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Simulated minimum detectable activity concentration (MDAC) for a real-time UAV airborne radioactivity monitoring system with HPGe and $LaBr_3$ detectors

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HIGHLIGHTS

- A real-time UAV airborne radioactivity monitoring system (NH-UAV) was developed.
- The efficiency calculations and MDAC values are given.
- NH-UAV is able to monitor major nuclear accidents, such as the Fukushima accident.
- The source term size can influence the detection sensitivity of the system.
- The HPGe detector possesses measurement thresholds on activity concentration.

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ABSTRACT

An automatic real-time UAV airborne radioactivity monitoring system with high-purity germanium (HPGe) and lanthanum bromide ($LaBr_3$) detectors (NH-UAV) was developed to precisely obtain small-scope nuclide information in major nuclear accidents. The specific minimum detectable activity concentration (MDAC) calculation method for NH-UAV in the atmospheric environment was deduced in this study for a priori evaluation and quantification of the suitability of NH-UAV in the Fukushima nuclear accident, where the MDAC values of this new equipment were calculated based on Monte Carlo simulation. The effects of radioactive source term size and activity concentration on the MDAC values were analyzed to assess the detection performance of NH-UAV in more realistic environments. Finally, the MDAC values were calculated at different shielding thicknesses of the HPGe detector to improve the detection capabilities of the HPGe detector, and the relationship between the MDAC and the acquisition time of the system was deduced. The MDAC calculation method and data results in this study may be used as a reference for in-situ radioactivity measurement of NH-UAV.

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1. Introduction

The unmanned aerial vehicle (UAV) aviation radiation monitoring system has numerous advantages, such as quick response, unlimited traffic conditions, and substantial reductions in radiation hazards for operators. Many research studies on UAV aviation radiation monitoring system have been conducted in recent years (Kurvinen et al., 2005; Pöllänen et al., 2009; Peräjärvi et al., 2008; Castelluccio et al., 2012; Airborne pods seek to tra; Lee et al., 2009; MacFarlane et al., 2014; Sanada and Torii, 2015). Among these studies, some UAVs are equipped with sampling systems. For example, the Finnish group has designed an aerial radioactivity monitoring system with a detector and a sampler (Kurvinen et al., 2005; Pöllänen et al., 2009; Peräjärvi et al., 2008). The Italian Institute of Health has developed an aerial platform equipped with a compact air sampling line and a complex of detectors for real time measurements (Castelluccio et al., 2012). Detection systems equipped with sampler are relatively complicated, and it is more difficult to determine the detection performance, such as MDAC.

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Besides, radioactive monitoring in major nuclear accidents is a demanding task because of various radionuclides and complex source terms. In particular, radioactivity in the distance superimposes on the detection spectrum, leading to considerable deviation in detection results. Thus, further research is necessary.

In this study, a UAV airborne radioactivity monitoring equipment based on a double detector system called "NH-UAV" was developed in Interdisciplinary InnoCentre for Nuclear Technology (IINT) in Nanjing University of Aeronautics and Astronautics (NUAA) to realize air radiation monitoring under major nuclear accidents. In the developed equipment, high-purity germanium (HPGe) and lanthanum bromide ($LaBr_3$) detectors could back up, supply, and verify the detection data of the other. Thus, the reliability of detection results was improved.

Minimum detectable activity concentration (MDAC) denotes the minimum amount of activity that a detection system can detect reliably (with a confidence limit of 95%) (Currie, 1968). The applicability of the newly developed monitoring equipment in a radioactive environment should be predicted. Meanwhile, for radionuclides, being detected by detectors is the prerequisite to be analyzed and processed. Thus, calculating the MDAC value of the new NH-UAV device is essential. However, in contrast to conventional detection on land, the radioactivity measurement of NH-UAV in air under major nuclear accidents is a type of volumetric source detection and then has the different definition and calculation method on the background and detection efficiency, for the background of the HPGe detector is volumetric source and the detection efficiency of the $LaBr_3$ detector is volumetric efficiency (Zhang et al., 2015). Therefore, the general MDAC calculation method is not completely suitable for NH-UAV.

The MDAC of this particular device in the Fukushima nuclear accident was calculated in this study based on the Monte Carlo (MC) method to evaluate the detection performance of NH-UAV in major accidents. Given the uncertainty of radiation leakage, the source term size and activity concentration were important factors that affected the detection capability of the detection system; hence, the MDAC of NH-UAV was studied on these two sides. Moreover, the measurement capabilities of this monitoring system were discussed with different acquisition time and shielding thicknesses of the HPGe detector.

2. Materials and methods

2.1. Description of the double detector system

The double detector system is the core unit of NH-UAV, comprising an HPGe semiconductor detector and a $LaBr_3$ scintillator detector. As shown in Fig. 1, B represents the $LaBr_3$ scintillator detector, whose probe is directly exposed to air, monitoring a wide range of radioactivity, including radioactive gases and radioactive aerosols. However, considerable deviations occur because of the radioactivity in the distance superimposes on the detection spectrum. C denotes the HPGe detector with wolfram collimator (1 cm), whose probe has a filter at the front, detecting the radioactivity adsorbed on the filter to precisely obtain small-scope nuclide information of radioactive aerosols. Because of the shielding in the device, the radioactive gases cannot be detected.

To obtain precise nuclide information, the detection data of the HPGe and $LaBr_3$ detectors should be corrected. A certain algorithm is utilized to validate, supply, and optimize the detection data to achieve the nuclide identification and activity concentrations of radioactive nuclides within a small scope (Cao et al., 2015).

In general, the process of radioactivity measurement of the HPGe detector consists of three steps. Firstly, the air flow enters from the air inlet (H) and goes out through the air exhaust (F), and then the radioactive aerosols are deposited on the filter membrane (G). Secondly, the filter membrane (with the radioactive aerosols) is transmitted by the motorized roller (E) to the HPGe probe (C) to be detected. Finally, the measured data is first framed with data transmission and then transmitted to the PC on the ground.

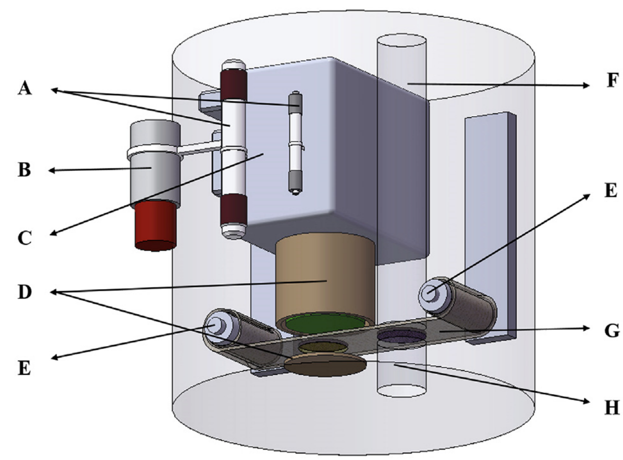

Fig. 1. General scheme of the double detector system: A: GM counters, B: $LaBr_3$ scintillator detector, C: HPGe semiconductor detector, D: collimator of HPGe detector, E: motorized roller, F: air exhaust, G: filter membrane, H: air inlet.

The HPGe gamma spectrometer (model trans-SPEC-DX-100T) is an ORTEC GEM Series P-type crystal (65 mm in diameter and 50 mm in length), its nominal relative efficiency is 40% and the FWHM at 1332 keV is approximately 2.3 keV. The $LaBr_3$ detector (Saint-Gobain) is a cylindrical crystal (38.1 mm × 38.1 mm) with 12% relative efficiency and the FWHM at 662 keV is approximately 29 keV.

2.2. Efficiency of the double detector system

Determining the efficiency of the double detector system is essential to NH-UAV for radioactivity measurement in the air. The detection efficiency of NH-UAV is composed of two parts.

The efficiency of the HPGe detector can be converted to the volumetric detection efficiency ε_H [(Bq m^{-3})$^{-1}$]:

$$\varepsilon_H = \varepsilon \cdot V_H \cdot P. \tag{1}$$

The volumetric efficiency ε_L [(Bq m^{-3})$^{-1}$] of the $LaBr_3$ detector is:

$$\varepsilon_L = \varepsilon \cdot V_L, \tag{2}$$

where ε is the photopeak efficiency at a specific energy, V_H (m^3) is the air volume through the filter during the sampling time, P is the filter adsorption efficiency (50%), and V_L (m^3) is the air volume for each γ-ray.

Then, the activity concentration A_X is expressed as follows (Khan et al., 2008):

$$A_X = \frac{N}{\varepsilon_X \cdot T_L \cdot I_\gamma}, \tag{3}$$

where A_X can be either the activity concentration A_H (Bq m^{-3}) of radioactive aerosols detected by the HPGe detector in a small area or the activity concentration A_L (Bq m^{-3}) of radioactive aerosols and radioactive gases detected by the $LaBr_3$ detector in a broad region; N is the counts under the peak; T_L is the acquisition time (10 s); I_γ is the emission probability of the γ-ray; and ε_X can be either the

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