Identification of gamma radionuclides using scintillator-based fiber-optic radiation sensor

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1. Introduction

Gamma-ray emitted from radionuclide has specific energies. In gamma-ray spectroscopy, gamma-spectra induced by interactions of gamma-ray with materials can identify and quantify the gamma-emitting radionuclides. Generally, the combination of an inorganic scintillator, a photomultiplier tube (PMT), and a multi-channel analyzer (MCA) has been widely used for gamma spectroscopy. But many electronics attached to the detector reduce the mobility and short-range measurements can increase the radiation exposure to the operator. In a previous study, we developed a fiber-optic radiation sensor (FORS) that can measure gamma spectra remotely [1]. Although FORS has many advantages, such as good flexibility, small sensing volume, remote sensing, and immunity to electromagnetic interference, it has difficulties to be used for radionuclide identification due to low energy resolution. Sensing probes composed of a small volume of scintillator cannot fully interact with incident gamma-ray, and the light pulse broadens due to intermodal dispersion of the plastic optical fiber.

In this study, a FORS is fabricated with a small-volume scintillator to identify and quantify the gamma-radionuclides without measuring gamma-spectra. The plastic optical fiber-coupled scintillator detector is composed of four different kinds of scintillator and four photon counting modules to measure the light-outputs from each scintillator simultaneously. With the ratio of light-output, the radionuclide can be identified, and the radionuclide can be quantified with light-output.

2. Methods and Results

2.1 Scintillator assembly

The sensing part has been grouped into two inorganic scintillators and two organic scintillators based on their physical properties. When gamma-ray interacts with the scintillator detector, the electron is produced through three major interactions, a Compton scattering, photoelectric absorption, and pair production [2]. The probability of interactions is affected by both the atomic number of the scintillator, and the energy of incident gamma-ray. Due to differences in constituents and quantum efficiency, these two groups have different light-output to the same gamma-ray. In earlier studies of the relationship between light-output and deposited energy, a mathematical model is derived about the theoretical light-output of the scintillator [3,4]. The light-output of inorganic scintillator is derived as equation (1),

$$L = \frac{E_d}{2.5E_g}\,\eta = \frac{E_d}{2.5E_g}\,\beta SQ \qquad (1)$$

where L is light-output of scintillator, E_d is deposited energy, E_g is bandgap energy of scintillator, η is overall quantum efficiency, β is conversion efficiency, S is transfer efficiency, and Q is luminescence quantum efficiency. In the same manner, the light-out of organic scintillator can be derived as equation (2),

$$L = \frac{E_d}{h\nu}\,\eta \qquad (2)$$

where h is Planck constant and ν is photon's frequency. The overall quantum efficiency of organic scintillator is around 2~4 % [5]. Based on the mathematical model, the scintillator emitted visible photons proportional to deposited energy in the scintillator.

Based on physical properties, we selected two different kinds of inorganic scintillators such as cerium-doped gadolinium aluminum gallium garnet (GAGG:Ce, Epic-Crystal), cerium-doped yttrium orthosilicate (YSO:Ce, Epic-Crystal), and two organic scintillators such as BCF-12, BCF-20 (Saint-Gobain). Table I lists the major physical properties of selected scintillators.

Table I: Physical properties of scintillators

Scintillator	Density [g/cm^3]	Light-yield [Photons/MeV]	Decay time [ns]	Emission wavelength [nm]	Hygroscopic
GAGG:Ce	6.6	42,000	90	530	No
YSO:Ce	4.5	10,000	50 – 70	420	No
BCF-12	1.05	~ 8000	3.2	435	No
BCF-20	1.05	~ 8000	2.7	492	No

To enhance light collection efficiency, reflector paint (BC-620, Saint-Gobain) and aluminum tape were applied to the scintillator surface. The scintillator holder was manufactured with brass which has a density of 8.73 g/cm^3. And a 0.5 m-long plastic optical fiber (CK-80, Mitsubishi Rayon Co., Ltd) with a diameter of 2 mm was attached to the end of each scintillator. The total size of scintillator assembly was a thick of 19 mm and a width of 19 mm and a height of 26 mm. Figure 1 shows a manufactured scintillator assembly.

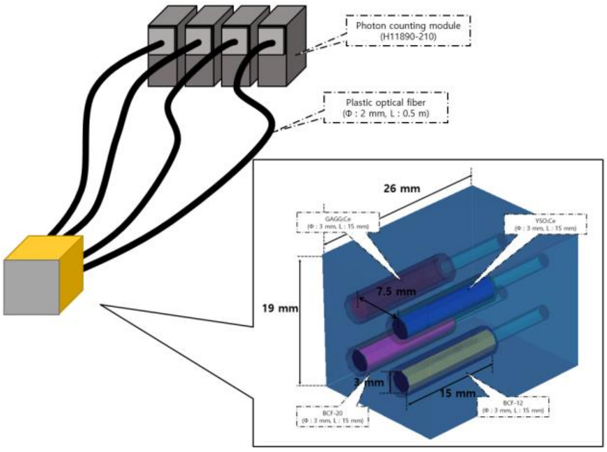

Fig. 1. Manufacture scintillator assembly

2.2 Experimental setup

Four kinds of radioactive sources such as ^{137}Cs, ^{60}Co ^{137}Cs and ^{60}Co were used to measure different energies of gamma radiation. The energies and activities of used check sources are listed in Table II.

Table II: Energies and activities of the gamma-ray sources

	Energy [MeV]	Activity [μCi]
^{137}Cs	0.662	39.93, 8.67, 4.00
^{60}Co	1.173, 1.332	37.47, 0.56, 0.20
^{133}Ba	0.081, 0.356	9.67
^{57}Co	0.014, 0.122, 0.136	6.28

The distance between source and a FORS is fixed 2.77 mm, considering the geometry of type D disk check sources manufactured by Eckert & Ziegler. To measure light-outputs from each scintillator simultaneously, four photon counting modules (H11890-210, Hamamatsu photonics) were used. And gamma survey meter (RadEye-G-10, Thermo Scientific) was also used as a reference detector to measure equivalent dose rates. Figure 2 shows the experimental setup to measure light-outputs of scintillator with photon counting modules, and Figure 3 shows the experimental setup to measure dose rate with a survey meter.

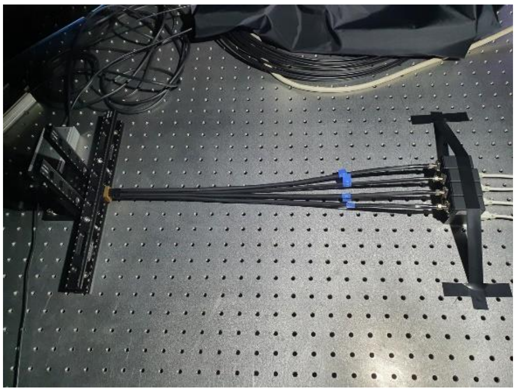

Fig. 2. Experimental setup to measure light-output with photon counting module.

Fig. 3. Experimental setup to measure dose-rate with a survey meter.

2.3 Results

Figure 4 shows a plot of the count rate of each scintillator as a function of dose rate (μSv/h) at three different ^{137}Cs sources.

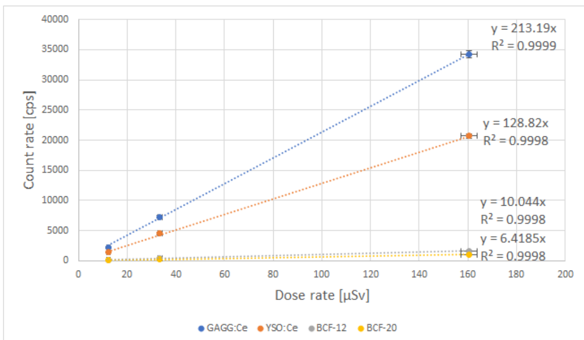

Fig. 4. Count rate (cps) as a function of dose rate (μSv/h) with ^{137}Cs

Figure 5 shows a plot of the count rate of each scintillator as a function of dose rate (μSv/h) at three different ^{60}Co sources.

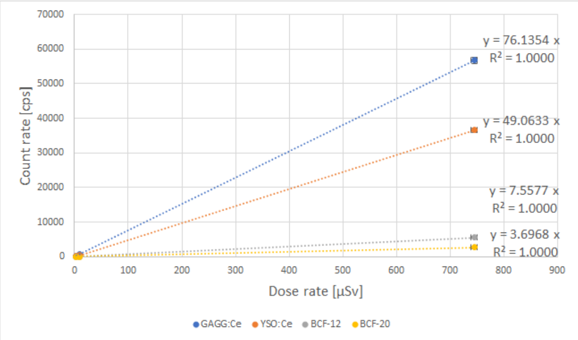

Fig. 5. Count rate (cps) as a function of dose rate (μSv/h) with ^{60}Co

It can be noticed that with the increase of dose rate, the count rate linearly increases at both ^{137}Cs and ^{60}Co. With a slope of each graph, the dose conversion factor can be derived in each scintillator. In both cases, GAGG:Ce has the largest slope between the four scintillators due to its high light-yield and density.

Figure 6 shows a plot of the ratio of light-output in the inorganic scintillator and the organic scintillator to the energy of incident gamma-ray. The vertical axis shows the ratios of light-outputs, and the horizontal axis represents the arithmetic mean of energies of emitted gamma-ray from radionuclide. The arithmetic means of energy emitted from gamma radionuclide are 1.25 MeV, 0.6617 MeV, 0.267 MeV and 0.114 MeV, for ^{60}Co, ^{137}Cs, ^{133}Ba and ^{57}Co, respectively. The light-output of the scintillator is affected by both energy and intensity of incident gamma-ray. By dividing the light-output of two scintillators, the intensity of incident gamma-ray canceled out. It can be noticed that with the increase of energy of incident gamma-ray, the ratio of light-output decreases. Although BCF-20 has the same light-yield and density as BCF-12, the measured photon is smaller than BCF-12 due to discordance emission spectrum with a sensitivity of photon counting module. As a result, the combination of GAGG:Ce which has the highest light-yield and BCF-20 has a sensitive ratio of light-output to incident energy.

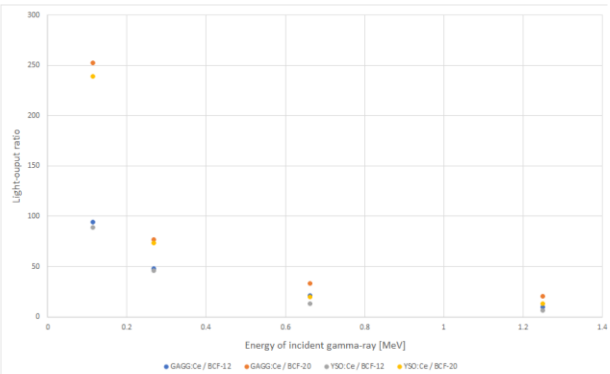

Fig. 6. Ratio of light-output as a function of energy of incident gamma-ray

3. Conclusions

In this study, the FORS is fabricated with four different kinds of scintillators. Due to different constituents, each scintillator emitted a different number of visible photons at the same energy of incident gamma-ray. With the ratios of light-output of the scintillators, four radionuclides such as ^{57}Co, ^{133}Ba, ^{137}Cs, and ^{60}Co can be identified. Dose conversion factors are also derived with dose rate and count rate to quantify the gamma-rays from different kinds of radionuclides.

Further studies will be carried out to identify radionuclides with various kinds of scintillators using light-output ratios.

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