Applied Radiation and Isotopes 67 (2009) 692–695

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

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

Difficulties in obtaining an HPGe detector for low-level measurements

E.M. Barnes *, S.A. Long, R.A. Tinker

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), 619 Lower Plenty Road, Yallambie, Victoria 3085, Australia

ARTICLE INFO

Keywords:
Low-level gamma-spectrometry
CTBTO
Minimum detectable activity

ABSTRACT

All low-level laboratories require HPGe detectors to meet certain technical specifications, some of which are not available from manufacturers prior to purchase. Ensuring an HPGe detector is fit for purpose requires the purchase and installation of a detector in the laboratory, incurring both financial risk and considerable time and effort. We show that the optimal HPGe crystal for low-level laboratories has a diameter matched to the source and a length providing 70% absorption of the gamma-rays of interest.

1. Introduction

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is a federal government agency charged with the responsibility of protecting the health and safety of people and the environment from the harmful effects of radiation. As part of this mission, ARPANSA operates and maintains the Australian Radionuclide Laboratory (AUL02), under contract to the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO). The role of the radionuclide laboratory is to carry out detailed analyses, by gamma-spectrometry, of filter samples received from the atmospheric particulate radionuclide monitoring stations of the International Monitoring System (IMS) network. These stations are designed to detect radioactive debris from atmospheric nuclear detonations. The radionuclide laboratories supporting the IMS, such as AUL02, are required by the CTBTO to corroborate the results from the IMS network, to clarify the presence or absence of fission or activation products in a suspect or irregular sample and provide more accurate and precise measurements.

The third requirement is particularly important for radionuclide laboratories supporting the CTBTO as the activity levels of fission or activation products are anticipated to be very low. Adding to this challenge the CTBTO stipulates limited timeframes for the reporting of results. To ensure radionuclide laboratories are capable of delivering this service, the CTBTO has defined a set of specifications, (shown in Table 1) that radionuclide laboratories must meet in order to be certified for operation.

Requirements for Minimum Detectable Activity (MDA) and peak shape (FWTM/FWHM) are relatively uncommon specifications and are not included in international standards, for example, the Standard Test Procedures for Germanium Gamma-Ray Detectors (ANSI/IEEE, 1996). Such specifications are generally not tested for or warranted by HPGe detector manufacturers. Obtaining a detector that met all of the specifications detailed in Table 1 proved difficult as neither the MDA or peak shape could be tested without purchasing a detector and testing it *in situ* at AUL02. Three detectors, each with a delivery time of 150 days, had to be tested before AUL02 obtained a detector that was appropriate.

The challenges faced by the radionuclide laboratories supporting the CTBTO are similar to those faced by all low-level gamma-spectrometry laboratories. Such laboratories must balance the throughput of samples against the measurement time required to provide a good statistical level of confidence in their measurements. To achieve a suitable throughput and provide good statistical measurements of low-activity samples, most laboratories require a detector that achieves the minimum MDA in a given time.

2. Trialled detectors

Details of the three detectors tested by AUL02 in the search for a detector capable of meeting all CTBTO specifications are shown in Table 2.

2.1. Detector One

Detector One with a 73 mm by 92 mm Ge crystal, a crystal volume of 384 ml and a relative efficiency of 77% failed only the MDA specification when placed in a typical low-level counting shield consisting of a 10 cm thick lead (lead taken from the certified Doe Run mine) with a Sn/Cu lining. A range of different shielding was trialled (Table 3) in an attempt to meet this criterion.

Under shielding conditions as recommended by the manufacturer, an MDA of 32.4 mBq was calculated, 35% above the 24 mBq

---

* Corresponding author. Tel.: +61 3 9433 2243; fax: +61 3 9432 9165.
E-mail address: emma.barnes@arpansa.gov.au (E.M. Barnes).

0969-8043/$ - see front matter Crown Copyright © 2009 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.apradiso.2009.01.012

Table 1
CTBT defined requirements for Certified IMS Radionuclide Laboratories.

Property	Requirement
Detector type	High resolution HPGe
Detector relative efficiency	⩾40%
Efficiency calibration measurement range	46.5–1836 keV
Efficiency calibration range (extrapolated)	30–2700 keV
Channels in spectrum	⩾8192
MDA for ^{140}Ba	⩽24 mBq
FWHM at 1332.5 keV	⩽2.3 keV
FWHM at 122.1 keV	⩽1.3 keV
FWTM/FWHM ratio at 1332.5 keV	⩽2.0

The MDA for ^{140}Ba is decay corrected to the start of spectral acquisition, with an acquisition time no longer than 7 days. The geometry used for the MDA calculation is a cylinder sample geometry with a diameter of 70 mm and a height of up to 6 mm (CTBT/PTS/INF.96, 2005).

Table 2
Tested parameters of the three detectors trialled at AUL02 in the search for a detector capable of meeting CTBT requirements.

Performance specifications	Detector One	Detector Two	Detector Three
Ge crystal volume (ml)	384	537	260
Ge crystal diameter (mm)	73.0	89.6	82.0
Ge crystal length (mm)	91.8	85.3	49.3
FWHM @ 1332.5 keV	2.02 keV	2.2 keV	1.94 keV
Peak to compton ratio, ^{60}Co	68:1	91:1	77:1
Relative efficiency at 1332.5 keV	77%	143%	79%
FWTM/FWHM, ^{60}Co	1.85	4.33	1.89
FWFM/FWHM, ^{60}Co	–	3.37	2.51
FWHM at 122.1 keV	1.07 keV	1.15 keV	0.71 keV
FWHM at 59.54 keV	–	1.05 keV	0.85 keV

The shaded figures represent values not warranted by the manufacturer.

Table 3
MDA figures achieved with Detector One, with varying levels of shielding.

Primary shielding	Secondary shielding	Detector location	MDA (mBq)
None	None	CRL	235.0
None	None	WBM	34.2
10 cm Pb	None	CRL	32.5
10 cm Pb	Extra 5 cm Pb on floor	CRL	32.1
10 cm Pb	4 cm inner Cu	CRL	28.6
10 cm Pb	Additional 5 cm inner Pb thickness	CRL	28.3
10 cm Pb	Increased inner Pb thickness (5 cm), additional Pb thickness (5 cm) on shield lid	CRL	28.2
10 cm Pb	4 cm inner Cu	WBM	26.4
10 cm Pb	None	WBM	25.8
10 cm Pb	Additional 5 cm inner Pb thickness	WBM	23.9

criterion within AUL02 (CTBTO Radionuclide Laboratory (CRL)). An additional 5 cm of Pb shielding decreased the MDA to 28.2 mBq. To determine the effect of best possible shielding conditions for an above ground radionuclide laboratory, the same shielding conditions were replicated in ARPANSA's walk-in Whole Body Monitor (WBM) shield (20 cm old iron and 10 cm lead). Although there was a further improvement in the MDA to 25.8 mBq, additional shielding resulted in no significant decrease in MDA.

As shown by the test results in Table 3, increasing the thickness of lead shielding beyond 10 cm had a minimal effect in further reducing counts from external gamma-rays, but may actually increase the background as a result of the influence of secondary radiations (Knoll, 2000). Despite slight improvements with varying shields, the MDA for Detector One still failed the CTBTO requirement.

2.2. *Detector Two*

After discussion with the detector manufacturers, a second detector with an 87 mm by 85 mm Ge crystal, a crystal volume of 537 ml and a relative efficiency of 143% (as tested) was purchased.

This detector was capable of achieving an MDA of 21.0 mBq which was within CTBTO specifications. However, as a direct result of the size of the Ge crystal the detector failed to achieve the CTBTO specification for Gaussian peak shape (⩽2.0 FWTM/FWHM for ^{60}Co at 1332.5 keV). Fig. 1 shows a comparison between spectra from Detector Two and Detector Three (currently in use at AUL02) for ^{60}Co at 1332.5 keV, both spectra were acquired with the same digital signal processing unit. The severe low-end tailing for Detector Two can be clearly seen with a FWHM of 2.2 keV and a FWTM/FWHM of 4.33 keV. The main contributing factor to the low-end tailing in Detector Two is the uncertainty of charge collection in some regions of the detector, effects of which can be exaggerated with larger crystal size (Gilmore and Hemingway, 1995).

2.3. *Detector Three*

After the failure of Detector Two to meet the peak shape CTBTO specification, further discussions with the manufacturer took place and it was agreed that they would provide ARPANSA with a detector that would meet CTBTO requirements. The manufacturers challenge was to decrease the Ge crystal volume to improve resolution while maintaining the MDA specification. From practical experience and Monte Carlo modelling, the manufacturers' constructed a low background cryostat with a crystal size of 82 mm by 49 mm, a Ge volume of 260 ml and relative efficiency of 79%. The manufacturer was unable to provide a warranty of the MDA capability of this detector as the background radiation resulting from detector location could only be assessed upon customer installation and commissioning.

After receipt, Detector Three was installed and acceptance tested *in situ* at AUL02 and was capable of achieving an MDA for ^{140}Ba of 19.4 mBq with an acquisition time of 7 days, and a FWTM/FWHM for ^{60}Co at 1332.5 keV of 1.89 for the two problematic CTBTO requirements. This detector is currently used by AUL02.

3. Selecting a detector for low-level measurements

We have shown that the specifications supplied by manufacturers are insufficient in assisting an operator to determine an appropriate detector for a low-level gamma-ray laboratory. The most important specification for such laboratories is the MDA for a particular radionuclide obtained within a given acquisition period using a particular measurement geometry.

Currie (1968) showed that

$$MDA \propto \frac{\sqrt{Background}}{Efficiency}$$

Low-level laboratories take great care to minimise the background for their measurements by situating the detector in low-background environments and using considerable shielding around their detectors. Detector manufacturers also minimise the amount of radioactive contaminants in the materials used to construct the detector cryostats and, where such contamination cannot be avoided, isolate the detector crystal from contaminated materials. As the level of radioactivity in the samples is low, the majority of

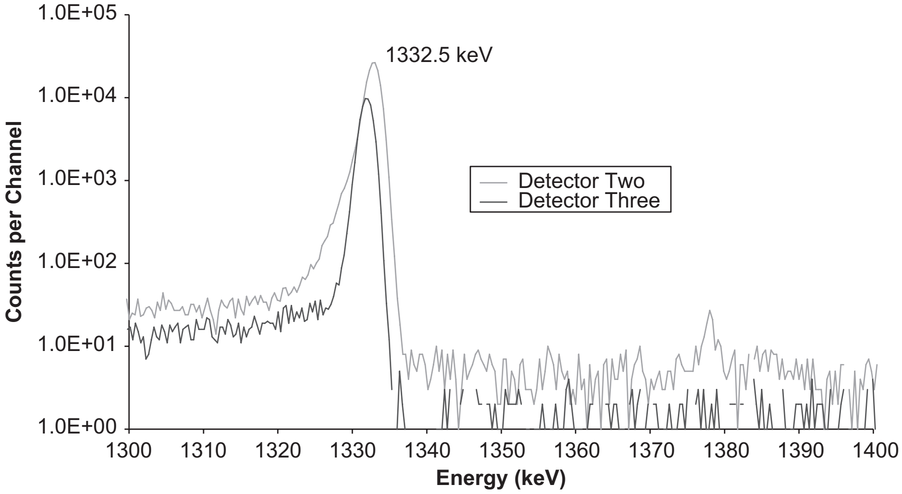

Fig. 1. ^{60}Co gamma-ray spectra comparison from Detector Two and Detector Three showing observed low-end tailing for the peak produced by Detector Two.

the background in low-level laboratories is due to cosmic rays and the background level is proportional to the volume of the detector crystal (Knoll, 2000).

Thus, for low-level gamma-ray measurements,

$$MDA \propto \frac{\sqrt{Volume}}{Efficiency}$$

In general, the MDA may be minimised by selecting a detector with the maximum efficiency for the measurement geometry and the minimum volume required to achieve this efficiency. Generally, both of these parameters are strongly influenced by the dimensions of the detector crystal.

Specifying the MDA for a particular radionuclide is not useful for the manufacturer as this cannot be determined prior to installation in the laboratory.

3.1. Effect of crystal diameter

Most low-level laboratories use measurement geometries in which the source is a right cylinder placed above the detector. The measurement efficiency for such an arrangement may be approximated to that of a disc source of same diameter as the real source placed at some distance above the detector. The detector may be assumed to be a planar detector when studying the effect of detector diameter, as this parameter dominates the geometric efficiency of the arrangement.

Knoll (2000) gives the solid angle subtended by the face of the detector from a disc source:

$$\Omega = \frac{4 \cdot \pi \cdot a}{s} \int_0^{\infty} \frac{e^{-d \cdot k} \cdot J_1(sk) \cdot J_1(ak)}{k} \, dk$$

Here a is the radius of the detector crystal, s is the radius of the source, d is the distance between the source and the detector crystal and $J_1(x)$ is a Bessel Function.

Fig. 2 shows the solid angle as a function of crystal diameter for various sized sources at a source-detector separation of 5 mm. The curves were calculated using numerical integration.

This figure shows that the solid angle and, hence, efficiency increases as the crystal diameter increases. The figure also shows that the rate of improvement rapidly decreases for diameters greater than the source diameter. For crystals with diameter larger than the source, increasing the crystal diameter has much less effect on efficiency than increases up to this point had.

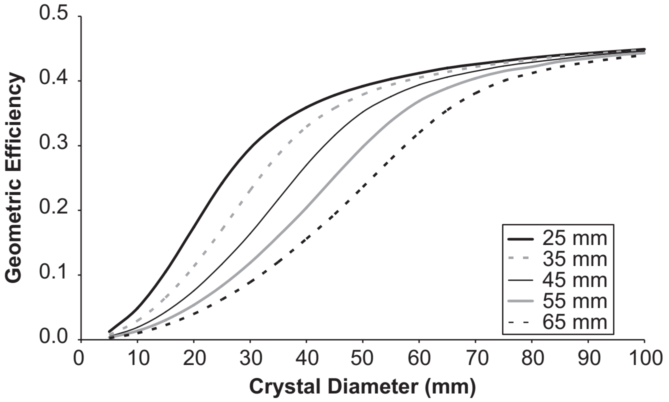

Fig. 2. Effect on geometric efficiency by increasing crystal diameter for several source diameters.

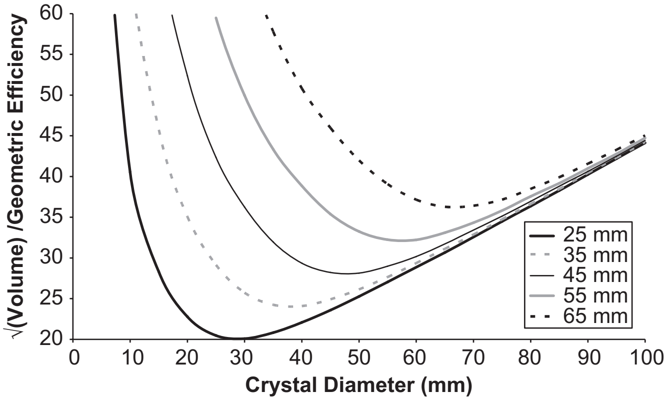

Fig. 3. Effect on MDA by increasing crystal diameter for sources of various diameters.

Assuming a crystal thickness of 50 mm, the MDA, based on the curves in Fig. 2, may be calculated.

Fig. 3 shows the trend in MDA with increasing crystal diameter for sources of various diameters. This figure clearly shows that there is a distinct minimum in MDA where the crystal diameter approximately matches that of the source.

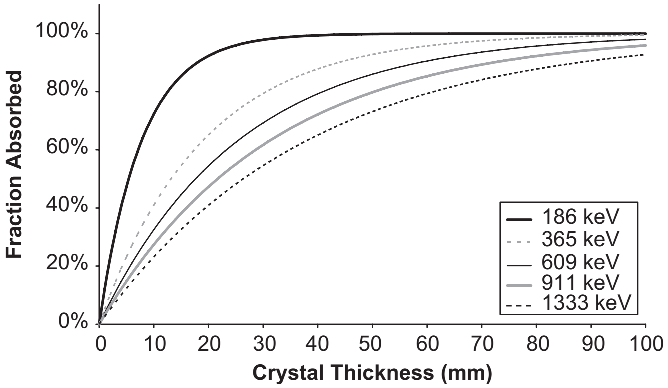

Fig. 4. Absorption curve as a function of crystal thickness for gamma-rays emitted at several energies.

3.2. *Effect of crystal length*

The measurement efficiency of a detector is the product of the geometric efficiency, ε_g, and the absorption efficiency, ε_a, at the energy of interest. The absorption efficiency is principally determined by the length of the detector crystal, t:

$$\varepsilon_a = 1 - e^{-\mu \cdot \rho \cdot t}$$

where μ is the absorption coefficient, and ρ is the density of Germanium.

Fig. 4 shows the absorption curves as a function of crystal thickness for gamma-rays emitted at several energies. This figure shows that absorption, and hence efficiency, increases with increasing crystal thickness. The figure also shows that, particularly for low-energy gamma-rays, the rate of improvement in efficiency decreases with increasing thickness.

Assuming a crystal diameter of 60 mm, the trend of MDA with crystal thickness can be calculated. Fig. 5 shows the trend of MDA with crystal thickness at several gamma-ray energies. This figure shows a clear minimum in MDA where the crystal is thick enough to provide approximately 70% absorption for the gamma-ray of interest.

3.3. *Other considerations*

By specifying a crystal diameter matched to the sample diameter and a crystal thickness providing approximately 70% absorption of the gamma-rays of interest, a purchaser can ensure that an HPGe detector has the minimum MDA for a particular radionuclide and measurement geometry. Most low-level laboratories use several different measurement geometries and are interested in several radionuclides. The actual specifications for crystal dimensions must be a compromise between the optimum dimensions for each of these geometries and gamma-ray energies.

The purchaser must also specify the type of crystal material, n- or p-type, as this influences both the efficiency at low energies and the resolution and, hence, the width of the energy-region over which the background is measured.

The construction of the detector cryostat may also influence the MDA due to the effects of radioactive contamination of the construction materials on the measurement.

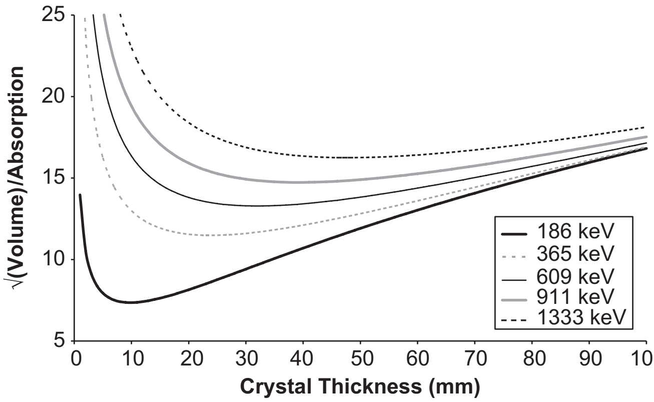

Fig. 5. Effect on MDA by increasing crystal thickness for gamma-rays emitted at several energies.

4. Conclusion

Experience has shown that finding a suitable detector for low-level gamma-ray measurements can be a costly, time consuming and frustrating exercise unless the operator has a clear set of specifications acceptable to the manufacturers. While MDA is the most important specification for low-level gamma-ray laboratories, it is not an acceptable specification for the manufacturers because it cannot be assessed prior to shipment as the MDA for a particular detector varies as the background varies with location (i.e. natural background, longitude, latitude, altitude).

We have demonstrated that, for a well-situated laboratory, increasing the amount of shielding beyond that normally used (lined, 10 cm lead shield) will not appreciably improve the MDA achievable with a particular detector. We have also shown that detectors with extraordinarily large relative efficiencies do not have correspondingly small MDAs for above-detector measurement geometries and that such detectors may have degraded peak shapes. It was our experience that the most appropriate detector for our application had the smallest volume HPGe crystal.

By specifying an HPGe crystal diameter matched to the source diameter and a crystal depth sufficient for approximately 70% absorption of the gamma-rays of interest, an operator can ensure that the detector will have the minimum MDA, for above-detector geometries, for a particular cryostat construction and detector type. Such specifications are acceptable to the detector manufacturers and provide a better assessment of the laboratory performance of the detector than the relative efficiency.

References

ANSI/IEEE, 1996. IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors. IEEE, New York.

CTBT/PTS/INF.96, 2005. Certification of Radionuclide Laboratories (Rev. 7).

Currie, L.A., 1968. Limits for qualitative detection and quantitative determination—application to radiochemistry. Analytical Chemistry 40, 586–593.

Gilmore, G., Hemingway, J., 1995. Practical Gamma-Ray Spectrometry. Wiley, Chichester.

Knoll, G.F., 2000. Radiation Detection and Measurement, third ed. Wiley, New York.