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Optimization of a measurement facility for radioactive waste free release by Monte Carlo simulation

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HIGHLIGHTS

- Monte Carlo simulations utilized for optimization of a novel free release facility.
- Cosmic radiation and chamber walls contribute most to the background.
- H*(10) rate inside the optimized facility decreased to 33% of the outside value.

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ABSTRACT

A novel free release measurement facility (FRMF) was developed within the joint research project “Metrology for Radioactive Waste Management” of the European Metrology Research Programme. Before and during FRMF design and construction, Monte Carlo calculations with MCNPX and PENELOPE codes were used to optimize the thickness of the shielding, the dimensions of the container, and the shape of detector collimators. Validation of the numerical models of the FRMF detectors and the results of the optimization are discussed in the paper.

1. Introduction

The free release measurement facility (FRMF) enables a verification of compliance with legal clearance levels for free release of radioactive waste. The design of such facilities involves selection of appropriate detectors, measurement electronics, material of shielded measurement chamber and mechanical hardware, as well as an operator console and associated software. The joint research project “Metrology for Radioactive Waste Management” (MetroRWM) of the European Metrology Research Programme (EMRP), which started in October 2011, includes within its research topics the development of new measurement methodologies and measurement devices for the assessment of radioactive waste. One of these systems is an improved facility for measurements related to the free release of radioactive waste, with traceability to national standards of EU member countries. Critical aspects of the new measurement facility are its modularity enabling to build the system dimensioned to match the supposed waste throughput, as well as improved spectrometric measurement and decreased minimum detectable activity. The measurement facility is fully transportable including the shielded chamber made of low-activity concrete blocks instead of environmentally unfriendly massive lead shielding (Suran et al., 2013).

This paper describes the optimization of the FRMF main parameters by means of Monte Carlo simulations using the PENELOPE and MCNPX. The aim of the optimization was to achieve maximum decrease of the detector count rate caused by natural background radiation inside the FRMF and to find optimal container dimensions for achieving maximum throughput of measured material.

2. Materials and methods

2.1. Free release measurement facility

The FRMF is a testing facility used for the measurement of the activity of waste released from nuclear sites into the environment. It consists of a walk-through shielded chamber with the inner width, length and height of 120 cm, 300 cm, and 200 cm, respectively, a conveyor for transportation of containers filled with the measured material, and four Interchangeable Detector Modules (IDM) High-Purity germanium (HPGe) detectors (ORTEC; Ge crystal volume 180 cm^3; FWHM@1332 keV ≈ 2.0 keV; rel. efficiency 50%) with Stirling cycle cooler. Two detectors are located above the measured material, the other two below. The shielded chamber is made of blocks from a composite, lead-free building material

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based on aggregate with a low internal content of radionuclides with a density of 2.4 g/cm^3. The activity concentrations of ^{40}K, ^{226}Ra and ^{228}Th in the composite material were measured and reached (10.6 ± 0.5) Bq/kg, (1.0 ± 0.1) Bq/kg and (0.7 ± 0.1) Bq/kg, respectively (k=1). Dose measurements performed after the FRMF construction showed that the ambient dose equivalent rate, H*(10), decreased from (101 ± 7) μSv/h outside to (33.5 ± 2.4) μSv/h inside the chamber (k=1).

2.2. Monte Carlo simulations

2.2.1. Monte Carlo codes

A complex model of the whole FRMF was created in the Monte Carlo code MCNPX (Fig. 1) and the calculations were done with the version v2.7e of the code (Pelowitz et al., 2011). A standalone model of the IDM detector was created in the PENELOPE code (Salvat et al., 2006) as well and used for optimization of the container dimensions. Results of all calculations were obtained with the statistical uncertainties below 3% (k=1).

2.2.2. Validation of the IDM detector models

Both IDM detector models were validated by measurements with point sources located 25 cm above the cryostat front face and 25 cm aside to the cryostat side wall. Measured and calculated full-energy peak detection efficiencies were compared for photon energies of 122 keV, 662 keV, 898 keV, 1173 keV, and 1332 keV.

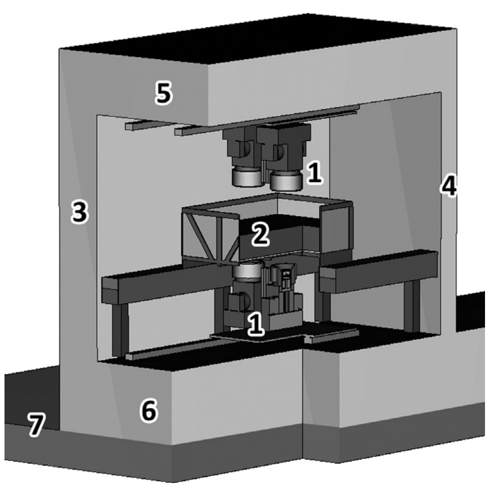

Fig. 1. Visualization of the FRMF Monte Carlo model. 1—IDM detectors, 2—container with load, 3—FRMF walls, 4—FRMF door, 5—FRMF ceiling, 6—FRMF floor, 7—hall floor.

2.2.3. Sources of natural background

For the optimization of the shielded chamber parameters, a total of five sources of natural radiation were considered: (1) concrete floor of the hall where the FRMF was located, (2) air in the hall, (3) composite material of the chamber, (4) air inside the shielded chamber, (5) cosmic rays. Main characteristics of the sources are presented in Table 1.

Mass or volume activities of the materials and cosmic ray fluence are typical average values only and may slightly differ from the real values depending on the location of the experimental site. Activity of air inside the chamber is an estimate based on the fact that a ventilation unit will flush the outer air inside the FRMF through aerosol filters in order to achieve a significant reduction of radon concentration. The calculated quantity was the count rate per hour per keV in seven energy windows in the energy range from 59 keV to 1.7 MeV, summed from all four IDM detectors (thereinafter "count rate"). This quantity was obtained from the simulation results stated in "number of detector counts per source particle" using particle yields and activities stated in Table 1. The energy windows of greater interest were ^{137}Cs (662 keV) and ^{60}Co (1.33 MeV) windows. Independent simulation was performed for each particle source from Table 1 and subsequently the simulated count rates were summed into the total count rate caused by all sources of natural background radiation (thereinafter "total count rate"). Variance reduction techniques and PTRAC file (Particle Track output) were utilized to increase the efficiency of the calculations. Other sources of radiation background like possible radionuclide contamination of lead collimators or radon decay products deposited on surfaces were neglected.

2.3. Optimization of shielded chamber thickness

The inner dimensions of the FRMF were fixed because they depend on the dimensions of the IDM detectors, mechanical parts of the FRMF and dimensions of the container filled with the measured material. Therefore, the Monte Carlo calculations were focused on shielded chamber thickness only.

2.4. Optimization of collimator shape

Four collimator shapes were studied: standard cone, enhanced cone with enlarged thickness of the conical part, pyramid, and enhanced pyramid with enlarged thickness of the pyramidal part (Fig. 2). The pyramidal collimators were taken into consideration because every detector measures count rate related to a square section area of the container. In addition, the simulations were performed for collimators at the standard position and shifted by 1.5 cm up or down. The collimators were made of lead. The study

Table 1
Characteristics of particle sources considered in the simulations.

Natural background source	Source dimensions	Energy spectrum	Activity	Total yield
Concrete floor of the hall	Volume, 15.6 × 9 × 0.3 m^3	Photons from ^{238}U series + ^{232}Th series + ^{40}K	30 Bq/kg + 30 Bq/kg + 300 Bq/kg	162.6 s^{-1}/kg for photons
Air in the hall	Volume, 15.6 × 9 × 6 m^3	Photons from ^{238}U series	100 Bq/m^3	179 s^{-1}/m^3 for photons
Composite material of the chamber	Whole volume of the composite material	Photons from ^{238}U series + ^{232}Th series + ^{40}K	1.0 Bq/kg 0.7 Bq/kg 10.6 Bq/kg	4.7 s^{-1}/kg for photons
Air inside the chamber	Whole volume of air inside the shielded chamber	Photons from ^{238}U series	1 Bq/m^3	1.8 s^{-1}/m^3 for photons
Cosmic rays	Rectangle, 2 × 3.2 m^2 (parallel particle beam perpendicular to chamber ceiling)	EXPACS database (Sato, 2006) of spectra of photons, electrons, neutrons, protons and muons at Earth surface (Prague coordinates and elevation) originated from interactions caused by cosmic particles	Particle distribution: 37% photons, 6% electrons, 37% neutrons, 1% protons, 19% muons	4.92 min^{-1}/cm^2 for all particles