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Design and fabrication of an in situ gamma radioactivity measurement system for marine environment and its calibration with Monte Carlo method

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HIGHLIGHTS

- Simulation, designing and making of sealing enclosure for a NaI(Tl) 2″ × 2″ to use 100 m water depth.
- Various experimental tests with and without enclosure by point sources.
- Carrying out the system in lab water environment with 10 m^3 volume and repeat the same tests.
- Measurement of the efficiency for designed system by KCl volumetric liquid source and comparison with the simulation results.
- Marine volumetric efficiency calibration based on the simulation results.

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ABSTRACT

Simulation, design and fabrication of a sealing enclosure is carried out for a NaI(Tl) 2″ × 2″ detector, to be used as in situ gamma radioactivity measurement system in marine environment. Effect of sealing enclosure on performance of the system in laboratory and marine environment (distinct tank with 10 m^3 volume) were studied using point sources. The marine volumetric efficiency for radiation with 1461 keV energy (from ^{40}K) is measured with KCl volumetric liquid source diluted in distinct tank. The experimental and simulated efficiency values agreed well. Marine volumetric efficiency calibration curve is calculated for 60 keV to 1461 keV energy with Monte Carlo method. This curve indicates that efficiency increasing rapidly up to 140.5 keV but then drops exponentially.

1. Introduction

Natural and artificial radionuclides enter to the sea water by various ways (Jones, 2001). The traditional laboratory analysis method, was used for detection and measurement of radioactivity in sea water. This method is time consuming and demands special facilities and know-how for the chemical treatment of the samples, introducing various uncertainties concerning the tracer-reference data and half-life limitations (Vlastou et al., 2006). For this reason nowadays improvement of the in situ radioactive measurement system in sea water is the most important priority of the marine sciences. A new method that is taken into consideration in the recent two decades is using of detectors for the in situ measurement of radioactivity in the aquatic environment.

The in-situ measurements with detectors offer many advantages against the laboratory analysis, such as monitoring on a continuous basis, recording of propagation and progression of the pollutant, mapping of large areas of seawater as well as in the vicinity of sunken objects (Vlastou et al., 2006). Nevertheless, the need for independent recalibration procedures when the source or setup characteristics change, is a serious drawback that limits the applicability of the in situ spectrometry as an absolute method (Tyler et al., 1996). The other disadvantages of the NaI(Tl) systems are poor energy resolution and the voltage drifts of the amplification signal, which can take place during the measurement, producing overlapping peaks (Vlachos et al., 2005). The main problems of the marine radioactivity measurements concern the determination of the detection efficiency and of the minimum detectable activity (MDA). Various methods have been developed

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for the determination of the MDA or the detection limit (Currie, 1995; Nir-El and Haquin, 2001). Monte Carlo simulations have been implemented during the last decade in order to study the γ-ray detector response features and efficiency calibration for different geometries and to validate improved performances of new detectors mainly at low energies (Ghanem, 2000; Karamanis, 2003; Hurtado et al., 2004). The Monte Carlo technique was also applied for the calculation of theoretically simulated spectra at the underwater (Vojtyla, 2001; Vlachos et al., 2005; Tsabaris et al., 2005; Vlastou et al., 2006; Mertens et al., 2007), as well as for substrate characterization (Ocone et al., 2004), but those at the open sea marine efficiency calibration in 4pi geometry and studies of the MDA in the whole energy interval are still pending (Bagatelas et al., 2010; Eleftheriou et al., 2013).

Marine gamma-ray spectrometers have been used for a range of applications including the continuous measurements with buoy operation (Aakenes et al., 1995; Wedekind et al., 1999; Osvath et al., 2005; Tsabaris et al., 2005), seabed mapping (Maucec et al., 2004; Osvath and Povinec, 2001; Tsabaris et al., 2008), mineral exploration (mainly for heavy minerals and phosphorites), sediment transport studies and investigations in relation to discharged and dumped nuclear wastes and at nuclear weapon test sites. IAEA-MEL used both high-efficiency NaI(Tl) and high-resolution HPGe spectrometry to investigate contamination with anthropogenic radionuclides in a variety of marine environments. Surveys at the South Pacific nuclear test sites of Mururoa and Fangataufa have been used to guide sampling in areas of high contamination around ground zero points. In the Irish Sea offshore from the Sellafield nuclear reprocessing plant, a γ-ray survey of seabed sediment was carried out to obtain estimates of the distribution and subsequently, for the inventory of ^{137}Cs in the investigated area (Jones, 2001).

In-situ radioactivity measurements in the marine environment using the γ-ray spectroscopy method are mainly performed using two detection systems: HPGe and NaI(Tl), see e.g. (Povinec et al., 1996; Osvath et al., 1999; Osvath and Povinec, 2001; Jones, 2001). The HPGe detectors have been used for quite a few applications in the marine environment during the last years, but they could only operate for a limited period of time (due to the limited holding time of cryostat-dewar) or in regions where power is supplied. The systems most commonly used for γ-radiation spectroscopy in seawater, are based on NaI(Tl) detectors, which are characterized by high-detection efficiency and low cost. This detection system is applied for the measurement at different depths of up to several thousand meters, either wirelessly or by using wire. Tsabaris and his colleagues have been done several experiments with system known as KATERINA in Hellenic Centre for Marine Research (HCMR). In this experiments natural radionuclides were analysied in water of Evoikos Gulf and Aegean Sea (Tsabaris et al., 2008). Patiris and his colleagues used such a system to detect the possibility of earthquake occurrence near the fault (Tsabaris et al., 2011).

Due to the importance of marine environment monitoring in Iran and to contribute to help decision makers at the national level to manage nuclear accidents resulting from Bushehr nuclear power plants in Persian Gulf, Sharif University of Technology carries out designing such a system.

2. Simulation, design and fabrication of sealing enclosure

Due to high sensitivity of crystal to moisture, one of the most important steps to use detectors in the aquatic environment is design and fabrication of convenient and reliable sealing enclosure. Polyethylene was suitable material that selected for making waterproof shield for detection system.

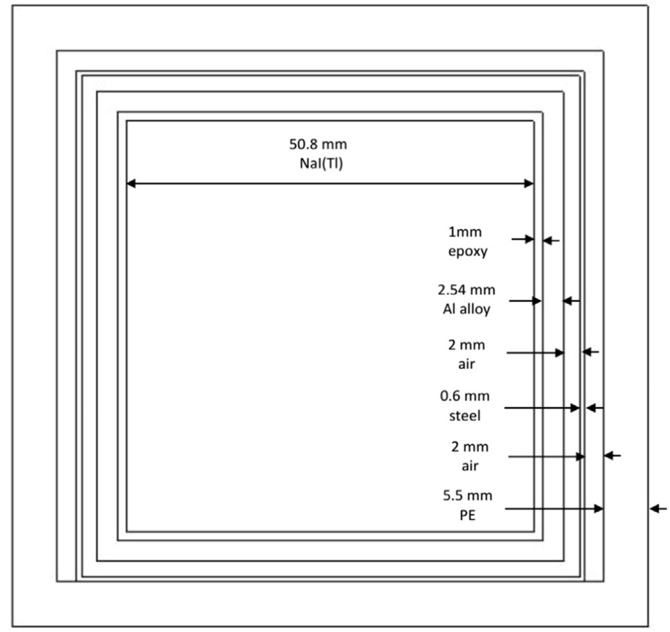

Fig. 1. The different layers of the detector together with enclosure.

The required thickness of Polyethylene for use at 100 m water depth was calculated by ANSYS mechanical analysis software. First, five different thicknesses of enclosure were designed in SolidWorks software and were import to ANSYS environment. Pressure analysis was done on each thickness and maximum tolerable pressure was calculated. Pressure obtained using Linear fit on results according to the thickness equation. Minimum required thickness of enclosure for use at 100 m water depth is 5.38 mm using this equation.

Enclosure was made with 5.5 mm thickness applying a confidence coefficient to calculated thickness. O-Ring and silicone wax were used to achieve reliable sealing mechanism. The different layers of the detector and enclosure is shown in Fig. 1.

3. Experimental results

3.1. Energy and FWHM calibration

The detection system was calibrated in the laboratory and marine environment with point sources. FWHM were calculated with Gaussian fit on twelve photopeaks of five point sources energy spectrum (^{137}Cs, ^{241}Am, ^{22}Na, ^{152}Eu and ^{60}Co). Measurements were repeated while protective cover removed. least squares fit applied to results by Mathematica software and Eq. (1).

$$FWHM = a + b\sqrt{E + cE^2} \tag{1}$$

a, b and c are in MeV, MeV$^{1/2}$ and MeV^{-1}, respectively. These parameters are unique for each detector and are used in the MCNPX code simulation (Pelowitz, 2008; Hakimabad et al., 2007). The values of these parameters are obtained as follows:

$a = -0.010396$ MeV
$b = 0.077662$ MeV$^{1/2}$
$c = -0.004347$ MeV^{-1}

The energy resolution of the system was not significance change using PE as a material of the protective cover.