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Radiation Detector Compensation System for Extreme Environments

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1. Introduction

Scintillator-based radiation detectors are widely utilized in various fields such as nuclear medicine, well logging, high-energy physics, reactor monitoring, and space exploration due to their excellent radiation detection efficiency, energy resolution, and robust performance in extreme environments, including high temperatures, radiation, humidity, and vibrations. However, when scintillation detectors are exposed to high temperatures or intense radiation, several factors can lead to changes in the overall gain of the detector. These include variations in the scintillator's light output, degradation of its transparency, changes in the gain of optical sensors such as Photomultiplier Tubes (PMTs) or Silicon Photomultipliers (SiPMs), and a reduction in the transmittance of optical sensor windows. These fluctuations compromise the stability of the energy-channel relationship in the gamma spectrum, causing shifts in the photopeak position. Consequently, this can introduce significant errors in qualitative and quantitative analyses using gamma spectroscopy, such as the identification of radioactive isotopes and the measurement of radioactivity concentration.

To mitigate such errors, various detector calibration and compensation methods have been developed. However, existing approaches primarily focus on compensating for temperature variations while neglecting output changes caused by radiation damage. Moreover, conventional temperature compensation methods have only been validated within limited temperature ranges, making them unsuitable for applications requiring operation at higher temperatures, such as planetary exploration or reactor monitoring systems.

In this study, as a preliminary step toward developing a radiation measurement output compensation system for extreme environments, we designed a radiation detector capable of operating in high-temperature and high-radiation environments. Additionally, we developed a temperature compensation system capable of stabilizing detector output across a temperature range from ambient conditions up to 150°C. The performance of the two developed temperature compensation systems was analyzed and compared in terms of their ability to mitigate variations in detector output.

2. Methods and Results

2.1 Experimental setup

The system consisted of a Ce:GPS scintillator (3 × 3 × 5 mm³, OXIDE Corporation, Japan) and a PMT (R3991AH-07, Hamamatsu). The signal output from the anode of the PMT was amplified and shaped through a front-end circuit before being transmitted to the FPGA (ADC-SoC).

For temperature measurement, a thermistor was used, taking advantage of its resistance variation with temperature. The voltage across the thermistor was measured using a voltage divider circuit, and the measured voltage values were acquired using the low-speed ADC (LTC2308) of the FPGA. The exact temperature was then determined by converting the measured resistance values using a pre-established resistance-to-temperature lookup table (LUT).

The variation in instrument output due to temperature changes was evaluated based on the position of the photopeak in the energy spectrum obtained by measuring a ^{137}Cs (72.61 μCi) source. While conventional temperature compensation systems have typically been conducted over a limited temperature range, this study was carried out over a wide temperature range from 25°C to 150°C at 25°C intervals, taking into account the internal environment of a nuclear reactor. The variation in instrument output caused by temperature changes was assessed by analyzing the shift in the photopeak position. The consistency of the instrument output was evaluated in terms of the coefficient of variation (CV), which was calculated as the ratio of the standard deviation of the photopeak position to its mean value.

2.2 Temperature compensation (pre- and post-compensation)

To compensate for detector output variations caused by temperature changes, two temperature compensation methods were developed. The first method, Pre-compensation, maintains a stable detector output by adjusting the voltage supplied to the detector based on the measured temperature. The second method, Post-compensation, keeps the detector output stable without altering the supplied voltage; instead, it adjusts the magnitude of the output signal by multiplying it by a specific factor based on the measured temperature.

(Figure 1)

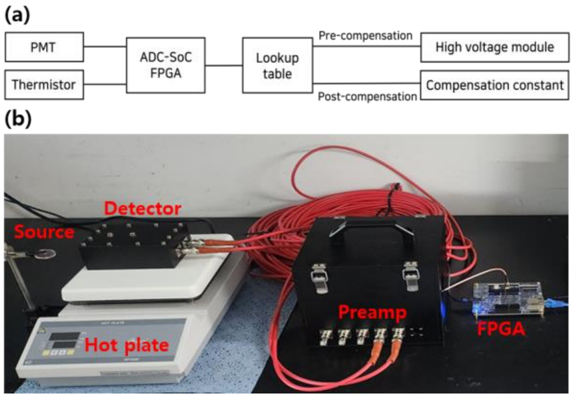

Fig. 1. (a) Schematic of temperature compensation system. (b) The preamplifier, SoC FPGA, PMT

Fig. 1. (a) is a schematic diagram illustrating two types of temperature compensation methods: pre-compensation, which adjusts the PMT supply voltage directly, and post-compensation, which applies correction factors. Fig. 1. (b) shows the high-temperature experimental setup of the detector. Considering the actual operating environment, the detector and preamplifier are connected via a 30-meter coaxial cable. Data was then acquired in real-time using an FPGA.

2.3 Pre-compensation

To adjust the voltage supplied to the detector, an 8-bit DAC (AD7801) and a high-voltage power supply module (C9619-50, Hamamatsu, Japan) were used. A pre-established temperature-to-supply voltage lookup table (LUT) was utilized to determine the appropriate voltage to be supplied to the detector based on the measured temperature. The final voltage supplied to the detector was controlled by adjusting the DAC output, which in turn regulated the output voltage of the high-voltage power supply module.

2.4 Post-compensation

A pre-established temperature-signal magnitude correction lookup table (LUT) was used to adjust the signal magnitude acquired within the FPGA by multiplying it by a specific factor based on the measured temperature. This ensured that the detector output remained stable.

2.5 Result and Discussion

In the temperature range of 25°C to 150°C, the coefficient of variation for the photopeak position of ^{137}Cs was 1.23% for the Pre-compensation method and 1.84% for the Post-compensation method. These values are significantly lower than the coefficient of variation before temperature compensation, which was 20.16% (Figure 2 and Table 1).

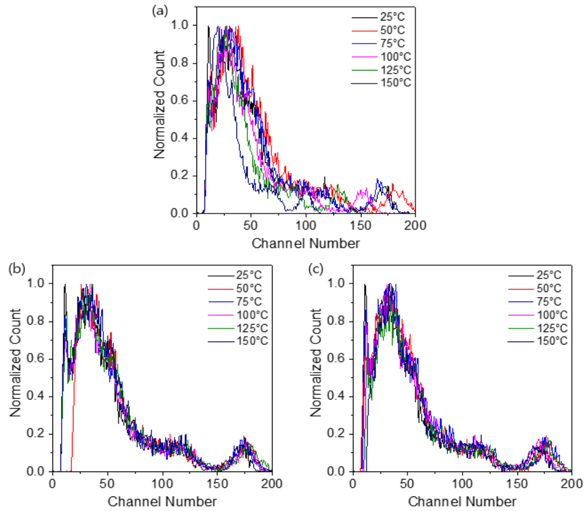

Fig. 2. Energy spectrum (a) Reference (b) Pre-compensation (c) Post-compensation

Table I: Comparison of the Mean Value, Standard Deviation, and Coefficient of Variation of the Photopeak Position with and without Temperature Compensation

Case	Avg of peak values (arb unit)	Standard deviation	The coefficient of variation(%)
Un-compensation	149.33	30.11	20.16%
Pre-compensation	174.17	2.14	1.23%
Post-compensation	171.72	3.16	1.84%

Since the spectrum was acquired using the high-speed ADC of the FPGA, the peak positions are represented in ADC channel numbers (arb units).

3. Conclusions

In this study, it was confirmed that both temperature compensation methods function effectively over a wide temperature range from 25°C to 150°C. This demonstrates that the detector output can be maintained consistently despite temperature variations.

Future research will focus on developing a method to measure radiation dose in real time and compensate the radiation detector output accordingly. Ultimately, the goal is to establish a complete radiation measurement output compensation system for extreme environments. This advancement is expected to contribute to reliable radiation monitoring and measurement even under harsh conditions.

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