Study of Backscattering Effects on Installed Area Monitors and/or Warning Devices for Gamma Radiation

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Abstract

This paper reports an experimental investigation into the backscatter effects on gamma radiation monitors. The study addresses deviations in measurement readings observed in wall-mounted monitors compared to free-air devices due to backscatter phenomena. Reinforced concrete test blocks were employed to simulate operational environments, with measurements conducted using three detector types: a radiation protection level dosimeter with ionization chamber, an air-kerma radiation monitor with counter tube, and a radiation detector with NaI(Tl) scintillator. Analysis of backscatter factors at varying distances and orientations revealed that: (1) backscatter factors decreased with increasing source-to-surface distance, and (2) central irradiation generally yielded higher backscatter factors than non-central irradiation. The experimental data provide essential reference for formulating or revising pertinent technical standards.

Full Text

Preamble

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The Research of Backscattering Effect on Installed Area Monitors and/or Warning Devices for Gamma Radiation

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Abstract

This paper reports an experimental investigation into backscatter effects on gamma readings observed in radiation monitors. The study addresses measurement deviations in wall-mounted monitors compared to free-air devices due to backscatter phenomena. Reinforced concrete test blocks were employed to simulate operational environments, with measurements conducted using three detector types: a radiation protection level dosimeter with ionization chamber, an air-kerma radiation monitor with counter tube, and a radiation detector with NaI(Tl) scintillator. Analysis of backscatter factors at varying distances and orientations revealed that: (1) backscatter factors decreased with increasing source-to-surface distance, and (2) central irradiation generally yielded higher backscatter factors than non-central irradiation. The experimental data provide essential reference for formulating or revising pertinent technical standards.

Keywords: Backscattered radiation, radiation monitoring

Introduction

With the continuous development and application of nuclear technology, human exposure pathways to ionizing radiation have become increasingly diversified [?, ?, ?]. As high-energy electromagnetic radiation, X-rays and γ-rays ionize materials by ejecting orbital electrons, thereby altering molecular structures. Such ionization induces biological damage, including DNA strand breaks and protein denaturation [?, ?]. Acute high-dose exposure may lead to systemic injury or mortality, while low-dose exposure poses carcinogenic risks [?, ?]. To enable timely monitoring of radiation doses and mitigate occupational hazards, X/γ radiation area monitors and alarm devices are widely utilized in radioactive waste repositories, industrial testing, healthcare facilities, and nuclear power plants.

The general principles under Item 5—particular procedures for area dosimeters in ISO 4037-3:2019—indicate that dosimeters for area monitoring shall be irradiated in free air (without phantom). However, installed area monitors are usually fixed on wall surfaces. Due to the backscattering effect, the measurement results of devices installed on a wall surface differ significantly from those of devices in free air. Therefore, the backscattering effect should be considered when calibrating installed area monitors and/or warning devices, and an appropriate phantom for simulating wall backscatter should be employed.

The investigation of backscattered radiation originated from fundamental formulas governing photon and electron cross-sectional scattering and collisions

[?, ?]. Hayward and Hubbell subsequently analyzed the energy distribution of ^{60}Co photons relative to backscattering angles [?, ?]. Hyodo conducted comprehensive research on backscattering phenomena [?, ?]. Fujita et al. and Mizukami developed an empirical formula to represent the variation in quantity and energy of backscattered photons with changing scattering block thickness [?, ?, ?]. Bourgois and Comte demonstrated that the proportion of monoenergetic photon scattering varies significantly with energy and material properties (e.g., water, steel), with their data being critical for shielding design and dose assessment [?, ?, ?]. Almayahi et al. examined the influence of plain concrete (2–30 cm thickness) on gamma-ray backscatter factors within the 0.088–1.253 MeV energy range, providing a theoretical foundation for material thickness detection [?, ?, ?]. Tanabe implemented a weighted averaging method to calculate backscatter factors for diagnostic kilovoltage X-ray beams, validating its accuracy through Monte Carlo simulations [?, ?].

While these studies employed diverse methodologies, they consistently demonstrate the non-negligible impact of backscattering effects on radiation measurements. To clarify the impact of backscattered radiation on measurement values of area monitors or warning devices installed on walls, this study fabricated wall-simulating phantoms in compliance with China's Specification for Mix Proportion Design of Ordinary Concrete (JGJ 55-2011). Comparative analysis of measurement data from wall-mounted devices revealed significant deviations attributable to backscattering effects. The findings demonstrate that backscattering effects must be accounted for during calibration procedures. Consequently, there exists an urgent need to formulate or revise specialized technical standards to regulate measurement methodologies, thereby ensuring the acquisition of precise and reliable monitoring data.

2.1 Test Block

To simulate the actual mounting environment for installed area monitors and/or warning devices, the test block was made of reinforced concrete (see Annex A), with its appearance as shown in Figure 1 [Figure 1: see original paper]. It is a cube measuring 1 m × 1 m × 0.6 m, fabricated according to JGJ55-2011.

2.2 Air-Kerma Facility for Gamma Radiation

The facility contains two radiation sources: one ^{60}Co source (activity 1.85$×10^{11}$ Bq) and one ^{137}Cs source (activity 3.7$×10^{11}$ Bq), along with a linear positioning system featuring 6-meter rails.

2.3 Radiation Detectors

For testing the response of different radiation detectors to backscattering radiation, three typical measuring devices were employed: a radiation protection level dosimeter with ionization chamber, an air-kerma radiation monitor with counter tube, and a radiation detector with NaI(Tl) scintillator.

2.3.1 Dosimeter of Radiation Protection Level

The radiation protection level dosimeter used in the experiment was manufactured by PTW in Germany, comprising a type 32002 spherical ionization chamber with a volume of 1 L and a type UNIDOS electrometer, as shown in Figure 3 [Figure 3: see original paper]. The effective point of measurement is defined at the center of the sphere. The dosimeter has been calibrated.

2.3.2 Air-Kerma Radiation Monitor

The air-kerma radiation monitor used in the experiment is model RD-02, manufactured by RADOS. The radiation detector is a Geiger counter, as shown in Figure 4 [Figure 4: see original paper], and the effective point of measurement is defined at the center of the cylinder. The monitor has been calibrated.

2.3.3 R700 Radiation Detector

The R700 radiation detector used in the experiment is equipped with a CS30A scintillation probe, manufactured by Coliy Technology GmbH, as shown in Figure 5 [Figure 5: see original paper]. The effective point of measurement is defined as 20 cm from the front surface of the cylinder. The radiation detector has been calibrated.

2.4 Auxiliary Equipment

A thermometer, barometer, hygrometer, and two laser positioning devices were used in this experiment. The thermometer and barometer were used to correct measurements from the radiation protection level dosimeter, while the laser positioning devices indicated the horizontal position and effective measuring point of the detectors. The hygrometer and thermometer measured and controlled ambient temperature and humidity during the experiment.

2.4.1 Glass-Stem Thermometer

The thermometer is a glass-stem type with a measuring range from 0 °C to 50 °C and a division value of 0.1 degree, as shown in Figure 6 [Figure 6: see original paper]. The thermometer has been calibrated.

2.4.2 Aneroid Barometer

The barometer is an aneroid type with a measuring range from 80 kPa to 106 kPa and a division value of 0.1 kPa, as shown in Figure 7 [Figure 7: see original paper]. It has been calibrated.

2.4.3 Laser Positioning Device

Two laser positioning devices were used in the experiment. One, shown in Figure 8 [Figure 8: see original paper], was applied to locate the effective measuring point of the detectors, while the other indicated the horizontal position, as shown in Figure 9 [Figure 9: see original paper]. The accuracy of these laser positioning devices does not exceed $±$1 mm.

2.5 Measurement Methods

Considering the dose rate range in the actual operating environment of installed area monitors and/or warning devices for gamma radiation, reference dose rates of several tens of milligray per hour were required at the measuring positions. This primarily involved determining an appropriate distance from the sources to the measuring plane. The parameters of the Air-Kerma gamma radiation fields were determined through a series of experiments.

To determine the relationship between backscattering coefficient and backscatter distance, the distances from the detectors to the test block were set to 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm in this experiment. The influence of beam incident angle on the backscattering coefficient was also considered by testing with the effective measuring point of the detectors positioned 20 cm away from the incident beam axis. Figure 10 [Figure 10: see original paper] and Figure 11 [Figure 11: see original paper] show examples of measurement on and off the beam axis, while Figure 12 [Figure 12: see original paper] and Figure 13 [Figure 13: see original paper] provide clear diagrams of the two conditions.

2.5.1 Preparation

A series of preparatory steps is necessary before the experiment, with its flow sheet shown in Figure 14 [Figure 14: see original paper]. Effective preparation can improve data quality, avoid mistakes, and improve efficiency. The steps include: adjusting ambient temperature and controlling humidity in the lab; placing the detector and adjusting the distance from the measuring plane to the source; warming up the measuring device to be tested; and measuring the radiation.

2.5.2 Steps

Detailed test procedures are as follows and shown in Figure 15 [Figure 15: see original paper]. First, make the effective measuring point of the detectors coincide with the center of the radiation field and adjust the distance of detectors from the test block to 5 cm (only RD-02 type), 10 cm, 15 cm, 20 cm, and 25 cm in the radiation fields of Cobalt-60 and Cesium-137. Perform repeated measurements 10 times at each position for one minute per measurement, with the average calculated as the measurement result. Second, position the effective measuring point of the detectors 20 cm away from the center of the radiation field, and adjust the distance repeatedly.

2.5 Backscattering Coefficient

This experiment uses the following equation to define the backscattering coefficient:

$$B = \frac{M_{\text{wall}} - M_{\text{free}}}{M_{\text{free}}}$$

Where: B is the backscattering coefficient at the measurement point, M_{wall} is the measurement result when the test block influences radiation scatter as a phantom, and M_{free} is the measurement result when the test block does not influence radiation scatter.

3.1 Method Analysis

The components of scattering are complex, relating to incident photon energy, angle, radiation field size, and other factors, making precise calculation of backscatter energy and intensity difficult. The experiments adopted a relative measurement method to determine the backscattering coefficient using three different detectors and two different energies. The experiment systematically investigated the spatial dependence of backscattering by adjusting the distance between the detector and test block (5–25 cm) as well as central and off-center positions within the radiation field. Notably, the test block composition (reinforced concrete) matched real-world wall materials, ensuring comparability between experimental conditions and practical scenarios. However, the absence of an X-ray radiation source in the experimental setup may limit the generalizability of the conclusions.

3.2 Results Analysis

This study performed systematic experimental measurements integrated with theoretical calculations based on Equation (1) to quantitatively characterize the backscattered radiation response properties of three distinct detector types. The results are shown in Table 1 through Table 3 . The standard uncertainties are 0.4%, 0.9%, and 0.2% for the 1L chamber, RD-02, and R700, respectively.

As observed in Figure 16 [Figure 16: see original paper] and Table 1 , the backscattering coefficients measured by the 1L spherical ionization chamber detector are generally higher in central positions compared to off-center positions. A comparative analysis of different radiation sources indicates that backscattering coefficients for ^{137}Cs are significantly higher than those for ^{60}Co. This phenomenon aligns with the findings of L. Bourgois et al., which demonstrate that low-energy photons (e.g., 662 keV) exhibit a higher proportion of scattered radiation than high-energy photons (e.g., 1.25 MeV), with small-angle scattering contributing more prominently. Notably, fluctuations in coefficients at specific distances (e.g., ^{137}Cs central position coefficient increasing from 0.12 at 15 cm to 0.13 at 20 cm) may correlate with dose gradients induced by the large volume of the ionization chamber. The effective measurement point of the ionization chamber, located at the spherical center, may experience deviations in integrated responses from theoretical predictions due to non-uniform backscattering fields affecting its internal dose distribution. Additionally, dose gradients within the chamber cavity lead to discrepancies compared to idealized conditions simulated by Monte Carlo methods, which must also be considered a non-negligible factor.

Figure 17 [Figure 17: see original paper] and Table 2 reveal an anomalous trend in the backscattering coefficients of RD-02: in the ^{137}Cs field, coefficients at off-center positions (e.g., 0.10 at 5 cm) exceed those at the central position (0.09). This result deviates from theoretical expectations, and potential causes are hypothesized as follows: (1) Geometric effects—the effective measurement point of the Geiger-Müller counter is defined as the cylindrical center, but its actual sensitive region may shift due to electric field distortion at the ends, altering the effective measurement position; (2) Directional dependence—the response of the cylindrical detector to non-axial radiation may be reduced due to geometric shielding effects, whereas scattering paths for off-center radiation are more complex, potentially enhancing localized responses; (3) Statistical uncertainties—with an experimental standard uncertainty of 0.9%, some observed discrepancies (e.g., central and off-center coefficients of 0.03 and 0.06, respectively, at 5 cm in the ^{60}Co field) may originate from measurement noise.

Figure 18 [Figure 18: see original paper] and Table 3 demonstrate that the backscattering coefficients of the R700 detector are the highest among the three detector types, with ^{137}Cs field coefficients significantly exceeding those of the ^{60}Co field. This is attributed to the high detection efficiency of the NaI(Tl) scintillator and its sensitive response to low-energy photons. Furthermore, minimal differences between coefficients at central and off-center positions under identical distances (e.g., 0.23 versus 0.22 at 5 cm in the ^{137}Cs field) suggest limited sensitivity to inhomogeneities in radiation field distributions, likely due to their wide dynamic range and isotropic response characteristics. All three detector types display a decreasing trend in backscattering coefficients with increasing distance, consistent with theoretical predictions. As distance increases, the backscattered photon flux diminishes due to geometric attenuation and air absorption, validating the necessity of expanding spatial dimensions in standard radiation fields to reduce scattering interference.

4. Conclusion

This study simulated real-world installation environments and utilized three distinct types of detectors to investigate the relationship between backscatter coefficients and three variables: detector type, radiation source, and measurement point location. Experimental results demonstrated that the backscatter coefficient decreases as the distance between the detector and test block surface increases. For measurements conducted on the same plane, the backscatter coefficient for ^{137}Cs radiation consistently exceeded that of ^{60}Co radiation. Furthermore, backscatter coefficients measured at the center of the radiation field were generally higher than those obtained from off-center positions, particularly for radiation protection-level dosimeters. While this research excluded X-ray radiation, subsequent studies will incorporate X-ray sources to enable comprehensive evaluation of backscattering effects. Through environmental simulations and multi-detector measurements, this investigation successfully assessed the impact of backscattered radiation on measurement accuracy for X/γ radiation area monitors and warning devices. These findings provide critical empirical evidence for developing and revising technical standards to standardize measurement methodologies in radiation detection systems.

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Appendix A: Test Block

The production method and composition of the test block used in this experiment are based on the Chinese Industrial Standard JGJ55-2011 *Specification for Mix Proportion Design of Ordinary Concrete*, and its compressive strength reaches 30 N/mm^2. The thickness of the test block and the internal reinforcement structure are similar to walls used in radiation protection and can reproduce the operating environment of installed area monitors and/or X and gamma radiation warning devices. Detailed structural parameters are as follows.

A.1 Reinforced Concrete Structure

The steel frame was made of 14 mm diameter rebars, forming a rectangular structure divided uniformly into 3 layers, with each layer composed of 21 $\times$ 27 rebars, as shown in Figure A.1 [FIGURE:A.1].

A.2 Cement

The concrete of the test block is composed of water, cement, sand, and stone. The mass proportion of water:cement:sand:stone is 0.38:1:1.11:2.72.

A.3 Test Block

The outermost layer of the steel frame is 3 cm from each test surface of the test block, and the test block is a rectangular parallelepiped measuring 1 m $\times$ 1 m

$\times$ 0.6 m, as shown in Figure A.2 [FIGURE:A.2] and Figure A.3 [FIGURE:A.3].

Note: Figure translations are in progress. See original paper for figures.