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**TECHNICAL MATERIAL**

# Characteristics of commercially available CdZnTe detector as gamma-ray spectrometer under severe nuclear accident

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Around sites of severe nuclear accidents such as the Fukushima Daiichi Nuclear Power Plant, *in-situ* measurements of gamma-ray energy spectra and identifying radionuclides are important for radiological protection from both external and internal dose uptake. For such applications, a commercially available CdZnTe spectrometer (Kromek GR-1) was characterized within the calibration fields at the Facility of Radiation Standards (FRS) of Japan Atomic Energy Agency (JAEA). The angular dependence of detection efficiency was studied using the photoelectric peak counts of the $^{137}$Cs and $^{226}$Ra gamma-rays. The efficiency was kept within 15 % degradation in the range from -135˚ to 135˚, which covers 85% of all incident angles, for gamma-rays above 242 keV. The usable dose ranges for peak-energy and energy spectrum measurements were investigated by evaluating the photoelectric peak channel and comparing the air kerma rates calculated from the measured gamma-ray spectra to the reference ones determined by the ionization chamber. The spectrometer could correctly measure the gamma-ray spectra and the photoelectric peak of the $^{137}$Cs gamma-ray below 200 μGy·h$^{-1}$ and 3 mGy·h$^{-1}$, respectively.

***Keywords: CdZnTe detector; gamma-ray spectrum; calibration field; angular dependency; air kerma; PHITS code; EGS code***

## 1. Introduction

Various radionuclides are widely dispersed around sites of severe nuclear accidents such as the Fukushima Daiichi Nuclear Power Plant, which increases the dose rate [1]. Identifying dispersed radionuclides with gamma-ray spectroscopy is significant for radiological protection from internal exposure. Furthermore, the gamma-ray energy spectrum in the environment is useful, not only for planning protection measures against external exposure but also for evaluating the effective dose as well as the ambient dose equivalent from air kerma rate provided by the radiation monitoring posts around nuclear facilities. It is for the above reasons that *in-situ* measurements of gamma-ray energy spectra are necessary [2].

A commercially available CdZnTe gamma-ray spectrometer (Kromek GR-1) was employed for the *in-situ* measurements of gamma-ray energy spectra. Its performance test was carried out in the gamma-ray calibration fields of FRS/JAEA [3]. The spectrometer consists of a CdZnTe semiconductor with a dimension of 10 mm × 10 mm × 10 mm, a preamplifier, a shaping amplifier, a high voltage power supply and a pulse height digitizer [4]. It sends the digitized pulse heights of the detected gamma-ray signals to a personal computer via universal serial bus (USB), which simultaneously powers the spectrometer.

Because gamma-rays radiate omnidirectionally in the environment, the angular dependence of the detection efficiency must be known. Kurosawa reported that there were no change among the pulse height spectra measured at the angles of 0°, 45° and 90° for the $^{137}$Cs gamma-rays [2]. As the more detailed angular dependence for lower energy gamma-rays were necessary, the detailed dependence was studied using gamma-rays emitted by not only $^{137}$Cs but also $^{226}$Ra. The correct energy evaluation of the emitted gamma-rays is necessary to identify the radionuclides in the environment. To accomplish this, the channel shift of the photoelectric peak in the pulse height spectrum was measured by varying the irradiated dose rate in the $^{137}$Cs and $^{60}$Co gamma-ray calibration fields of the FRS/JAEA. Using the channel shift, the usable dose range for gamma-ray peak energy measurement was evaluated. Furthermore, the dose range, in which the gamma-ray energy spectrum can be correctly measured, was investigated in the gamma-ray calibration fields of the FRS/JAEA. This paper describes the angular dependence and usable air kerma rate range of the CdZnTe spectrometer as an *in-situ* gamma-ray spectrometer.

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## 2. Experimental procedures

### *2.1. Angular dependence*

The angular dependence of the detection efficiency of the spectrometer was studied using the counts of the photoelectric peaks observed in the pulse height spectrum for the gamma-rays from a 1.11 GBq $^{137}$Cs source and a 222 MBq $^{226}$Ra source. **Figure 1** shows the measurement setup of the angular dependence. The distances from the sources to the spectrometer and the air kerma rates at the spectrometer were 1.16 m and 48.9 μGy·h$^{-1}$ for the $^{137}$Cs source, and 1.01 m and 42.0 μGy·h$^{-1}$ for the $^{226}$Ra source, respectively. The spectrometer was fixed on a horizontal rotary table with a stepper motor (IAI ROBO ROTARY RCP2-RTCL). The angle of the gamma-ray incidence to the spectrometer was remotely varied from -180° to 180° by controlling the table with a personal computer.

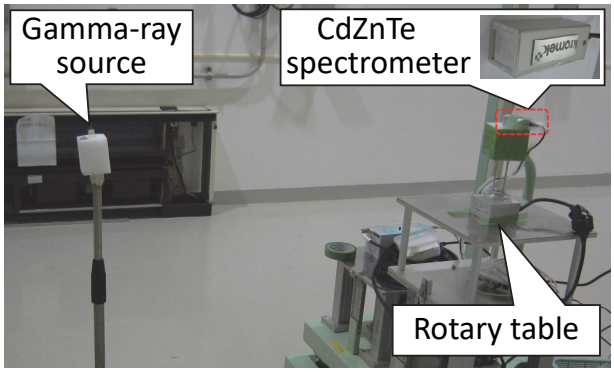


Figure 1. Experimental setup for the angular dependence measurement using a $^{137}$Cs source and a $^{226}$Ra source.

### *2.2. Usable dose ranges*

*2.2.1 Gamma-ray peak energy*

The upper dose limits to measure the gamma-ray peak energies from the $^{137}$Cs and $^{60}$Co sources were studied for air kerma rates ranging between 0.003 mGy·h$^{-1}$ and 5 mGy·h$^{-1}$ by using the gamma-ray calibration fields of the FRS/JAEA. The spectrometer was placed at the calibration points where the reference air kerma rates were determined using our reference ionization chamber which was calibrated for the $^{137}$Cs gamma-rays at the National Metrology Institute of Japan (NMIJ/AIST). The pulse height spectra were remotely obtained by the personal computer in the control room using the spectrum acquisition software K-Spect, provided by Kromek Ltd. The photoelectric peak channels were calculated from the pulse height spectra using the K-Spect software as well.

*2.2.2 Gamma-ray energy spectrum*

The usable dose range of the spectrometer was evaluated by comparing the measured air kerma rates to the reference ones. The measured air kerma rates were derived using the energy spectra, which were obtained by unfolding the measured pulse height spectra, and the fluence to air kerma conversion coefficient, found in ICRP publication 74[5]. The pulse height spectra for the gamma-ray energy spectrum measurements were obtained as described in 2.1.1.

## 3. Spectrum unfolding

An unfolding procedure is necessary to derive the gamma-ray energy spectrum from the pulse height spectrum acquired by the spectrometer because the acquired spectrum is different from the true gamma-ray spectrum. This is primarily due to the Compton continuum. The unfolding was performed with the MAXED code from the UMG package[6]. The MAXED code uses an algorithm applying the maximum entropy principle to the unfolding problem.

Response functions of the spectrometer used in the unfolding procedure were calculated using the EGS mode in the PHITS 2.88 code[7,8]. The pulse height spectra were calculated for incident photons with energies from 40 keV to 3 MeV, at 5 keV intervals. The calculated response functions of the detector were broadened using a Gaussian distribution that had an energy resolution experimentally measured as a function of gamma-ray energy. The standard deviation $\sigma$ of the Gaussian distribution was given by the following equation

$$\sigma = a + b \times \sqrt{E + c \times E^2} \tag{1}$$

where $E$ is the pulse height in MeV and $a$, $b$ and $c$ are parameters fitted to the experimental energy resolution[9]. The resolution was determined from the measured pulse height spectra for several gamma-ray point sources as shown in **Figure 2**. As the measured resolution varied markedly due to the each measurement statistics, the parameters were selected not to surpass the measured resolution to have a successful unfolding.

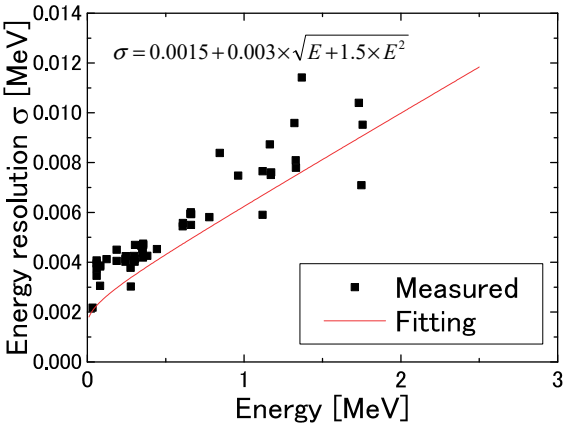


Figure 2. Energy resolution curve of the spectrometer using the peaks of $^{241}$Am, $^{133}$Ba, $^{226}$Ra, $^{137}$Cs and $^{60}$Co gamma-rays.

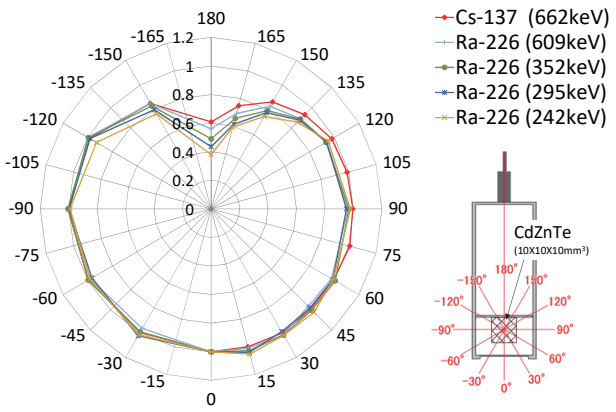


Figure 3. Angular dependence of the photoelectric peak counts using the $^{137}$Cs and $^{226}$Ra sources.

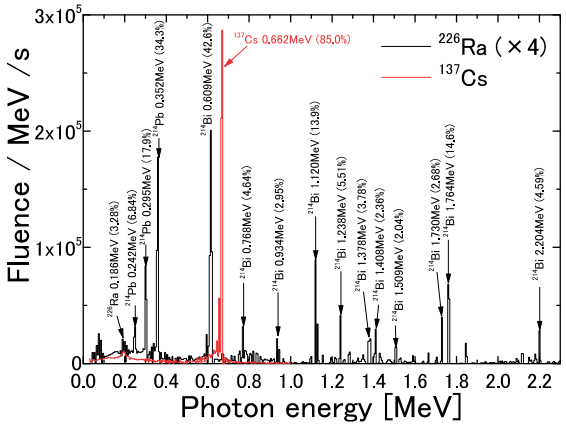


Figure 4. Gamma-ray energy spectra unfolded with the MAXED code in the $^{137}$Cs and $^{226}$Ra gamma-ray calibration fields at FRS/JAEA. The reference air kerma rates were 48.9 μGy·h$^{-1}$ and 42.0μGy·h$^{-1}$ for the 1.11 GBq $^{137}$Cs and the 222 MBq $^{226}$Ra sources, respectively.

## 4. Results and discussions

### *4.1. Angular dependence*

**Figure 3** shows the measured angular dependence of the detection efficiency for the gamma rays from the $^{137}$Cs and $^{226}$Ra sources. They are normalized to the efficiency for gamma-rays that entered at 0°. It was found that the efficiency was kept within 15% degradation, in the range from -135° to +135°, for gamma-rays above 242 keV. This result corresponds to the previous research reported by Kurosawa [2]. The angular range covers 85% of all incident angle and the angular dependence satisfy the requirement specified in the Japanese Industrial Standard [10]; the efficiency should kept within 25% in the range from -90° to 90°. Therefore, the spectrometer is applicable to *in-situ* measurements of gamma-ray spectra in an environment where the gamma-rays are omnidirectional.

### *4.2. Unfolding test using gamma-ray sources*

In order to verify the unfolding procedure, the pulse height spectra of the gamma-rays from the 1.11 GBq $^{137}$Cs and the 222 MBq $^{226}$Ra sources were measured and their gamma-ray energy spectra were obtained by unfolding the pulse height spectra as shown in **Figure 4**. Then, the air kerma rates were calculated from the unfolded spectra by using the conversion coefficients for air kerma per unit fluence found in ICRP publication 74 [5]. They were compared to the reference air kerma rates as shown in **Table 1**. The reference and measured air kerma rates were consistent within 3%; hence, the gamma-ray spectra were correctly unfolded.

Table 1. The reference and measured air kerma rates in the $^{137}$Cs and $^{226}$Ra gamma-ray calibration fields at FRS/JAEA.

| Source | Air kerma rate [μGy·h$^{-1}$] Reference (R) | Measured (M) | M/R ratio |
|---|---|---|---|
| $^{137}$Cs | 48.9 | 48.8 | 0.999 |
| $^{226}$Ra | 42.0 | 41.0 | 0.974 |

### *4.3. Usable dose ranges*

#### *4.3.1 Gamma-ray peak energy*

**Figure 5** shows the relationship between the reference air kerma rate and the gamma-ray peak channel measured in the $^{137}$Cs and $^{60}$Co gamma-ray calibration fields. The peak channel decreased markedly at 4 mGy·h$^{-1}$ and 6 mGy·h$^{-1}$ for the $^{137}$Cs and $^{60}$Co gamma-rays, respectively. These results are consistent with the results reported by Suzuki et al.; in their report, the peak shift was observed at 2.5 mGy·h$^{-1}$ and the peak could not be identified at 5 mGy·h$^{-1}$ [11].

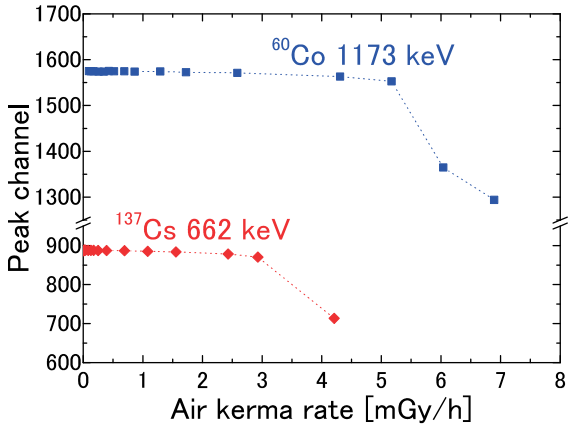


Figure 5. Photoelectric peak channels of the $^{137}$Cs and $^{60}$Co gamma-rays observed in the pulse height spectra measured by the spectrometer.

#### *4.3.2 Gamma-ray energy spectrum*

**Figure 6** shows the relationship between the reference air kerma rate and the M/R ratio, which is calculated by dividing the measured air kerma rate by the reference air kerma rate. It was found that the gamma-ray energy spectrum could be correctly measured below 200 μGy·h$^{-1}$ with the spectrometer in both $^{137}$Cs and $^{60}$Co gamma-ray fields. **Figure 7** shows

the M/R ratio as a function of the count rate of the spectrometer. Though there are two points above 8,000$s^{-1}$ which deviate the data trend, the M/R ratio holistically drops around 7,000 $s^{-1}$; this means that the upper limit of the usable dose range was restricted by the count rate of the spectrometer rather than the air kerma rate.

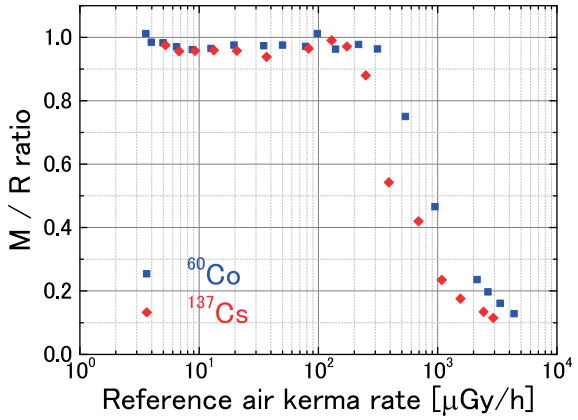


Figure 6. Ratio of the measured air kerma rate to the reference one as a function of the reference air kerma rate in the $^{137}$Cs and $^{60}$Co gamma-ray calibration fields at FRS/JAEA.

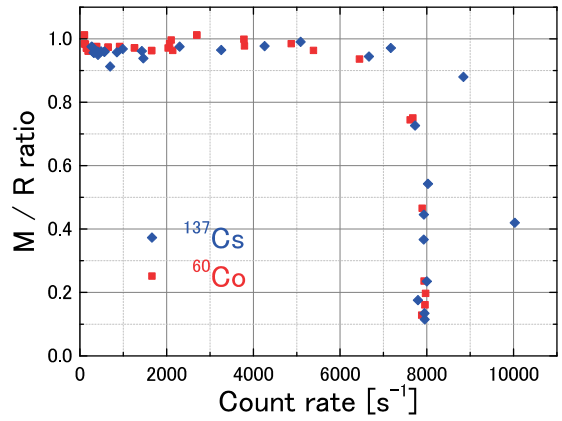


Figure 7. Ratio of the measured to the reference air kerma rate as a function of the count rate of the spectrometer.

## 5. Conclusion

A performance test of a commercially available CdZnTe gamma-ray spectrometer was carried out in the gamma-ray calibration fields of the FRS/JAEA. Angular dependency tests determined that the detection efficiency was found to be kept within 15% degradation, in the range from -135° to +135°, for the gamma-rays above 242 keV. This angular range covers 85% of all incident angles and is sufficiently wide to measure the gamma-ray energy spectra in an environment where omnidirectional radiation exists.

The spectrometer was able to measure gamma-ray photoelectric peaks below 3 mGy·$h^{-1}$ in the $^{137}$ Cs gamma-ray calibration field; this means that the radionuclides dispersed in the environment can be identified with the spectrometer below a few milligray per hour.

The gamma-ray energy spectra were obtained by unfolding the measured pulse height spectra in the $^{137}$Cs, $^{226}$Ra and $^{60}$Co calibration fields up to 5 mGy·$h^{-1}$. The air kerma rates calculated from the unfolded spectra and the reference air kerma rates were consistent below 200 μGy·$h^{-1}$ and at 7,000 $s^{-1}$; this means that the gamma-ray energy spectra were correctly unfolded using the response function and the MAXED code within this dose range. Because the gamma-ray spectra are essential information for precise dose uptake estimations, the developed method using this spectrometer is worthwhile to plan radiological protection measures against severe nuclear accidents. Moreover, the effective dose or ambient dose equivalent rate in the environment can be evaluated from the air kerma rate provided by a radiation monitoring post and a conversion factor which can be precisely determined by measuring the gamma-ray energy spectrum with the developed method and using the conversion coefficients specified in the ICRP publication 74 report in the accident[5].

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