiring the spectrum
<i>box_idXXX_pos1_det1</i>	1 – Position $_{1/3}$	1 _{detector} : up – right
<i>box_idXXX_pos1_det2</i>	1 – Position $_{1/3}$	2 _{detector} : up – left
<i>box_idXXX_pos1_det3</i>	1 – Position $_{1/3}$	3 _{detector} : down – right
<i>box_idXXX_pos1_det4</i>	1 – Position $_{1/3}$	4 _{detector} : down – left
<i>box_idXXX_pos2_det1</i>	2 – Position $_{2/3}$	1 _{detector} : up – right
<i>box_idXXX_pos2_det2</i>	2 – Position $_{2/3}$	2 _{detector} : up – left
<i>box_idXXX_pos2_det3</i>	2 – Position $_{2/3}$	3 _{detector} : down – right
<i>box_idXXX_pos2_det4</i>	2 – Position $_{2/3}$	4 _{detector} : down – left
<i>box_idXXX_pos3_det1</i>	3 – Position $_{3/3}$	1 _{detector} : up – right
<i>box_idXXX_pos3_det2</i>	3 – Position $_{3/3}$	2 _{detector} : up – left
<i>box_idXXX_pos3_det3</i>	3 – Position $_{3/3}$	3 _{detector} : down – right
<i>box_idXXX_pos3_det4</i>	3 – Position $_{3/3}$	4 _{detector} : down – left



The measured spectra are reported in the different formats, such as CHN, SPC, GSPC.

The measured gamma spectra were analysed by GAMWIN program. The reported activity values are generated by the GAMWIN software supporting the operation of FRMF. Overview of gamma spectroscopy measurements for real waste containers is presented in Annex 4.

3.5.2. The HPGe analysis software

The purpose of this chapter is to describe background data and algorithm used in the FRMF for analysis of the measurement spectra. The GAMWIN software has the functions for searching and determination of areas of the peaks, identification of nuclides and their activity.

The GAMWIN software provides the report taking into account the sum of 12 spectra. All values in the reports are generated by GAMWIN software [4] taking into account the following aspects:

3.5.2.1. Nuclide library

Table 4. GAMWIN nuclide library (export file from FRMF database)

Nuclide	Half life	Unit	Energy [keV]	Yield [%]	Key Line
Na-22	1,4E+006	Minute	1274,54	99,94	K
K-40	1,3E+009	Year	1460,81	10,67	K
Mn-54	312,70	Day	834,83	99,97	K
Co-57	270,90	Day	122,06	85,51	
			136,43	10,60	K
Co-60	5,27	Year	1173,23	99,86	
			1332,51	99,98	K
Zn-65	244,40	Day	1115,52	50,75	K
Se-75	119,78	Day	96,73	3,41	
			121,11	16,70	
			136,00	59,20	
			264,65	59,80	K
			279,53	25,20	
			400,65	11,40	
Sr-85	64,84	Day	513,99	99,27	K
Y-88	106,60	Day	898,02	93,40	
			1836,01	99,38	K
Nb-94	2,0E+004	Year	702,63	100,00	
			871,10	100,00	K
Nb-95M	5196,00	Minute	235,69	25,00	K
Zr-95	64,02	Day	724,18	43,70	
			756,72	55,30	K
Ru-106	368,20	Day	621,84	9,80	K
			1050,47	1,73	
Cd-109	464,00	Day	88,03	3,72	K
Ag-110M	3,6E+005	Minute	657,75	94,40	K
			677,61	10,68	
			706,67	16,68	
			763,93	22,28	
			818,02	7,30	
			884,67	72,60	
			937,48	34,20	
			1384,27	24,26	
			1505,00	13,06	
Sn-113	115,10	Day	391,69	64,90	K
Sb-124	60,20	Day	602,71	98,10	K
			645,84	7,24	
			722,78	11,80	
			1691,04	50,00	
Sb-125	2,77	Year	176,29	6,30	
			427,89	29,33	K
			463,38	10,35	
			600,56	17,80	
			600,77	18,40	
			606,64	5,02	
			635,90	11,32	
Ba-133	10,50	Year	79,62	2,55	

Nuclide	Half life	Unit	Energy [keV]	Yield [%]	Key Line
			81,00	33,00	
			276,40	6,90	
			302,71	18,62	
			355,86	62,27	K
			383,85	8,70	
Cs-134	2,06	Year	563,23	8,38	
			569,29	15,43	
			604,66	97,60	K
			795,76	85,40	
			801,84	8,73	
			1365,15	3,04	
Cs-137	30,17	Year	661,65	85,12	K
Ce-139	137,66	Day	165,85	80,35	K
Ce-144	284,20	Day	133,53	10,80	K
Eu-152	12,70	Year	121,78	29,24	
			244,67	7,62	
			344,30	27,00	K
			778,90	12,99	
			964,00	14,58	
			1085,80	10,29	
			1112,07	13,58	
			1408,08	21,21	
Eu-154	8,50	Year	123,10	40,46	
			248,04	6,60	
			723,30	19,70	
			873,20	11,30	
			996,30	10,70	
			1004,80	17,60	
			1274,80	35,50	K
U-235	3,8E+006	Year	143,76	10,50	
			163,35	4,70	
			185,72	54,00	K
			205,31	4,70	
Am-241	2,3E+008	Minute	59,54	36,30	

3.5.2.2. Efficiency calibrations

The HPGe detectors were calibrated by the partner from Czech Metrology Institute (CMI). Examples of efficiency calibrations coefficients are as indicated below:

Table 5. Examples of efficiency calibrations per JRC waste materials (metal, cement, soft tissue)

Spectrum Description: Steel- Metal Box position: SUM Filling – 100% Density [g/cm3]: - 0.8 Box type: JRC Orange container=JRC ISPRA box	Spectrum Description: Gravel- Cement Box position: SUM Filling – 80% Density [g/cm3]: - 0.933 Box type: JRC Orange container with Big-bag = JRC BOX without walls	Spectrum Description: Fibreglass - Soft tissue Box position: SUM Filling [%]: 100 Density [g/cm3]: 0,075 Box type: Drum 2001
Calibration Pairs : Energy Efficiency Unc. [keV] [%]	Calibration Pairs : Energy Efficiency Unc. [keV] [%]	Calibration Pairs : Energy Efficiency Unc. [keV] [%]
50,00 1,756E-005 0,04	50,00 9,804E-005 0,02	50,00 1,783E-005 0,05
59,54 4,049E-005 0,03	59,54 1,802E-004 0,02	59,54 1,231E-004 0,02
65,00 5,994E-005 0,03	65,00 2,304E-004 0,02	65,00 2,452E-004 0,02

Spectrum Description: Steel- Metal Box position: SUM Filling - 100% Density [g/cm3]: - 0.8 Box type: JRC Orange container=JRC ISPRA box	Spectrum Description: Gravel- Cement Box position: SUM Filling - 80% Density[g/cm3]: - 0.933 Box type: JRC Orange container with Big-bag = JRC BOX without walls	Spectrum Description: Fibreglass - Soft tissue Box position: SUM Filling [%]: 100 Density [g/cm3]: 0,075 Box type: Drum 200l
81,00 1,406E-004 0,02	81,00 3,727E-004 0,02	81,00 7,660E-004 0,01
90,00 1,996E-004 0,02	90,00 4,445E-004 0,01	90,00 1,088E-003 0,01
100,00 2,677E-004 0,01	100,00 5,104E-004 0,01	100,00 1,400E-003 0,01
121,78 4,068E-004 0,01	121,78 6,035E-004 0,02	121,78 1,888E-003 0,01
140,00 4,965E-004 0,01	140,00 6,388E-004 0,02	140,00 2,126E-003 0,01
165,90 5,743E-004 0,01	165,90 6,535E-004 0,02	165,90 2,255E-003 0,01
200,00 6,080E-004 0,01	200,00 6,280E-004 0,02	200,00 2,185E-003 0,01
244,70 5,906E-004 0,01	244,70 5,723E-004 0,02	244,70 2,003E-003 0,01
276,40 5,668E-004 0,02	276,40 5,377E-004 0,02	276,40 1,866E-003 0,01
302,90 5,460E-004 0,02	302,90 5,076E-004 0,02	302,90 1,768E-003 0,01
344,28 5,130E-004 0,02	344,28 4,690E-004 0,02	344,28 1,617E-003 0,01
400,00 4,717E-004 0,02	400,00 4,269E-004 0,02	400,00 1,460E-003 0,01
460,00 4,407E-004 0,02	460,00 3,953E-004 0,02	460,00 1,333E-003 0,01
520,00 4,108E-004 0,02	520,00 3,673E-004 0,02	520,00 1,217E-003 0,01
583,19 3,903E-004 0,02	583,19 3,476E-004 0,02	583,19 1,133E-003 0,01
661,65 3,632E-004 0,02	661,65 3,250E-004 0,02	661,65 1,041E-003 0,01
700,00 3,534E-004 0,02	700,00 3,153E-004 0,02	700,00 1,008E-003 0,01
778,90 3,358E-004 0,02	778,90 2,992E-004 0,02	778,90 9,413E-004 0,01
867,37 3,204E-004 0,02	867,37 2,860E-004 0,02	867,37 8,782E-004 0,01
964,08 3,017E-004 0,02	964,08 2,714E-004 0,02	964,08 8,251E-004 0,01
1050,00 2,912E-004 0,02	1050,00 2,607E-004 0,02	1050,00 7,845E-004 0,01
1112,10 2,825E-004 0,02	1112,10 2,521E-004 0,02	1112,10 7,537E-004 0,01
1222,00 2,708E-004 0,02	1222,00 2,430E-004 0,02	1222,00 7,101E-004 0,01
1332,52 2,602E-004 0,02	1332,52 2,353E-004 0,02	1332,52 6,726E-004 0,01
1408,00 2,525E-004 0,02	1408,00 2,268E-004 0,02	1408,00 6,481E-004 0,01
1528,10 2,418E-004 0,02	1528,10 2,209E-004 0,02	1528,10 6,145E-004 0,01
1764,52 2,230E-004 0,02	1764,52 2,034E-004 0,02	1764,52 5,559E-004 0,01
2000,00 2,063E-004 0,02	2000,00 1,925E-004 0,02	2000,00 5,074E-004 0,02
2350,00 1,837E-004 0,02	2350,00 1,730E-004 0,02	2350,00 4,453E-004 0,01
Energy Knee: 300,00 [keV]	Energy Knee: 300,00 [keV]	Energy Knee: 300,00 [keV]
Efficiency curve type for low energies: GAMWIN Degree polynomial: 4	Efficiency curve type for low energies: GAMWIN Degree polynomial: 5	Efficiency curve type for low energies: GAMWIN Degree polynomial: 5
$\ln(\text{Efficiency}) = \text{Sum}(\text{bn} \cdot (\ln(\text{Energy}) - \ln(\text{Knee}))^{(n-1)})$ b1 = -7,50827150E+00 b2 = -3,53396709E-01 b3 = 2,91700783E-01 b4 = 1,46460572E+00 b5 = 3,30254331E-01	$\ln(\text{Efficiency}) = \text{Sum}(\text{bn} \cdot (\ln(\text{Energy}) - \ln(\text{Knee}))^{(n-1)})$ b1 = -7,58058434E+00 b2 = -5,84076062E-01 b3 = 1,01189697E-01 b4 = 7,75967846E-01 b5 = 2,45375532E-01 b6 = 5,87677474E-02	$\ln(\text{Efficiency}) = \text{Sum}(\text{bn} \cdot (\ln(\text{Energy}) - \ln(\text{Knee}))^{(n-1)})$ b1 = -6,33133395E+00 b2 = -4,71519443E-01 b3 = 1,01988573E+00 b4 = 2,95655781E+00 b5 = 2,15181127E+00 b6 = 7,51815519E-01
Efficiency curve type for high energies: GAMWIN Degree polynomial: 4	Efficiency curve type for high energies: GAMWIN Degree polynomial: 4	Efficiency curve type for high energies: GAMWIN Degree polynomial: 4
$\ln(\text{Efficiency}) = \text{Sum}(\text{an} \cdot \ln(\text{Energy})^{(n-1)})$ a1 = -9,47635373E+01 a2 = 5,56324127E+01 a3 = -1,30590733E+01 a4 = 1,34472816E+00 a5 = -5,17171386E-02	$\ln(\text{Efficiency}) = \text{Sum}(\text{an} \cdot \ln(\text{Energy})^{(n-1)})$ a1 = -5,07127394E+01 a2 = 2,98071375E+01 a3 = -7,37734036E+00 a4 = 7,87031331E-01 a5 = -3,10999277E-02	$\ln(\text{Efficiency}) = \text{Sum}(\text{an} \cdot \ln(\text{Energy})^{(n-1)})$ a1 = -5,02529397E+01 a2 = 2,99774952E+01 a3 = -7,33224359E+00 a4 = 7,74590716E-01 a5 = -3,04771675E-02

Important!

At the time of the measurement campaign, for JRC containers (Drum, Orange containers and Orange containers with Big bag):

- The instrument has no calibration factor for quantification of activity for the non-homogeneous sample;
- The use of already existing factors corresponding to non-homogeneous sample introduces additional uncertainties;
- To be clarified whether the instrument gives a negative answer for free release when the non-homogeneous sample is detected regardless the amount of activity.

3.5.2.3. Activity calculation for full energy gamma lines

Activity in Bq is determined for each energy line which has been assigned a nuclide. The efficiency calibration used for the activity calculation is presented in the Table 5. Nuclide activity for the given energy line is given by the formula as described in [4]:

$$A = 100 * \frac{P}{T_L * \epsilon * Y}$$

where

- A - Activity [Bq]
- P - Net peak area [counts]
- ϵ - Full-energy peak efficiency coefficient for energy of calculated nuclide line
- T_L - Measurement time (Live Time)[seconds]
- Y - Yield of energy lines [percentage]

3.5.2.4. Minimum Detectable Activity (MDA) analysis

The FRMF software calculates automatically the Minimum Detectable Activity (MDA). MDA represents the minimum amount of radioactive nuclide, which could have been determined. It is calculated by the following formula as described in [4]

$$MDA = \frac{100 * L_D}{T_L * \epsilon * Y} \text{ [Bq]}$$

where MDA- the Minimal Detectable Activity [Bq]

- T_L - measurement time (Live Time) [seconds]
- ϵ - the efficiency coefficient for energy
- γ - the yield of energy line in percentage
- L_D - the minimum detectable net peak area [counts]

$$L_D = k_{1-\alpha}^2 + 2 \cdot k_{1-\alpha} * \sqrt{B}$$

includes $k_{1-\alpha}$ - a quantile of standard normal distribution for given probability α ,

B- a value considered for the background value applied for determination of peak net area and as the background uncertainty value.

$$B = \sum_{i=R}^S B_i + u_{bkg}^2 ,$$

includes

R - The first channel of peak area

S - The last channel of peak area

B_i - The background in i^{th} channel

The background uncertainty is computed according to the formula:

$$u_{bkg} = \sqrt{\left(\frac{n}{m}\right)^2 * B_{LR}}$$

n - Number of channels in peak area

m - Number of channels used for background calculation on both left and right side

B_{LR} - Sum of background left and right

u_{bkg} - The uncertainty of background [counts]

3.5.2.5. Homogeneity test

The homogeneity check is based on a statistical approach – Chi-Square Test. Each container is measured in three positions by four HPGe detectors. The obtained twelve spectra (see Table 3) are used for the analysis of the homogeneity.

The measured spectra are scaled by efficiency calibrations. Subsequently, each spectrum is divided into energy windows. The total counts in each energy window and for each spectrum are calculated and are compared with given limits as described in [5]. For described purposes, it was evaluated whether counts in a given energy window have the expected distribution within twelve spectra files. If the hypotheses are not rejected, then the container is considered as homogeneous.

The Figure 14 shows an example of the visualised non-homogenous distribution for one of the measured sample shown in Figure 15.

Figure 14. The values $\chi_{i,*}^2$ showed the homogeneity distribution within energy and $\chi_{j,*}^2$ presented homogeneity distribution within spectra files.

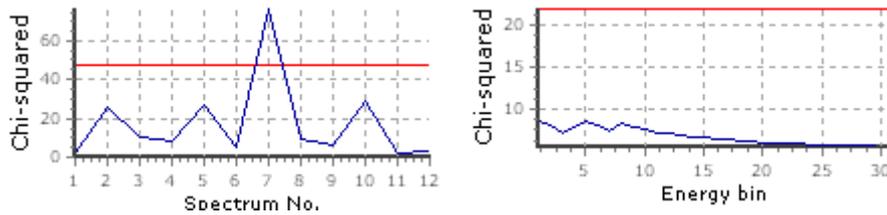


Figure 15. Mapping of the identified non homogeneity



4. Discussion and Further Actions

The gamma spectroscopy measurement results under the MetroDecom measurement campaign were automatically analysed with the FRMF software based on the clearance levels indicated in the Table 6. The measurements with the FRMF device demonstrated the capability to measure radioactivity levels below indicated limits.

Table 6. The free release clearance levels, as they are set in the FRMF software

Nuclide	Limit [Bq/g]
Co-60	0.3
Cs-137	0.3
Am-241	0.3
Ba-133	3
Co-57	3
Co-58	0.3
Eu-152	0.3
K-40	3
Mn-54	0.3
Np-237	0.3
Pu-240	0.3
Sb-125	3
Sr-90	3
Zn-65	0.3
AG-108m	0.3
Ni-63	300
Ni-59	300
Ag-110m	0.3

The results of samples with localised non-homogeneity

Measurements of JRC Ispra waste containers with the FRMF showed that the instrument is capable of providing spatial information that can be used for the localization of non-homogeneity.

The instrument developer has included the information resulting by the localization process in the reporting workflow; however the quality aspects as well as applicability of the provided data are yet questionable and not tested.

The instrument provides an estimation of the position for the localised non-homogeneity by means of graphical tools which indicate the container compartment and the position of the detector producing the most intense signal.

After the analysis of gamma spectra, the identification of gamma peaks and the determination of the total counts from the respective ROIs, the instrument provide information regarding the amount of the detected radionuclides by application of energy and geometry dependent detection efficiency factors derived by Monte Carlo simulations.

Despite the significance of these factors for the activities reported by the instrument, the developer does not provide enough information regarding the geometries for which the

factors are applicable. In addition to the absence of information, it should be noted that in the occasion of inhomogeneous distribution of radionuclides in a volume, it is important that estimation exists regarding the dimensions and the geometry of the localized non-homogeneity in the sample.

Considering the aforementioned points the activities reported by the instrument for the cases of localized non-homogeneity should be treated with caution since it is unknown whether the applied calibration factors correspond to the actual situation. Additionally it should be noted that the calibration factors used for the determination of non-homogeneity in the sample are still not validated for typical measurement scenarios.

The ROI based peak search algorithm

As far as the peak search algorithm is concerned, the comparison of the results provided by the implementation of either technique showed that for short measuring times ROI peak search technique is more sensitive in the detection of existing peaks. However, it was noted that along with the actual energy lines the method reports also non-existing isotopes: a fact that results in incorrect estimation of the waste total activity content.

Under the current FRMF setup and the applied activity quantification methods, reporting of results should be subject to further decay correction and the interference correction algorithm e.g., Ra-226/U-235.

The further actions

For the purpose of the project, the spectra and relevant measurement protocols are shared only within the MetroDecom project consortium and cannot be published or disseminated without agreement of JRC.

Based on the achievements of the measurement campaign in ISF, further revision and dissemination of the project's results is expected as a best practice and technical reports at the end of the MetroDecom project.

References

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- [2] Bogucarska T, Pedersen B, Silva Pestana L, Varasano G, " Investigation of the use of neutron counting for segregation of alpha-active decommissioning waste ", Publications Office of the European Union, Luxembourg, 2017, PUBSY No. JRC107756.
- [3] COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure.
- [4] *SW GAMWIN: Instruction Manual*. Třebíč, ENVINET a.s., 2013.
- [5] *Test for Homogeneity*, Třebíč, NUVIA a.s., 2017

List of abbreviations and definitions

FRMF Free Release Measurement Facility

HPGe High Purity Germanium Detector

ROI Region of Interest

ISF Interim Storage Facility

Waste is the measured material which was already measured and officially classified as material clearable according to existing JRC licenses.

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Annexes

Annex 1. Overview of weight measured by FRMF and compared with operator declarations

Container NR	Transport NR	Transport date	Material type	Weight Brutto, kg	Tara, kg	FRMF Meas. Mat. Weight, kg	Estimated material weight (weight brutto - tara), kg	Weight diff., kg	Weight diff, %
1	1	28.06.2016	Metal	645.5	108.8	534	536.7	2.7	0.50%
2	2	28.06.2016	Metal	570.4	110(*)	460	460.4	0.4	0.09%
3	3	28.06.2016	Metal	559.4	109.2	447	450.2	3.2	0.71%
4	4	28.06.2016	Metal	733.5	109.8	623	623.7	0.7	0.11%
5	5	30.06.2016	Metal	604.5	109.6	493	494.9	1.9	0.38%
6	6	30.06.2016	Metal	716	109.2	607	606.8	-0.2	-0.03%
7	7	30.06.2016	Metal	648.5	108.8	539.1	539.7	0.6	0.11%
8	8	30.06.2016	Metal	709.5	110(*)	598	599.5	1.5	0.25%
9	9	7.07.2016	Metal	676	108.7	567.1	567.3	0.2	0.04%
10	10	7.07.2016	Metal	595.6	109.5	487	486.1	-0.9	-0.19%
11	11	7.07.2016	Cement	492.3	116.8	375	375.5	0.5	0.13%
12	12	7.07.2016	Cement	526	117	410	409	-1	-0.24%
1	13	12.07.2016	Metal	644.5	108.8	539	535.7	-3.3	-0.62%
3	14	12.07.2016	Metal	652.5	110	547	542.5	-4.5	-0.83%
11	15	12.07.2016	Cement	549.3	116.8	433	432.5	-0.5	-0.12%
12	16	12.07.2016	Cement	505.5	117	389.9	388.5	-1.4	-0.36%
4	17	14.07.2016	Metal	481.2	109.8	375.1	371.4	-3.7	-1.00%
5	18	14.07.2016	Metal	597	109.6	490.1	487.4	-2.7	-0.55%
12	19	14.07.2016	Cement	581.4	117	463.9	464.4	0.5	0.11%
11	20	14.07.2016	Cement	546.8	116.8	Not meas.	430		
6	21	19.07.2016	Metal	689.5	109.2	583.1	580.3	-2.8	-0.48%
7	22	19.07.2017	Metal	678	108.8	571.1	569.2	-1.9	-0.33%
11	23	19.07.2018	Cement	543.8	116.8	428.9	427	-1.9	-0.44%
12	24	19.07.2019	Cement	532	117	417.9	415	-2.9	-0.70%
9	25	21.07.2016	Metal	712	108.7	603	603.3	0.3	0.05%
10	26	21.07.2016	Metal	662	109.5	553.1	552.5	-0.6	-0.11%
11	27	21.07.2016	Cement	520.8	116.8	Big volume	404		
12	28	21.07.2016	Cement	565	117	448	448	0	0.00%
1	29	06.09.2016	Metal	452	108.8	342	343.2	1.2	0.35%
3	30	06.09.2016	Metal	735	109.2	627	625.8	-1.2	-0.19%
11	31	06.09.2016	Cement	574.4	116.8	457	457.6	0.6	0.13%
12	32	06.09.2016	Cement	558.6	117	Not meas.	441.6		
10	33	20.09.2016	Metal	326.5	109.5	215	217	2	0.92%
4	34	20.09.2016	Metal	662	109.8	553	552.2	-0.8	-0.14%
9	35	20.09.2016	Metal	615	108.7	507	506.3	-0.7	-0.14%
11	36	22.09.2016	Cement	527.6	116.8	Not meas.	410.8		
12	37	22.09.2016	Cement	573.4	117	457	456.4	-0.6	-0.13%
1	38	22.09.2016	Metal	553.8	108.8	Not meas.	445		

Container NR	Transport NR	Transport date	Material type	Weight Brutto, kg	Tara, kg	FRMF Meas. Mat. Weight, kg	Estimated material weight (weight brutto - tara), kg	Weight diff., kg	Weight diff, %
2	39	27.09.2016	Metal	570.4	110(*)	459	460.4	1.4	0.30%
6	40	27.09.2016	Metal	689.5	109.2	Not meas.	580.3		
7	41	27.09.2016	Metal	678	108.8	569	569.2	0.2	0.04%
8	42	27.09.2016	Metal	709.5	110(*)	598	599.5	1.5	0.25%
F	43	29.09.2016	Cement	678	110(*)	Not meas.	568(**)		
F	44	29.09.2016	Plastic	172	110(*)	Not meas.	62(**)		
11	45	06.10.2016	Cement	539.8	116.8	422	423	1	0.24%
12	46	06.10.2016	Cement	497	117	377	380	3	0.79%
	47	06.10.2016	Soft material	40.4	25(*)	15	15.4	0.4	2.60%
	48	06.10.2016	Soft material	37.6	25(*)	12	12.6	0.6	4.76%
	49	18.10.2016	Soft material	39	25(*)	13	14	1	7.14%
	50	18.10.2016	Soft material	38	25(*)	12	13	1	7.69%
11	51	18.10.2016	Cement	551.1	116.8	433	434.3	1.3	0.30%
12	52	18.10.2016	Cement	574.2	117	456	457.2	1.2	0.26%
	53	20.10.2016	Soft material	40.4	25(*)	14	15.4	1.4	9.09%
	54	20.10.2016	Soft material	37	25(*)	12	12	0	0.00%
11	55	20.10.2016	Cement	529.2	116.8	411	412.4	1.4	0.34%
12	56	20.10.2016	Cement	482	117	Not meas.	365		
	57	25.10.2016	Soft material	34.5	25(*)	Not meas.	9.5		
11	58	25.10.2016	Cement	485.8	116.8	367	369	2	0.54%
12	59	25.10.2016	Cement	496.2	117	377	379.2	2.2	0.58%
4	60	25.10.2016	Metal	359.6	109.8	249	249.8	0.8	0.32%
3	61	27.10.2016	Metal	408	109.2	297	298.8	1.8	0.60%
11	62	27.10.2016	Cement	534.8	116.8	419	418	-1	-0.24%
12	63	27.10.2016	Cement	483.6	117	368	366.6	-1.4	-0.38%
11	64	08.11.2016	Cement	410	116.8	292	293.2	1.2	0.41%
12	65	08.11.2016	Cement	539.2	117	424	422.2	-1.8	-0.43%
F	66	10.11.2016	Metal	509.4	110(*)	402	399.4(**)	-2.6	-0.65%
F	67	10.11.2016	Metal	376.5	110(*)	266	266.5(**)	0.5	0.19%
11	68	15.11.2016	Cement	500.4	116.8	381	383.6	2.6	0.68%
12	69	15.11.2016	Cement	496.4	117	377	379.4	2.4	0.63%
11	70	17.11.2016	Cement	486.4	116.8	367	369.6	2.6	0.70%

(*)- Weight of reference container

(**)- Reported weight of material

Annex 2. Summary of the measurement by passive neutron counters

Meas. day	Container NR	Transport NR	Transport date	Material type	Meas. time	File ID	Weight	Filling	Density, g/cm ³	t, C
28.06.2016	1	1	28.06.2016	Metal	300	1505	534	100	0.89	22.9
28.06.2016	2	2	28.06.2016	Metal	300	1509	460	100	0.77	23.6
29.06.2016	3	3	28.06.2016	Metal	3600	1525	447	100	0,75	23.6
30.06.2016	4	4	28.06.2016	Metal	300	1534	623	100	1.04	23
1.07.2016	5	5	30.06.2016	Metal	300	1560	494	100	0.82	23.3
1.07.2016	6	6	30.06.2016	Metal	300	1561	607	100	1.01	23.3
5.07.2016	5	5	30.06.2016	Metal	300	1577	493	100	0.82	23.3
5.07.2016	5	5	30.06.2016	Metal	300	1578	493	100	0.82	23.3
5.07.2016	7	7	30.06.2016	Metal	300	1582	536	100	0.89	22.9
5.07.2016	7	7	30.06.2016	Metal	7200	1585	536	100	0.89	22.9
6.07.2016	8	8	30.06.2016	Metal	300	1594	598	100	1.00	23.2
6.07.2016	7	7	30.06.2016	Metal	7200	1604	539.1	100	0.9	24
7.07.2016	12	12	7.07.2016	Cement	300	1612	410	100	0.68	23.4
7.07.2016	11	11	7.07.2016	Cement	7200	1615	375	100	0.6	23.7
11.07.2016	10	10	7.07.2016	Metal	300	1626	487	100	0.81	24
11.07.2016	9	9	7.07.2016	Metal	300	1628	567.1	100	0.95	24
12.07.2016	1	13	12.07.2017	Metal	300	1657	539	100	0.90	24.1
12.07.2016	3	14	12.07.2016	Metal	300	1662	547	100	0.91	24.1
12.07.2016	12	16	12.07.2016	Cement	300	1673	389.9	80	0.80	24.4
14.07.2016	4	17	14.07.2016	Metal	300	1695	375.1	100	0.63	23.7
15.07.2016	5	18	14.07.2019	Metal	300	1701	490.1	100	0.80	23.5
15.07.2016	12	19	14.07.2016	Cement	300	1711	463.9	80	0.97	23.7
15.07.2016	11	20	14.07.2016	Cement	900	1714	337.9	80	0.70	23.7
15.07.2016	11	20	14.07.2016	Cement	21600	1717	337.9	80	0.70	23.7
19.07.2016	6	21	19.07.2016	Metal	300	1737	583.1	100	0.97	24
19.07.2016	7	22	19.07.2017	Metal	300	1740	571.1	100	0.95	24

19.07.2016	12	24	19.07.2019	Cement	300	1743	417.9	80	0.9	24
19.07.2016	11	23	19.07.2018	Cement	300	1746	428.9	80	0.89	24
21.07.2016	9	25	21.07.2016	Metal	300	1753	603	100	1.00	24.4
21.07.2016	10	26	21.07.2016	Metal	300	1756	553.1	100	0.90	24.4
21.07.2016	12	28	21.07.2016	Cement	300	1762	448	80	0.93	24.5
20.09.2016	1	29	06.09.2016	Metal	3600	3084	342	100	0.57	21.5
20.09.2016	3	30	06.09.2016	Metal	3600	3086	627	100	1.05	22.8
21.09.2016	11	31	06.09.2016	Cement	1200	3096	457	100	0.76	22.5
21.09.2016	12	32	06.09.2016	Cement	1200	3098	432	100	0.72	22.6
21.09.2016	12	32	06.09.2016	Cement	900	3100	432	100	0.72	22.2
21.09.2016	4	34	20.09.2016	Metal	1200	3102	553	100	0.92	22.6
21.09.2016	10	33	20.09.2018	Metal	1200	3104	215	60	0.60	22.6
22.09.2016	9	35	22.09.2016	Metal	1200	3113	507	80	1.06	21.5
22.09.2016	1	38	22.09.2016	Metal	1200	3115	437	80	0.91	22.6
22.09.2016	11	36	22.09.2016	Cement	1200	3117	402	80	0.84	22.5
23.09.2016	12	37	22.09.2016	Cement	1200	3126	457	80	0.95	22.7
27.09.2016	7	41	27.09.2016	Metal	1200	3138	569	100	0.95	21.1
27.09.2016	6	40	27.09.2016	Metal	1200	3140	170	40	0.71	22.5
28.09.2016	2	39	27.09.2016	Metal	1200	3142	459	100	0.77	21.5
28.09.2016	8	42	27.09.1016	Metal	1200	3151	598	100	1.00	21.8
29.09.2016	F	44	29.09.2016	PLASTIC	1200	3163	58	80	0.12	22
29.09.2016	F	43	29.09.2016	Cement	1200	3165	568	100	0.95	21.8
30.09.2016	F	43	29.09.2016	Cement	1200	3187	568	100	0.95	21.8
30.09.2016	F	44	29.09.2016	PLASTIC	1800	3179	58	80	0.12	19.7
17.10.2016	12	46	06.10.2016	Cement	1200	3232	377	80	0.8	17.8
17.10.2016	11	45	06.10.2016	Cement	1200	3235	422	80	0.9	18.2
17.10.2016		47	06.10.2016	Drum	1200	3238	15	100	0.1	18.2
17.10.2016	12	46	06.10.2016	Cement	1200	3241	377	80	0.8	17.8
17.10.2016		48	06.10.2016	Drum	1200	3242	12	100	0.06	17.9

18.10.2016		49	18.10.2016	Drum	1200	3251	13	100	0.07	16.4
18.10.2016		50	18.10.2016	Drum	1200	3254	12	100	0.1	18.2
18.10.2016	11	51	18.10.2016	Cement	1200	3257	433	80	0.9	18.3
19.10.2016	12	52	18.10.2016	Cement	1200	3260	456	80	1.0	18.2
20.10.2016		53	20.10.2016	Drum	1200	3270	14	100	0.07	17.8
20.10.2016		54	20.10.2016	Drum	1200	3273	12	100	0.1	18.2
20.10.2016	11	55	20.10.2016	Cement	1200	3276	411	100	0.7	18.2
20.10.2016	12	56	20.10.2016	Cement	1200	3279	365	100	0.608	17.8
25.10.2016		57	25.10.2016	Drum	1200	3291	15	100	0.1	16.9
25.10.2016	11	58	25.11.2016	Cement	1200	3294	367	100	0.61	16.6
26.10.2016	12	59	25.10.2016	Cement	1200	3297	377	80	0.8	17.2
26.10.2016	4	60	25.10.2016	Metal	1200	3313	249	60	0.69	17.4
27.10.2016	3	61	27.10.2016	Metal	1200	3330	297	80	0.6	16.7
27.10.2016	11	62	27.10.2016	Cement	1200	3334	419	80	0.9	17.4
27.10.2016	12	63	27.10.2016	Cement	1200	3337	368	80	0.8	14.5
8.11.2016	11	64	8.11.2016	Cement	1200	3350	292	80	0.6	14.9
08.11.2016	12	65	8.11.2016	Cement	1200	3353	424	80	0.9	14.5
10.11.2016	F	66	10.11.2016	Metal	1200	3374	403	80	0.8	14.3
10.11.2016	F	67	10.11.2016	Metal	3600	3377	266	60	0.7	14.1
11.11.2016	F	67	10.11.2016	Metal	1200	3388	266	60	0.74	13.8
16.11.2016	F	66	10.11.2016	Metal	3600	3403	402	80	0.8	12.7
16.11.2016	11	68	15.11.2016	Cement	1200	3410	381	80	0.79	13
17.11.2016	11	70	17.11.2016	Cement	3600	3423	367.0	80	0.8	12

Annex 3. Reporting of the measurement by plastic scintillation detectors

Meas. day	Container NR	Transport NR	Transport date	Material type	Meas. time	File ID	Weight	Filling	Density, g/cm ³	t, C
5.07.2016	5	5	30.06.2016	Metal	300	1581	493	100	0,8216	23.3
5.07.2016	7	7	30.06.2016	Metal	300	1584	536	100	0.89	22.9
5.07.2016	7	7	30.06.2016	Metal	3600	1587	536	100	0.89	22.9
6.07.2016	8	8	30.06.2016	Metal	900	1596	598	100	1	23.2
6.07.2016	8	8	30.06.2016	Metal	600	1599	598	100	1	23.6
6.07.2016	5	5	30.06.2016	Metal	900	1601	493	100	0,8216	23.3
6.07.2016	5	5	30.06.2016	Metal	600	1600	493	100	0,8216	23.3
6.07.2016	5	5	30.06.2016	Metal	450	1602	493	100	0,8216	23.3
5.07.2016	6	6	30.06.2016	Metal	450	1603	607	100	1.0116	
7.07.2016	12	12	7.07.2018	Cement	900	1614	410	100	0.68	23.6
7.07.2016	11	11	7.07.2016	Cement	3600	1617	375	100	0.6	23.7
12.07.2016	1	13	12.07.2019	Metal	900		539	100	0.9	24.1
14.07.2016	4	17	14.07.2018	Metal	300	1697	375.1	100	0.63	23.7
14.07.2016	5	18	14.07.2018	Metal	300	1700	490.1	100	0.82	23.9
15.07.2016	5	18	14.07.2021	Metal	900	1703	490.1	100	0.8	23.5
15.07.2016	12	19	14.07.2018	Cement	900	1713	463.9	80	0.97	23.7
15.07.2016	11	20	14.07.2016	Cement	300	1716	337.9	80	0.7	23.7
19.07.2016	6	21	19.07.2016	Metal	900	1739	583.1	100	1	24
19.07.2016	7	22	19.07.2019	Metal	900	1742	571.1	100	0.95	24
19.07.2016	12	24	19.07.2021	Cement	900	1745	417.9	80	0.9	24
19.07.2016	11	23	19.07.2020	Cement	900	1748	428.9	80	0.89	24
21.07.2016	9	25	21.07.2018	Metal	900	1755	603	100	1	24.4
21.07.2016	10	26	21.07.2016	Metal	900	1758	553.1	100	0.9	24.4
21.07.2016	12	28	21.07.2018	Cement	900	1764	448	80	0.93	24.5
20.09.2016	3	30	06.09.2017	Metal	7200	0	627	100	1.05	22.8

Meas. day	Container NR	Transport NR	Transport date	Material type	Meas. time	File ID	Weight	Filling	Density, g/cm ³	t, C
17.10.2016	12	46	06.10.2016	Cement	900	3234	377	80	0.8	17.8
17.10.2016	11	45	06.10.2016	Cement	900	3237	422	80	0.9	18.2
17.10.2016		47	06.10.2016	Drum	900	3240	15	100	0.1	18.2
17.10.2016		48	06.10.2016	Drum	3600	3244	12	100	0.06	17.9
18.10.2016		49	18.10.2018	Drum	900	3253	13	100	0.07	16.4
18.10.2016		50	18.10.2018	Drum	900	3256	12	100	0.1	18.2
18.10.2016	11	51	18.10.2016	Cement	900	3259	433	80	0.9	18.3
19.10.2016	12	52	18.10.2016	Cement	900	3262	456	80	1	18.2
20.10.2016		53	20.10.2016	Drum	900	3272	14	100	0.07	17.8
20.10.2016		54	20.10.2018	Drum	900	3275	12	100	0.1	18.2
20.10.2016	11	55	20.10.2016	Cement	900	3278	411	100	0.7	18.2
20.10.2016	12	56	20.10.2018	Cement	900	3281	365	100	0.608	17.8
25.10.2016	F	44	29.09.2016	PLASTIC	900	3289	58	80	0.12	17.8
25.10.2016	F	43	29.09.2016	Cement	900	3290	568	100	0.95	17.1
25.10.2016		57	25.10.2016	Drum	900	3293	15	100	0.1	16.9
25.10.2016	11	58	25.11.2018	Cement	900	3296	367	100	0.61	16.6
26.10.2016	12	59	25.10.2016	Cement	900	3299	377	80	0.8	17.2
26.10.2016	4	60	25.10.2018	Metal	900	3315	249	60	0.69	17.5
27.10.2016	3	61	27.10.2018	Metal	900	3332	297	80	0.6	16.7
27.10.2016	11	62	27.10.2018	Cement	900	3336	419	80	0.9	17.4
27.10.2016	12	63	27.10.2018	Cement	900	3339	368	80	0.8	14.5
8.11.2016	11	64	8.11.2018	Cement	900	3352	292	80	0.6	14.9
08.11.2016	12	65	8.11.2018	Cement	900	3355	424	80	0.9	14.5
10.11.2016	F	66	10.11.2018	Metal	900	3376	403	80	0.8	14.3
10.11.2016	F	67	10.11.2018	Metal	3600	3379	266	60	0.7	14.1
11.11.2016	F	67	10.11.2018	Metal	900	3390	266	60	0.74	14.2
16.11.2016	F	66	10.11.2018	Metal	3600	3405	402	80	0.8	12.7

Meas. day	Container NR	Transport NR	Transport date	Material type	Meas. time	File ID	Weight	Filling	Density, g/cm ³	t, C
16.11.2016	11	68	15.11.2018	Cement	900	3412	381	80	0.79	
16.11.2016	12	69	15.11.2018	Cement	3600	3415	377	80	0.8	12.7
17.11.2016	11	70	17.11.2018	Cement	3600	3425	367.0	80	0.8	12.7

Annex 4. Overview of gamma spectroscopy measurement reports

Meas. day	Container NR	Transport NR	Transport date	Container type	Material type	Meas. time	File ID
28.06.2016	1	1	28.06.2016	Orange	Metal	900	1506
28.06.2016	2	2	28.06.2016	Orange	Metal	900	1510
28.06.2016	2	2	28.06.2016	Orange	Metal	4320	1512
29.6.2016	2	2	28.06.2016	Orange	Metal	900	1521
29.06.2016	3	3	28.06.2016	Orange	Metal	43200	1526
30.06.2016	4	4	28.06.2016	Orange	Metal	900	1535
1.07.2016	6	6	30.06.2016	Orange	Metal	900	1562
5.07.2016	5	5	30.06.2016	Orange	Metal	900	1579
5.07.2016	7	7	30.06.2016	Orange	Metal	900	1583
5.07.2016	7	7	30.06.2016	Orange	Metal	21600	1586
6.07.2016	8	8	30.06.2016	Orange	Metal	900	1595
6.07.2016	8	8	30.06.2016	Orange	Metal	7200	1598
6.07.2016	7	7	30.06.2016	Orange	Metal	21600	1605
7.07.2016	12	12	7.07.2017	Orange with Big-Bag	Cement	900	1613
7.07.2016	11	11	7.07.2016	Orange with Big-Bag	Cement	21600	1616
11.07.2016	10	10	7.07.2016	Orange	Metal	900	1627
11.07.2016	9	9	7.07.2016	Orange	Metal	3600	1630
12.07.2016	1	13	12.07.2018	Orange	Metal	900	1658
12.07.2016	3	14	12.07.2016	Orange	Metal	900	1663
12.07.2016	11	15	12.07.2016	Orange with Big-Bag	Cement	9000	1668
12.07.2016	12	16	12.07.2016	Orange with Big-Bag	Cement	900	1674
14.07.2016	4	17	14.07.2017	Orange	Metal	900	1696
14.07.2016	5	18	14.07.2017	Orange	Metal	900	1699
15.07.2016	5	18	14.07.2020	Orange	Metal	900	1702
15.07.2016	12	19	14.07.2017	Orange with Big-Bag	Cement	900	1712
15.07.2016	11	20	14.07.2016	Orange with Big-Bag	Cement	900	1715

Meas. day	Container NR	Transport NR	Transport date	Container type	Material type	Meas. time	File ID
16.07.2016	11	20	14.07.2016	Orange with Big-Bag	Cement	21600	1718
19.07.2016	6	21	19.07.2016	Orange	Metal	900	1738
19.07.2016	7	22	19.07.2018	Orange	Metal	900	1741
19.07.2016	12	24	19.07.2016	Orange with Big-Bag	Cement	900	1744
19.07.2016	11	23	19.07.2019	Orange with Big-Bag	Cement	900	1747
21.07.2016	9	25	21.07.2017	Orange	Metal	900	1754
21.07.2016	10	26	21.07.2016	Orange	Metal	900	1757
21.07.2016	12	28	21.07.2017	Orange with Big-Bag	Cement	900	1763
20.09.2016	1	29	06.09.2016	Orange	Metal	1200	3083
20.09.2016	1	29	06.09.2016	Orange	Metal	7200	3085
20.09.2016	3	30	06.09.2016	Orange	Metal	7200	3087
21.09.2016	11	31	06.09.2016	Orange with Big-Bag	Cement	3600	3097
21.09.2016	12	32	06.09.2016	Orange with Big-Bag	Cement	3600	3099
21.09.2016	12	32	06.09.2016	Orange with Big-Bag	Cement	900	3101
21.09.2016	4	34	20.09.2017	Orange	Metal	3600	3103
21.09.2016	10	33	20.09.2019	Orange	Metal	3600	3105
22.09.2016	9	35	22.09.2017	Orange	Metal	3600	3114
22.09.2016	1	38	22.09.2017	Orange	Metal	3600	3116
22.09.2016	11	36	22.09.2016	Orange with Big-Bag	Cement	3600	3118
23.09.2016	12	37	22.09.2017	Orange with Big-Bag	Cement	3600	3127
27.09.2016	7	41	27.09.2017	Orange	Metal	3600	3139
27.09.2016	6	40	27.09.2017	Orange	Metal	3600	3141
28.09.2016	2	39	27.09.2017	Orange	Metal	3600	3143
28.09.2016	8	42	27.09.1017	Orange	Metal	75600	3152
29.09.2016	F	44	29.09.2017	Orange	Plastic	3600	3164
29.09.2016	F	43	29.09.2017	Orange	Cement	3600	3166
30.09.2016	F	43	29.09.2017	Orange	Cement	61200	3168

Meas. day	Container NR	Transport NR	Transport date	Container type	Material type	Meas. time	File ID
30.09.2016	F	43	29.09.2017	Orange	Cement	900	3188
30.09.2017	F	44	29.09.2016	Orange	Plastic	82800	3180
6.10.2016	F	44	29.09.2016	Orange	Plastic	1200	3190
6.10.2016	F	44	29.09.2016	Orange	Plastic	3600	3192
17.10.2016	12	46	06.10.2016	Orange with Big-Bag	Cement	3600	3233
17.10.2016	11	45	06.10.2016	Orange with Big-Bag	Cement	3600	3236
17.10.2016		47	06.10.2016	Drum	Soft tissue	3600	3239
17.10.2016		48	06.10.2016	Drum	Soft tissue	21600	3243
18.10.2016		49	18.10.2017	Drum	Soft tissue	3600	3252
18.10.2016		50	18.10.2017	Drum	Soft tissue	3600	3255
18.10.2016	11	51	18.10.2016	Orange with Big-Bag	Cement	3600	3258
19.10.2016	12	52	18.10.2016	Orange with Big-Bag	Cement	54000	3261
20.10.2016		53	20.10.2016	Drum	Soft tissue	3600	3271
20.10.2016		54	20.10.2017	Drum	Soft tissue	3600	3274
20.10.2016	11	55	20.10.2016	Orange with Big-Bag	Cement	3600	3277
20.10.2016	12	56	20.10.2017	Orange with Big-Bag	Cement	3600	3280
25.10.2016		57	25.10.2016	Drum	Soft tissue	3600	3292
25.10.2016	11	58	25.11.2017	Orange with Big-Bag	Cement	3600	3295
26.10.2016	12	59	25.10.2016	Orange with Big-Bag	Cement	3600	3298
26.10.2016	4	60	25.10.2017	Orange	Metal	3600	3314
27.10.2016	3	61	27.10.2017	Orange	Metal	3600	3331
27.10.2016	11	62	27.10.2017	Orange with Big-Bag	Cement	3600	3335
27.10.2016	12	63	27.10.2017	Orange with Big-Bag	Cement	3600	3338
9.11.2016	11	64	8.11.2017	Orange with Big-Bag	Cement	3600	3351
08.11.2016	12	65	8.11.2017	Orange with Big-Bag	Cement	3600	3354
10.11.2016	F	66	10.11.2017	Orange	Metal	3600	3375
10.11.2016	F	67	10.11.2017	Orange	Metal	57600	3378

Meas. day	Container NR	Transport NR	Transport date	Container type	Material type	Meas. time	File ID
11.11.2016	F	67	10.11.2017	Orange	Metal	3600	3389
16.11.2016	F	66	10.11.2017	Orange	Metal	57600	3404
16.11.2016	11	68	15.11.2017	Orange with Big-Bag	Cement	3600	3411
16.11.2016	12	69	15.11.2017	Orange with Big-Bag	Cement	57600	3414
17.11.2016	11	70	17.11.2017	Orange with Big-Bag	Cement	57600	3424

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