ARTICLE IN PRESS

Radiation Physics and Chemistry ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Characterisation of a radionuclide specific laboratory detector system for the metallurgical industry by Monte Carlo simulations

Jaroslav Šolc [a,*], Pavel Dryák [a], Hannah Moser [b], Thierry Branger [c], Eduardo García-Toraño [d], Virginia Peyrés [d], Faidra Tzika [e], Guillaume Lutter [e], Marco Capogni [f], Aldo Fazio [f], Aurelian Luca [g], Branko Vodenik [h], Carlos Oliveira [i], Andre Saraiva [i], Laszlo Szucs [j], Tomasz Dziel [k], Oleksiy Burda [l], Dirk Arnold [l], Jozef Martinkovič [m], Teemu Siiskonen [n], Aleksi Mattila [n]

[a] CMI, Czech Metrology Institute, Radiová 1a, 102 00 Praha 10, Czech Republic
[b] BEV/PTP, Bundesamt für Eich- und Vermessungswesen, Arltgasse 35, A-1160 Wien, Austria
[c] CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91191 Gif-sur-Yvette Cedex, France
[d] CIEMAT, Metrología de Radiaciones Ionizantes, Avenida Complutense 40, 28040 Madrid, Spain
[e] EC-JRC-IRMM, Institute for Reference Materials and Measurements, Retieseweg 111, 2440 Geel, Belgium
[f] ENEA-INMRI, Via Anguillarese, 301 Santa Maria di Galeria, 00123 Roma, Italy
[g] IFIN-HH, 30 Reactorului Street, 077125 Magurele, Ilfov, Romania
[h] IJS, Institute Jožef Stefan, Jamova 39, 1000 Ljubljana, Slovenia
[i] IST, Instituto Superior Técnico, Universidade de Lisboa, Estrada Nacional 10 (km 139.7), 2695-066 Bobadela LRS, Portugal
[j] MKEH, Magyar Kereskedelmi Engedélyezési Hivatal, Németvölgyi út 37-39, 1124 Budapest, Hungary
[k] NCBJ, Narodowe Centrum Badań Jądrowych, ul. Andrzeja Sołtana 7, 05-400 Otwock, Świerk, Poland
[l] PTB, Physikalisch-Technische Bundesanstalt, Bundesallee 100, D 38116 Braunschweig, Germany
[m] SMU, Slovenský metrologický ústav, Karloveská 63, 842 55 Bratislava 4, Slovak Republic
[n] STUK, Radiation and Nuclear Safety Authority, P.O. Box 14, FIN-00881 Helsinki, Finland

HIGHLIGHTS

- The recommended laboratory detector is an extended-range germanium semiconductor detector with the relative efficiency of 30%–40%.
- Capabilities of different Monte Carlo codes to determine true coincidence summing corrections were compared.
- Identical model of the recommended laboratory detector system implemented in different Monte Carlo codes is freely available to end-users.

ARTICLE INFO

Article history:
Received 6 October 2014
Accepted 4 January 2015

Keywords:
Metrology
Ionising radiation
Gamma-ray spectrometry
Coincidence summing
Metallurgy
Monte Carlo simulation
EURAMET

ABSTRACT

One of the outputs of the European Metrology Research Programme project “Ionising radiation metrology for the metallurgical industry” (MetroMetal) was a recommendation on a novel radionuclide specific detector system optimised for the measurement of radioactivity in metallurgical samples. The detection efficiency of the recommended system for the standards of cast steel, slag and fume dust developed within the project was characterized by Monte Carlo (MC) simulations performed using different MC codes. Capabilities of MC codes were also tested for simulation of true coincidence summing (TCS) effects for several radionuclides of interest in the metallurgical industry. The TCS correction factors reached up to 32% showing that the TCS effects are of high importance in close measurement geometries met in routine analyses of metallurgical samples.

1. Introduction

The European Metrology Research Programme (EMRP) project IND04 “Ionising Radiation Metrology for the Metallurgical Industry” (MetroMetal) is a joint research project (JRP) participated by 13 European metrological institutes (CIEMAT – Spain, leader of

* Corresponding author. Fax: +420 266 020 466.
E-mail address: jsolc@cmi.cz (J. Šolc).

http://dx.doi.org/10.1016/j.radphyschem.2015.01.003
0969-806X/© 2015 Elsevier Ltd. All rights reserved.

Please cite this article as: Šolc, J., et al., Characterisation of a radionuclide specific laboratory detector system for the metallurgical industry by Monte Carlo simulations. Radiat. Phys. Chem. (2015), http://dx.doi.org/10.1016/j.radphyschem.2015.01.003

the JRP; BEV/PTP – Austria; CEA – France; CMI – Czech Republic; ENEA – Italy; IFIN-HH – Romania; IJS – Slovenia; IST – Portugal; MKEH – Hungary; NCBJ – Poland; PTB – Germany; SMU – Slovakia; STUK – Finland), one international organisation (JRC-IRMM, European Commission) and an associated engineering company (ENVINET, Czech Republic). The general aim of the project is to improve radioactivity measurements in metallurgical industry at each stage of the smelting process. This includes:

- Designing and development of reference standards for radioactivity measurements;
- Recommendations on optimal measurements configurations (detectors, geometry, etc.) and procedures (traceability, determination of detection efficiency and true coincidence summing correction (TCSC) factors, etc.) for the gamma-ray detection systems (scrap portals, cast steel, slag, and fume dust).

The current paper focuses on the characterisation of the recommended detector system from the point of view of Monte Carlo (MC) simulations. Within the MetroMetal project, the work is a necessary step in the development of the new instrument for laboratory measurements of radioactivity in cast steel, slag, and fume dust.

2. Materials and methods

2.1. The recommended laboratory detector system

A survey among end-users in Europe revealed that the majority of measurement systems today is based on scintillation detectors. A comparison study between various detectors was prepared by the project partners focusing on laboratory measurement of radioactivity in cast steel, slag, and fume dust. The study was concluded with a recommendation on a detector system with the following features:

- Germanium semiconductor detector with the relative efficiency of 30%–40% and with improved detection efficiency at energies below 40 keV;
- Prismatic or cylindrical lead shielding of at least 5 cm thickness;
- PMMA or aluminium cylindrical sample chamber with a minimum diameter of 100 mm placed on the top of the sensitive face of the detector in order to protect it from mechanical impacts and possible radioactive contamination;
- Electrical cooling system.

Despite a lower detection efficiency of a germanium detector as compared to a scintillation one, the former possesses superior energy resolution, which results in a significant advantage in terms of nuclide identification and spectral analysis. Based on the specifications, two prototype detector systems were designed and constructed at two partner laboratories – PTB (Germany) and CIEMAT (Spain) (García-Toraño et al., in preparation). Both prototypes were demonstrated at several end-user sites.

2.2. Calibration standards

Currently, there is a lack of calibration standards for radioactivity monitoring at each stage of the smelting process. In order to make SI (The International System of Units) traceable radioactivity measurements possible, various radionuclide calibration standards with a wide range of specific activities were prepared and are now available to end-users. Four sets of sources were used for interlaboratory comparisons (ILCs) among the project partners

Table 1
Specifications of cylindrical sources. Elemental composition of the source matrix (not presented here) was taken from a chemical and X-ray fluorescence analysis.

	Radius (cm)	Height (cm)	Density (g/cm^3)	Container wall thickness (cm)	Container bottom thickness (cm)
Cast steel	1.75	1.00	7.75	–	–
Slag	3.60[a]	1.81[a]	2.185	0.17	0.12
Fume dust	3.48[a]	1.87[a]	0.707	0.10	0.10

[a] Radius or height of the source matrix.

Tzika et al. (in preparation a,b): two sets of cast steel sources of independent origin contaminated with ^{60}Co of ~1 Bq/g, one set of black slag sources with ^{226}Ra of ~10 Bq/g, and one set of fume dust sources with ^{137}Cs of ~10 Bq/g. The ILCs aimed (a) to test the measurement methods proposed within the project and (b) to provide the data for certification of specific activity of the sources.

2.3. Monte Carlo simulations

The aim of the MC simulations was to calculate (a) full-energy peak (FEP) detection efficiency (DE) and total DE and (b) TCSC factors for three ILC cylindrical sources (Table 1) positioned inside the sample chamber of the recommended detector system (Table 2), and (c) to compare capabilities of different MC codes based on the results of (a) and (b).

The model of the recommended detector system including the sources was created in MC codes EGSnrc, GEANT3, GESPECOR, MCNP, and PENELOPE. The project partners were free to use any version or modification of the MC codes, decay data libraries, cross-section tables and particle cut-off energies (Table 3). Although the results of the simulations performed with the same MC code by different project partners might be correlated, the differences may occur due to utilisation of other versions of the code, decay data library or simulation parameters.

2.3.1. Detection efficiencies

The FEP DE and total DE were calculated for ^{60}Co (1332 keV) in cast steel, ^{226}Ra (186 keV) in slag, and ^{137}Cs (662 keV) in fume dust. No TCS effects were considered.

2.3.2. TRUE coincidence summing corrections

The TCS effect is caused by coincident detection of photons generated in a cascade during the radionuclide decay. For close sample-to-detector geometries occurring in laboratory activity measurements in metallurgical industry, the TCS effect has significant influence on the shape of a detector pulse-height spectrum. Unless the detector is calibrated with a calibration source of the same matrix, dimensions, density, and radionuclide content as the measured sample, the TCSC factors for radionuclides with complex decay schemes have to be calculated for an accurate determination of sample activity.

Direct calculation of the TCSC factors is possible with

Table 2
Main parameters of the MC model of the recommended detector system.

Parameter	Value
Ge crystal diameter	57 mm
Ge crystal height	61 mm
Dead layer thickness	Upper: 3 μm, lateral: 500 μm
End cap window thickness	0.5 mm beryllium
Sample chamber bottom thickness	1.0 mm carbon
Cylindrical lead shielding thickness	50 mm