Optimizing Scintillator Thickness and GEB Parameters for Beta Spectroscopy in Plastic Scintillation Detectors

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1. Introduction

One of the radiation monitoring systems in nuclear power plants, the condenser air removal system continuously evaluates the amount of fission products leaked from the primary to the secondary system by measuring the β-ray emitted from inert gases. During a leakage event, the major β-emitting nuclides in inert gases include ^{133}Xe, ^{85}Kr, ^{85m}Kr, ^{135}Xe, ^{137}Xe, ^{41}Ar, ^{88}Kr, and ^{87}Kr. To evaluate the leakage rate, it is essential to determine the specific radioactivity concentration (μCi/cc) of β-emitting nuclides and the detection efficiency (cpm/μCi/cc). While the radioactivity concentration of β-emitting nuclides can be readily obtained through sampling and gamma spectroscopic analysis of the primary coolant, determining the detection efficiency is more challenging. This is because the efficiency calculation involves complex computational processes. Additionally, the values provided by system manufacturers are typically limited to only one or two radionuclides, restricting the accuracy of the leakage rate evaluation. If energy spectrum analysis from β-rays, similar to gamma spectroscopy, were possible, real-time leakage rate evaluation would become significantly more feasible without the need for preliminary work or complex calculations. Accurately measuring the β-energy spectrum is essential for beta spectroscopy, and one of the key factors influencing this process is the thickness of the scintillator. If the scintillator is too thin, β-ray energy may not be fully transmitted, making it difficult to obtain the complete energy spectrum. Conversely, if it is too thick, the detection efficiency for γ-rays increases, which can interfere with β-ray measurement. Thus, optimizing the scintillator thickness is crucial for accurate beta spectroscopy. In this study, as a preliminary investigation for beta spectroscopy, we aim to determine the optimal scintillator thickness for β-spectrum measurement.[2] By comparing the MCNP simulated spectrum with the actual detector spectrum, we seek to derive the appropriate thickness that maximizes measurement accuracy. Additionally, to accurately describe the detector response function, we applied Gaussian Energy Broadening (GEB) to the simulated spectrum and extracted the GEB parameters a, b and c. A genetic algorithm (GA) was used for this optimization process. GA is an evolutionary method inspired by natural selection and is effective in solving complex nonlinear problems with large search spaces.[1,3]

2. Material and Methods

2.1 Scintillator Thickness Optimization using MCNP

To select the optimal scintillator thickness for β-spectrum measurement, energy spectra for different thicknesses were obtained using the F8 tally in the MCNP simulation. The geometry was modeled as shown in Figure 1. The scintillator's density and diameter were set to 1.05 g/cm³ and 5.08 cm, respectively, while the thickness was varied from 0.5 cm to 1.5 cm in 0.05 cm increments during the simulation. The radionuclides used in the MCNP were ^{14}C, ^{147}Pm, ^{99}Tc, ^{36}Cl, and ^{90}Sr/^{90}Y (0-2.5MeV), Based on the simulated results, the optimal scintillator thickness was selected to accurately measure the full energy spectrum of the radionuclides while minimizing the influence of γ-rays. The selected thickness was then applied to the actual detector for measurement.

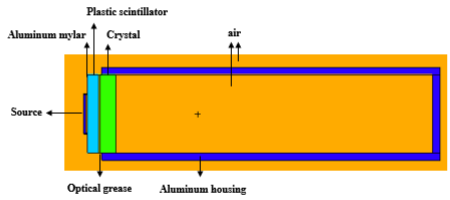

Fig 1. Schematic of the detector simulated in the MCNP

2.2 Experimental setup

We conducted β-spectrum measurements using a plastic scintillation detector to compare the simulated spectrum with the actual measured spectrum. The detector's scintillator was a plastic scintillator from Epic Crystal, and the PMT used was a Hamamatsu H7195. The detector output signal was amplified through an ORTEC 673 amplifier, as shown in Figure 2, and then processed by an AMPTEK MCA 8000D multi-channel analyzer, with the raw data stored on a PC in 1024 bins.

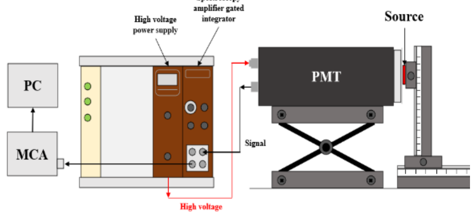

Fig 2. Experimental setup

2.3 GEB parameter optimization algorithm

GEB was applied to describe the energy response function of the detector. GEB is a process that applies a Gaussian function to the simulated spectra to reproduce the energy broadening effect observed in the energy spectra measured by an actual detector. The corresponding equations are given below.

$$S^*(E,A) = f(E_0,A) * S(E_0) \qquad (1)$$

where S^* is the energy-broadened spectrum, f is the Gaussian function, S is the originally deposited energy spectrum before GEB, $*$ is the convolution operator.

$$f(E_0,A) = Ce^{-((E-E0)/A)^2} \qquad (2)$$

$$A = \frac{\text{FWHM}}{2\sqrt{\ln 2}} \qquad (3)$$

$$FWHM = a + b\sqrt{E + cE^2} \qquad (4)$$

where E is the broadened energy; E_0 is the unbroadened energy; C is a normalization constant; and A is the Gaussian width.

Figure 3 illustrates the GA used to optimize the GEB parameters a, b and c. In each generation, the GA evaluates the fitness of 3000 randomly sampled parameter sets based on the mean squared error (MSE) between the normalized GEB-applied simulated spectra and the normalized measured spectra across five β-emitting radionuclides. The MSE is define1d as below.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(S^*(E_i,a,b,c) - S_{exp}(E_i))^2 \qquad (5)$$

where S_{exp} is Normalized measured spectrum, n is number of energy bin.

In each generation, the 60 best-performing parameter sets (lowest total MSE) are selected. New candidates are generated by applying ± 5% mutations to these elite sets. The process iterates up to 100 generations or until the minimum MSE falls below 1×10^{-18}.

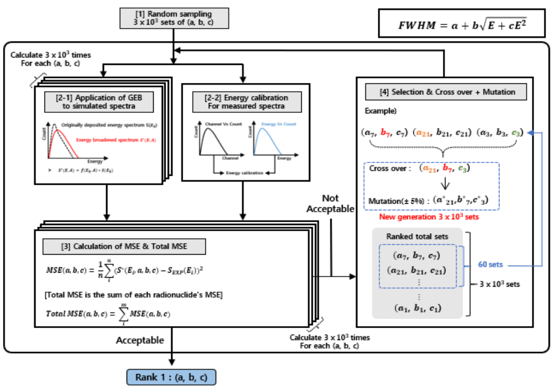

Fig 3. A flowchart of parameter optimization using a genetic algorithm

3. Result and Discussion

Table 1 presents the maximum energy of each radionuclide and the corresponding minimum scintillator thickness required for measurement.

Table 1. Required scintillator thickness based on the maximum energy of each radionuclide.

Radionuclide	Maximum energy [KeV]	Scintillator thickness [cm]
^{14}C	156	0.5
^{147}Pm	224.5	0.5
^{99}Tc	293.6	0.5
^{36}Cl	709	0.6
$^{90}Sr/^{90}Y$	2283.9	0.7

Experimental results indicate that a scintillator thickness of 0.7 cm or greater allows for accurate measurement of the entire $^{90}Sr/^{90}Y$ spectrum, which has the highest maximum energy. Accordingly, the scintillator thickness in the detector was set to 0.7 cm.

Figure 4 compares measured and simulated β-energy spectra. Since simulated spectra does not incorporate the detector's energy response function, noticeable differences from the measured values are observed

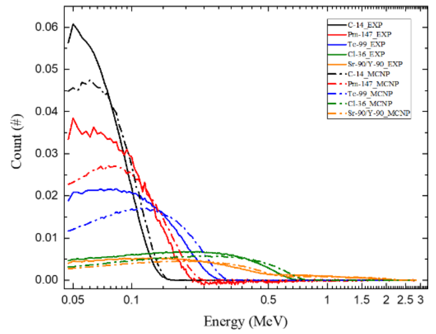

Fig 4. Comparison of normalized simulated spectra and normalized measured spectra

To compensate for these differences, spectra was generated by applying GEB using the optimized parameter values obtained through a genetic algorithm. Figure 5 shows comparisons between the simulated spectra with GEB applied and the actual measured spectra. The optimized parameter values are a = -0.0325, b = 0.2283, and c = 2.0958 with a total MSE of 9.59E-07.

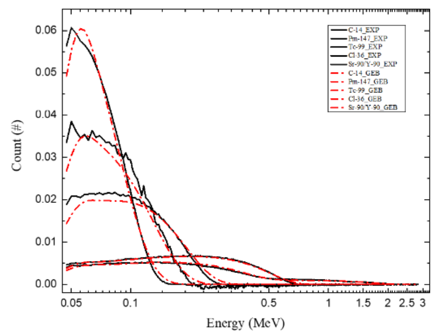

Fig 5. Comparison of GEB-applied simulated spectra and measured spectra

4. Conclusion

In this study, as a preliminary investigation for beta spectroscopy, we conducted research on optimizing the plastic scintillator thickness. Additionally, we applied a genetic algorithm and GEB to align the simulated spectra with the actual measured spectra. Simulated results showed that a 0.7 cm scintillator effectively captures the entire target radionuclide spectrum. Applying GEB with genetic algorithm-derived para-meters successfully replicated the detector's response function. In future studies, we plan to simulate the spectra of key β-radionuclides during leakage events, thereby enabling a more precise beta spectroscopy analysis.

ACKNOWLEDGEMENT

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REFERENCES

[1] Wonku Kim, “Parametric Optimization for Estimating Beta Detection Efficiency in Thin Plastic Scintillation Detector”, (2024)
[2] Mai Nguyen Trong Nhan, “Efficiency Calculation of Plastic Scintillator for in situ Beta Measurement System”,
[3] E. Eftekhari Zadeh, "Gaussian Energy Broadening Function of an HPGe Detector in the Range of 40 keV to 1.46 MeV" (2014)