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

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Abstract

The condenser air removal system in pressurized water reactors is employed to monitor the leakage of inert fission gases from the primary to the secondary system by detecting emitted β-rays. Conventional detection methods utilize gross counting mode, in which the detector response is significantly affected by variations in the nuclide composition of the sampled gas. This dependence introduces uncertainties in leakage rate estimation, thereby limiting the reliability of current monitoring practices. To address this issue, β-ray spectroscopy based on energy-resolved spectral analysis has been proposed as a means to improve the accuracy of leakage quantification. As a preliminary investigation, this study focuses on the optimization of scintillator thickness and the characterization of detector response using Gaussian Energy Broadening (GEB). Monte Carlo simulations were conducted using MCNP, and a genetic algorithm was applied to derive optimal GEB parameters a, b and c. The simulated spectra, convolved with the optimized parameters, demonstrated excellent agreement with the measured spectra obtained from the experimental setup. These findings support the feasibility of implementing β-spectrum-based diagnostics for real-time and accurate assessment of primary-to-secondary leakage in nuclear power plants.

Introduction

- The condenser air removal system monitors β-rays emitted from inert gases to detect primary-to-secondary leakage in pressurized water reactors
- β-emitting nuclides in inert gases include ^{133}Xe, ^{85}Kr, ^{85m}Kr, ^{135}Xe, ^{137}Xe, ^{41}Ar, ^{88}Kr, and ^{87}Kr
- The thickness of the plastic scintillator has a significant impact on the energy resolution of the beta spectrum
- Gaussian Energy Broadening (GEB) was applied to the simulated spectra to account for the detector's energy response characteristics
- GEB parameters a, b and c were optimized using a genetic algorithm by minimizing the mean squared error (MSE) between simulated and measured spectra across five radionuclides

Materials and methods

- **Scintillator Thickness Optimization using MCNP**
  - The optimal scintillator thickness was evaluated using MCNP simulations with the F8 tally
  - The scintillator thickness was varied from 0.5 cm to 1.5 cm in 0.05 cm increments
  - β-emitting radionuclides were simulated: ^{14}C, ^{147}Pm, ^{99}Tc, ^{36}Cl, and ^{90}Sr/^{90}Y
  - Simulated energy spectra were analyzed to determine the thickness that captures the full β-spectrum

- **Experimental setup**
  - The beta spectrum detection was performed using the H7195 PMT from Hamamatsu.
  - The detector signals were amplified using the ORTEC 673 amplifier and analyzed with the AMPTEK MCA 8000D multi-channel analyzer.

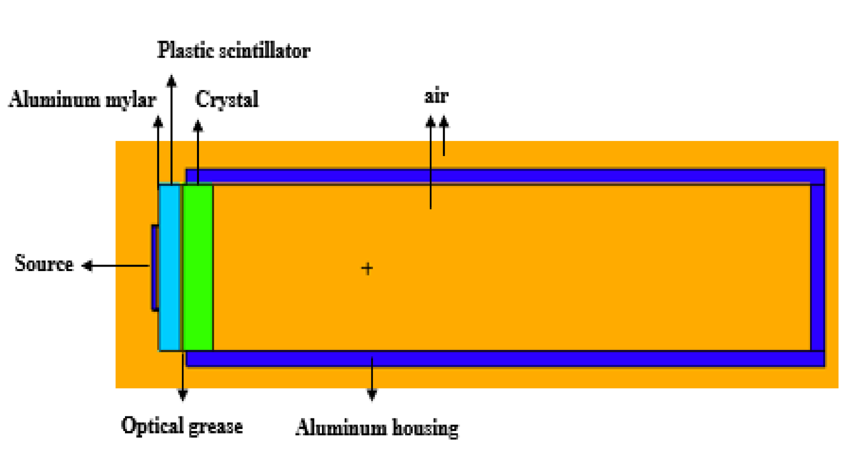

Fig 1. Schematic of the detector simulated in the MCNP

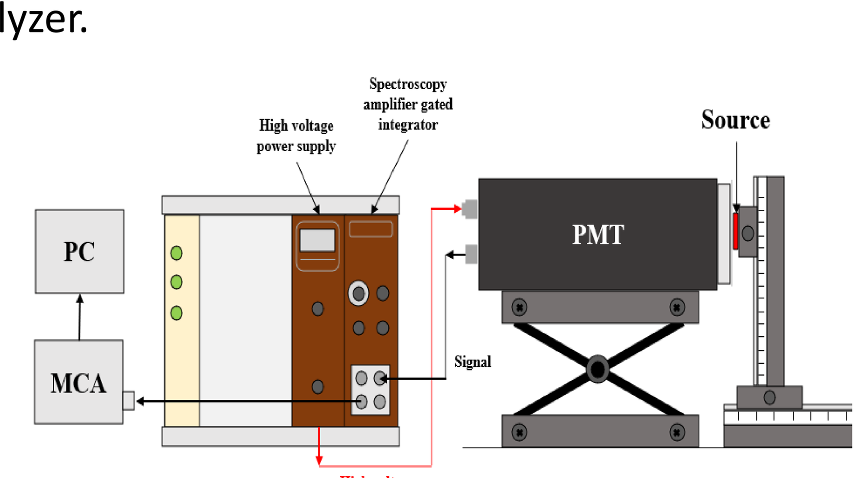

Fig 2. Experimental setup

- **GEB parameter optimization algorithm**
  - GEB was applied to simulate the detector's energy resolution effect
  - 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

$$f(E_0,A) = Ce^{-\left(\frac{E-E_0}{A}\right)^2} \qquad (2)$$

$$A = \frac{FWHM}{2\sqrt{ln2}} \qquad (3)$$

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

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

- Each GA generation evaluates 3,000 randomly sampled parameter sets
- Fitness is measured as the MSE between normalized GEB-applied simulated spectra and normalized measured spectra.

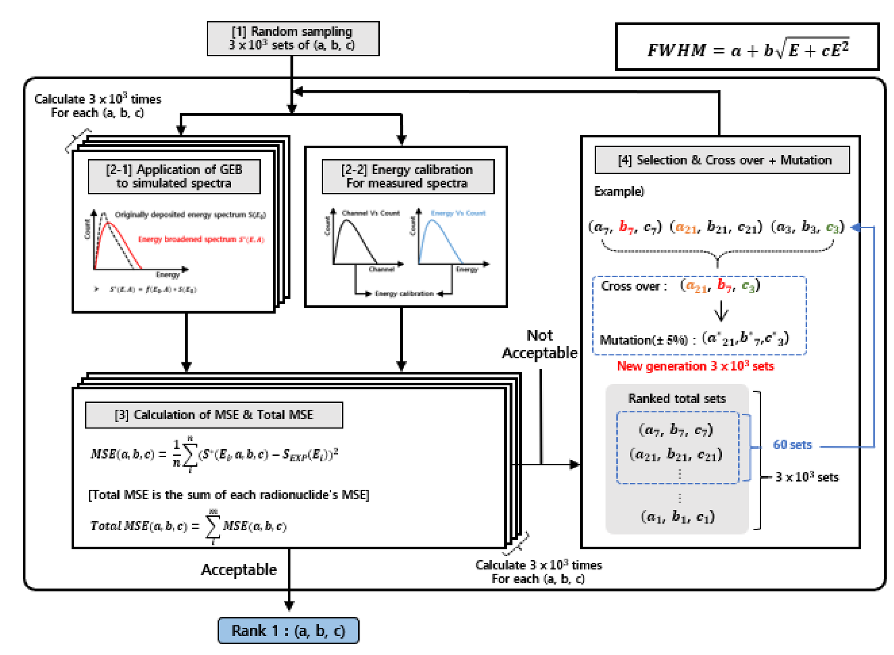

Fig 3. A flowchart of parameter optimization using a genetic algorithm

- MSE equations is given below :

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

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

Results

- **Effect of scintillator thickness on simulated β-Spectrum without GEB**
  - The required minimum scintillator thickness was evaluated based on the maximum β-energy of each radionuclide.
  - Simulation results showed that a thickness of 0.7 cm or greater is sufficient to fully measure the ^{90}Sr/^{90}Y spectrum, which has the highest endpoint energy

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

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

- **Comparison of GEB-applied simulated and measured β-Spectrum**

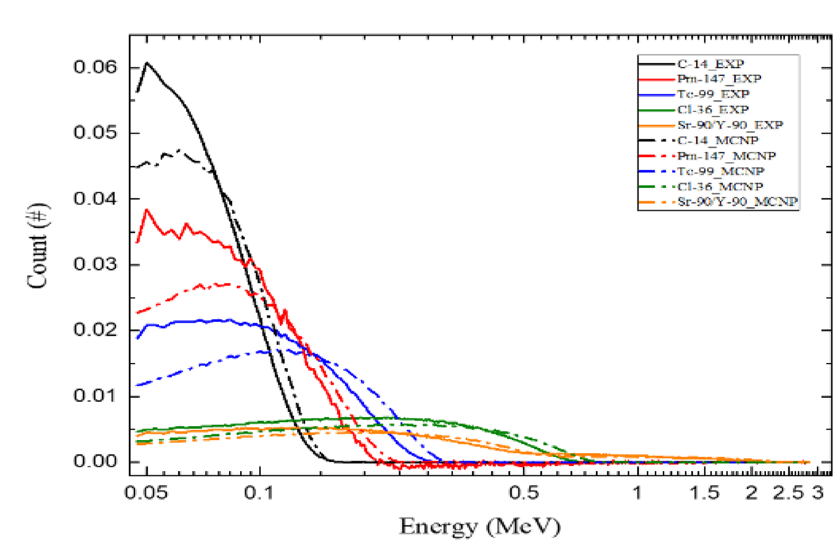

Fig 4. Comparison of normalized simulated spectra and normalized measured spectra

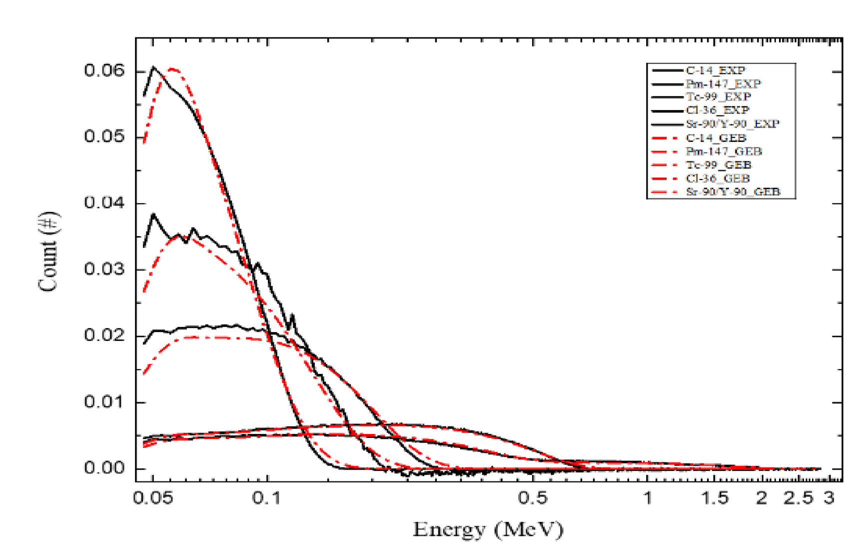

Fig 5. Comparison of GEB-applied simulated spectra and measured spectra

- The optimized GEB parameters were found to be a = -0.0325, b = 0.2283, and c = 2.0958.
- The total MSE between GEB-applied simulated spectra and measured spectra was minimized to 9.59×10^{-7}.
- The GEB-applied spectra showed strong agreement with experimental data, validating the detector response function modeling

Conclusion

- The optimal scintillator thickness was determined to be 0.7 cm through MCNP simulations, enabling complete measurement of high-energy β-spectra such as ^{90}Sr/^{90}Y.
- GEB parameters a, b and c were optimized using a genetic algorithm, and when applied to the simulated spectra, the resulting curves closely matched the experimentally measured spectra

References

[1] Wonku Kim. (2024) .Parametric Optimization for Estimating Beta Detection Efficiency in Thin Plastic Scintillation Detector.

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