Development of non-sampling atmospheric radionuclide online measurement system

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Date: 2025-06-14T00:00:00+00:00

Abstract

For the prompt monitoring of radionuclides released into the atmosphere by various nuclear facilities and sudden nuclear accidents, a nonsampling atmospheric radionuclide online measurement system (NSAROMS) that is based on NaI(Tl) scintillators was developed. Compared with traditional measurement methods, this online system eliminates the enrichment sampling process. The selection of the detector, the design of the ground gamma-ray shielding device, and the detection efficiency of the measurement system were simulated using Monte Carlo simulation. A calibration experiment was subsequently carried out to measure the detection efficiency of the system, and the relative error between the detection efficiency obtained by calibration and the detection efficiency obtained by Monte Carlo simulation was within 5%. The minimum detectable activity concentrations (MDACs) for several common atmospheric radionuclides, including ^{214}Pb, ^{214}Bi, ^{7}Be, ^{22}Na, ^{134}Cs, ^{137}Cs, ^{131}I, and ^{40}K, were calculated on the basis of the measured detection efficiencies for a system measurement duration of 30 minutes. Finally, preliminary applications were carried out in Mianyang, Leshan, Yibin, and Guangyuan, with measured average atmospheric radon concentrations of $7.87 \pm 0.23\,\mathrm{Bq/m^3}$, $4.48 \pm 0.15\,\mathrm{Bq/m^3}$, $4.30 \pm 0.13\,\mathrm{Bq/m^3}$, and $9.90 \pm 0.29\,\mathrm{Bq/m^3}$, respectively. The NSAROMS meets the requirements for monitoring atmospheric radionuclides in nuclear facilities. It can accurately measure the activity concentrations of radionuclides in the atmosphere and offers advantages such as convenience, a wide measurement range, low detection limits, and the ability to perform onsite online measurements at nuclear facilities.

Full Text

Preamble

Development of a Nonsampling Atmospheric Radionuclide Online Measurement System

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For the prompt monitoring of radionuclides released into the atmosphere by nuclear facilities and sudden nuclear accidents, we developed a Nonsampling Atmospheric Radionuclide Online Measurement System (NSAROMS) based on NaI(Tl) scintillators. This online system eliminates the enrichment sampling process required by traditional methods. Monte Carlo simulations were employed to guide detector selection, design the ground gamma-ray shielding device, and estimate detection efficiency. Subsequent calibration experiments validated the system' s detection efficiency, yielding relative errors within 5% between experimental and simulated values. Minimum detectable activity concentrations (MDACs) for common atmospheric radionuclides—including ^{214}Pb, ^{214}Bi, ^{7}Be, ^{22}Na, ^{134}Cs, ^{137}Cs, ^{131}I, and ^{40}K—were calculated for a 30-minute measurement duration based on the measured detection efficiencies. Preliminary field applications in Mianyang, Leshan, Yibin, and Guangyuan measured average atmospheric radon concentrations of 7.87 ± 0.23 Bq/m^3, 4.48 ± 0.15 Bq/m^3, 4.30 ± 0.13 Bq/m^3, and 9.90 ± 0.29 Bq/m^3, respectively. The NSAROMS meets monitoring requirements for atmospheric radionuclides at nuclear facilities, offering accurate activity concentration measurements with advantages of convenience, wide measurement range, low detection limits, and onsite online capability.

Keywords: Atmospheric radionuclides, Online measurement, Gamma ray measurements, Detection efficiency calibration

Introduction

Atmospheric radionuclides refer to radioactive species present in the atmosphere, typically as gases and aerosols. Based on their origins, these radionuclides can be classified into primordial, cosmogenic, and artificial categories [1]. Primordial atmospheric radionuclides such as ^{222}Rn, ^{214}Bi, and ^{214}Pb are decay products of

natural uranium and thorium series that humans commonly encounter in the atmospheric environment [2-4]. Cosmogenic radionuclides like ^{7}Be and ^{22}Na arise primarily from nuclear reactions between cosmic rays and atmospheric nuclei of carbon, hydrogen, oxygen, and other elements [5-7]. Artificial radionuclides —including ^{131}I, ^{137}Cs, and ^{3}H—originate from nuclear testing, accidents, and routine emissions from nuclear power plants operating within regulatory limits [8-10].

These radionuclides enter the human body through inhalation, skin deposition, and ingestion, causing continuous ionizing radiation damage. Consequently, rapid monitoring of atmospheric radionuclides is critically important [11-13]. Traditional activity concentration measurements rely on enrichment sampling methods such as gas filtration, inertial impaction, and electrostatic collection [14-16]. After sampling, specimens must be transported to laboratories or detector units for analysis [17-19], making the complete measurement process complex and time-consuming.

During nuclear emergencies, atmospheric radionuclides disperse more rapidly and widely than in other environmental compartments. Early and accurate determination of atmospheric activity concentrations is therefore essential for assessing radioactive contamination, predicting dispersion, and implementing effective public protection measures against external and internal radiation exposure. To simplify measurement procedures and reduce response times, we developed the NSAROMS using a large-volume NaI(Tl) scintillation detector. This system eliminates enrichment sampling through direct atmospheric measurement. However, since soil radionuclide activity concentrations far exceed atmospheric levels—for instance, ^{40}K in Chinese soils ranges from 269-7834.4 Bq/kg compared to only 5.04-483.72 μBq/kg (6.5-624 μBq/m^3) in air [20-23] —ground gamma rays significantly interfere with measurements. Furthermore, traditional static and dynamic calibration methods cannot be applied to this online system [24-28], and Monte Carlo simulation of the large detection volume suffers from slow convergence and excessive computational demands.

To address these challenges, this paper presents a ground gamma-ray shielding device design and a mathematical calibration model based on the point source simulation method. Both Monte Carlo simulations and experimental validations demonstrate the model' s effectiveness. Finally, MDAC estimates for several common natural and facility-emitted radionuclides are provided based on calculated detection efficiencies and measured background spectra.

II. Principle

A. Measurement Principles

The detector is modeled as a point detector within a spherical coordinate system (Fig. 1 [Figure 1: see original paper]). The effective detection volume forms a spherical cone, with any differential volume element dv expressed as:

$$dv = r^2 \sin\phi d\theta d\phi dr$$

where r is the distance from the volume element to the origin (representing measurement depth in the atmosphere), with its maximum value taken as the 95% attenuation distance for each energy; ϕ is the angle between the line connecting the volume element to the origin and the z-axis, with a maximum value equal to half the angular aperture of the ground gamma-ray shielding device; and θ is the angle between the projection of that line onto the x-y plane and the x-axis.

Assuming radionuclides are uniformly distributed in air with activity concentration AC, the number of gamma photons emitted from an arbitrary differential volume element that reach the detector per unit time, dI, is:

$$dI = \frac{ACe^{-\mu_E r}}{4\pi r^2} \sin\phi d\theta d\phi dr$$

where μ_E is the attenuation coefficient for gamma rays of energy E, obtained by fitting mass attenuation coefficients from the NIST X-ray mass attenuation coefficient table (Standard Reference Database 126) for radiation energies of 0.001–20 MeV in dry air and multiplying by air density [29]. Integrating Eq. (2) yields the total photon flux I:

$$I = \frac{AC(1 - e^{-\mu_E r})}{4\pi\mu_E}(1 - \cos\phi)$$

The net peak area of characteristic peaks in the energy spectrum represents the number of specific gamma photons reaching the detector [30]. Assuming complete shielding of ground gamma rays, the atmospheric radionuclide activity concentration can be calculated via:

$$AC = \frac{n}{\varepsilon\eta V t}$$

where n is the net peak area after background subtraction, ε is the detection efficiency for the characteristic energy, η is the gamma-ray branching ratio, V is the effective detection volume, and t is the measurement time. The effective detection volume is:

$$V = \int_0^{2\pi} \int_0^{\phi_0} \int_0^{d} r^2 \sin\phi dr d\phi d\theta = \frac{2\pi d^3}{3}(1 - \cos\phi_0)$$

where ϕ_0 is the half-opening angle of the shielding device and d is the maximum detectable distance, defined as the distance where photon flux attenuates to 5% in air:

$$d = \frac{\ln(20)}{\mu_E}$$

B. Source Peak Detection Efficiency (SPDE)

Source peak detection efficiency (SPDE) is the ratio of full-energy peak count rate per unit activity in a source with complex geometry (volume, surface, or gaseous) to the actual gamma emission rate. It serves as an equivalent estimate of full-energy peak efficiency for complex geometries. Given the NSAROMS' s extremely large detection volume, traditional calibration methods are inapplicable. Therefore, we employ the representative point method, calculating SPDE from full-energy peak efficiencies measured at representative points within the detection region.

For a point source with activity A at position (r, ϕ, θ) within the detection volume, the full-energy peak detection efficiency $\varepsilon(r, \phi, \theta)$ is:

$$\varepsilon(r, \phi, \theta) = \frac{n}{A\eta t}$$

The SPDE for a spherical cap with base radius r is:

$$\varepsilon_p(r) = \frac{\int_0^{\phi_0} \int_0^{\theta_0} \varepsilon(r, \phi, \theta) r^2 \sin\theta d\theta d\phi}{S}$$

where S is the spherical cap surface area. The SPDE within the spherical conical volume from r_0 to r_1 is:

$$\varepsilon_v = \frac{\int_{r_0}^{r_1} S\varepsilon_p(r)dr}{\int_{r_0}^{r_1} Sdr} = \frac{\int_{r_0}^{r_1} \varepsilon_p(r)dr}{r_1 - r_0}$$

Substituting the spherical cap area and cone volume formulas yields:

$$\varepsilon_v = \frac{\int_{r_0}^{r_1} \varepsilon_p(r)r^2dr}{\int_{r_0}^{r_1} r^2dr} = \frac{3}{r_1^3 - r_0^3} \int_{r_0}^{r_1} \varepsilon_p(r)r^2dr$$

SPDE for volumetric sources can thus be calculated from discrete point efficiencies using Eq. (8) and Eq. (10).

C. Minimum Detectable Activity Concentration (MDAC)

MDAC represents the lowest activity concentration reliably detectable at a specified confidence level (e.g., 95%) [31], enabling verification of system monitoring capabilities. MDAC is expressed as:

$$MDAC = \frac{L_D}{\varepsilon \eta V t}$$

where L_D is the detection limit, calculated as [32]:

$$L_D = k^2 + 2k\sigma_0$$

with k as the one-sided confidence interval factor (1.645 for 95% confidence) and σ_0 as the standard deviation of background counts. At 95% confidence:

$$MDAC = \frac{2.71 + 4.65\sqrt{N_B}}{\varepsilon \eta V t}$$

where N_B is the total background count in the characteristic energy peak during measurement time. Equations (5), (10), and (13) demonstrate that MDAC depends on background count, detection efficiency, and maximum detectable distance.

III. Measurement System Design

A. Structural Design

As shown in Fig. 2 [Figure 2: see original paper], the NSAROMS comprises three main units: an atmospheric radionuclide detection unit, an analysis and control unit, and a meteorological detection unit.

The atmospheric radionuclide detection unit includes a ground gamma-ray shielding device, a NaI(Tl) scintillation detector, and a digital spectrometer. The trumpet-shaped directional shielding section and fixed base shield gamma rays from the ground and structures, improving detection limits and reducing environmental interference. The NaI(Tl) detector and digital spectrometer detect gamma rays from atmospheric radionuclide decay, process them into spectra, and transmit data to the computer for activity concentration calculations.

The analysis and control unit consists of an industrial computer, power controller, and uninterruptible power supply (UPS). It analyzes gamma-ray spectra, meteorological data, and GPS information while controlling both detection units and ensuring stable power. The UPS provides approximately 10 hours of backup operation during main power loss.

The meteorological detection unit integrates a compact weather station, video monitor, and GPS module to record temperature, humidity, PM2.5, PM10, rainfall, and surveillance footage. These data support source term analysis, atmospheric dispersion modeling, and climate impact assessment.

B. Design of the Detector and Ground Gamma-Ray Shielding Device

Detector selection for online systems requires balancing detection efficiency, energy resolution, intrinsic radioactivity, and cost-effectiveness. Using the Geant4 toolkit (a C++ Monte Carlo simulation package [32]), we simulated gamma-ray detection efficiencies for various scintillators (NaI(Tl), $CeBr_3$, $LaBr_3$(Ce), BGO, CsI(Tl)) across 0.1–3 MeV. To reduce computation time, we modeled a hemispherical 10-meter radius source filled with atmospheric radionuclides, with the detector positioned vertically to maximize efficiency.

Fig. 3 [Figure 3: see original paper] shows simulated efficiencies for NaI(Tl) detectors with sensitive volumes of 1 in. (1 in. × 1 in.), 2 in. (2 in. × 2 in.), 3 in. (3 in. × 3 in.), 5 in. (5 in. × 5 in.), 2 L (2 in. × 4 in. × 16 in.), and 4 L (4 in. × 4 in. × 16 in.). Detection efficiency increases with sensitive volume, particularly in the low-energy region. Fig. 4 [Figure 4: see original paper] compares different detector types with identical volume (3 in. × 3 in.). Above 0.2 MeV, BGO shows highest efficiency, followed by $CeBr_3$, $LaBr_3$(Ce), CsI(Tl), and NaI(Tl). Between 0.1–0.2 MeV, efficiency variations arise from encapsulation materials (MgO and Al) [34, 35].

Since increasing sensitive volume improves efficiency more significantly than changing detector type, we selected a NaI(Tl) scintillator for its availability in large volumes (2 L or 4 L), acceptable energy resolution, absence of intrinsic radioactivity, and relatively low cost [36–39].

The ground gamma-ray shielding device adopts a trumpet shape to facilitate detection volume calculation and effective ground gamma shielding. To optimize detection efficiency and shielding performance, we simulated various opening angles using Geant4 with an initially selected 2 L NaI(Tl) detector. An interfering source positioned 10 meters away and 6 meters high (matching typical building heights near nuclear facilities) evaluated shielding effectiveness.

We defined the Optimal Opening Angle Parameter (OAP) as the ratio of atmospheric radionuclide detection efficiency to interfering source efficiency:

$$OAP = \frac{\varepsilon_E}{\varepsilon_{SE}}$$

where ε_E and ε_{SE} are detection efficiencies for gamma rays from atmospheric and interfering sources, respectively. Using 3.6 cm thick lead (providing >95% shielding for <0.975 MeV gamma rays and 82.27% for 3 MeV gamma rays), we simulated OAP values for 1–3 MeV gamma rays across different half-opening angles ϕ_0 (Fig. 5 [Figure 5: see original paper]). The optimal half-opening angle

ranges from 20° to 30°; we selected 30° (60° opening angle) to ensure detection performance.

We fabricated a 60° horn-shaped shielding device with 3.6 cm lead filling and 2 mm stainless steel structural support. The system uses an XTD-100 digital spectrometer from Chengdu Newray Technology Co. Ltd., with technical specifications listed in Table 1 .

To verify that the 2 L NaI(Tl) detector (2 in. × 4 in. × 16 in.) and shielding design meet MDAC requirements for nuclear facility environments, we measured the background spectrum in a sealed lead chamber. Using Eq. (13) with simulated detection efficiencies for a 10 m radius hemispherical source, preliminary calculations yielded MDACs of 6.40$±0.24$Bq/m^{3}$ for ^{137}Cs and 6.01$±0.24$Bq/m^{3}$ for ^{134}Cs for 30-minute measurements. These values are below the derived air concentration limits for public exposure (20.70 Bq/m^3 for ^{137}Cs and 14.43 Bq/m^3 for ^{134}Cs under fast lung absorption), confirming the design meets online monitoring requirements [40].

C. Software Design

The measurement software employs multithreading to enhance data processing efficiency, enabling simultaneous measurement, processing, and transmission. As shown in Fig. 6 [Figure 6: see original paper], the operational flow is:

1. **Parameter Initialization**: The system reads default parameters for measurement, communication, calculation, and display functions.
2. **Thread Creation**: Upon starting measurement, four concurrent threads are launched: a measurement thread, an energy spectrum stabilization thread, a calculation/storage/display thread, and a data transmission thread. These threads communicate via message queues.

The measurement thread performs continuous automated monitoring of atmospheric radionuclide activity concentrations and meteorological parameters. The stabilization thread monitors spectra in real time, adjusting parameters to prevent drift and maintaining system status. The calculation thread processes spectra to determine activity concentrations, storing and displaying results. The transmission thread sends measurement data to designated servers or storage units.

IV. Calibration Experiment

A. Detection Efficiency Simulation

We constructed a complete system model using Geant4 (Fig. 7(a) [Figure 7: see original paper]), incorporating manufacturer specifications for all components except simplified photomultiplier tube and multichannel analyzer representations. A spherical coordinate system was established at the shielding device' s spherical cone vertex to simulate point, layer, and volume detection efficiencies at various atmospheric depths. Leveraging central symmetry, point sources

were uniformly distributed on spherical surfaces at each atmospheric depth according to θ and ϕ angles, with their x-y plane projection shown in Fig. 7(b) [Figure 7: see original paper].

A ^{226}Ra source in radioactive equilibrium was used experimentally. Simulation calculations focused on high-probability gamma rays from its decay progeny: 0.351 MeV (from ^{214}Pb), 0.609 MeV (from ^{214}Bi), and 1.764 MeV (from ^{214}Bi) [36]. Using the G4EmLivermorePhysics model, we simulated point, layer, and volume detection efficiencies at different atmospheric depths and compared volume efficiencies calculated via Eq. (8) and Eq. (10) with direct simulation results.

Fig. 8 [Figure 8: see original paper] compares directly simulated volumetric detection efficiencies with those calculated from point efficiencies for various gamma energies at different thicknesses, using r=120 cm as the reference plane. Excellent agreement was observed, with relative deviations within $±$4%, validating the theoretical calibration approach.

B. Detection Efficiency Experiment

The experimental platform combined the NSAROMS with calibration structures fabricated from 3D-printed photosensitive resin and carbon fiber to minimize gamma attenuation while maintaining mechanical strength and rigidity for elevated source positioning. Seven fewer source positions were used at each height compared to simulations due to the support rod' s physical width, particularly affecting the smallest radius circle at the top.

To avoid interference from surrounding structures, experiments were conducted in an open area >50 m from tall buildings (Fig. 10 [Figure 10: see original paper]). The ^{226}Ra standard source activity was 1.88×10^7 Bq (3% uncertainty), with its equilibrium decay spectrum shown in Fig. 11 [Figure 11: see original paper]. The source tray remained perpendicular to the support rod (Fig. 9 [Figure 9: see original paper]), ensuring consistent detector orientation and minimizing shape-related measurement variations, particularly at short distances.

Point source detection efficiency was measured at various distances. At 600 cm, significant support rod deformation at azimuthal angles $\phi = \pi/6$ and $\phi = \pi/10$ substantially affected results, so these data were excluded from final analysis.

C. Detection Efficiency and MDAC Discussion

Mean square errors of layer point source detection efficiencies from simulation and experiment are shown in Fig. 12 [Figure 12: see original paper]. Both simulation and experimental data show minimum errors at 300 cm measurement distance, indicating detector shape effects become negligible beyond this distance.

Fig. 13 [Figure 13: see original paper] compares experimentally measured layer detection efficiencies (via interpolation integration) with simulated val-

ues. Within the experimental height range, simulated and measured efficiencies show high consistency with relative errors within 5%. The increasing relative error at greater heights primarily results from slight downward deformation of the carbon fiber support rod under load.

When the detection system is simplified as spherical, the total spectrum count rate M can be expressed as [41]:

$$M = KEAC\pi \int_0^{r_1} e^{-\mu_E r} \left(r^2 - r\sqrt{r^2 - r_d^2} \right) dr$$

where r_1 is the gas radius and r_d is the simplified detector sphere radius.

The detection efficiency for gamma rays of specific energy at each layer is:

$$\varepsilon_p(r) = \frac{FEK}{E} e^{-\mu_E r} \left(r^2 - r_d^2 \right)$$

Logarithmic transformation with correction coefficients for $r < 300$ cm yields:

$$\ln(\varepsilon_p(r)) = a - \mu_E r + b \ln \left(\frac{r^2 - r_d^2}{r^2} \right) \quad (r < 300 \text{ cm})$$

For $r \geq 300$ cm, detector shape effects are negligible, so Eq. (18) applies:

$$\ln(\varepsilon_p(r)) = c - \mu_E r + \ln \left(\frac{r^2 - r_d^2}{r^2} \right) \quad (r \geq 300 \text{ cm})$$

Fitting layer detection efficiency variations using Eq. (17) and Eq. (18) yields coefficients a, b, and c for different gamma energies. Fig. 14 [Figure 14: see original paper] shows experimental fitting curves, with parameters listed in Table 2 .

After obtaining the layer efficiency formula, Eq. (10) calculates the volume detection efficiency for atmospheric radionuclides. Fig. 15 [Figure 15: see original paper] compares measured, calculated, and simulated volume detection efficiencies, showing relative errors within 5% across different thicknesses. This confirms the calibration method' s high feasibility and accuracy.

In practice, determining maximum detectable distances for different gamma energies is essential. We used the 95% attenuation distance as the system' s maximum detectable distance in air for efficiency and volume calculations. Based on Eq. (5), Eq. (6), Eq. (18), Eq. (19), and Table 2 parameters, detection efficiencies for 0.351, 0.609, and 1.764 MeV gamma rays were calculated (Table 3). Uncertainties represent synthetic values dominated by standard source uncertainty.

Fitting the measured efficiencies yields an energy-dependent system detection efficiency expression (Eq. 19):

$$\ln(\varepsilon_E) = -19.56 - 1.476 \times \ln(E) \quad (R^2 = 0.9969)$$

Detection efficiencies for various atmospheric radionuclides calculated via Eq. (20) are shown in Table 4 .

Using Eq. (13) with the background spectrum, 30-minute MDACs for ^{214}Pb (0.351 MeV), ^{214}Bi (0.609 MeV), and ^{214}Bi (1.764 MeV) are $2.74\$\pm0.08Bq/m^{\{3\},2.85\pm0.9Bq/m}\{3\}, and 8.94\pm0.27Bq/m\hat{}\{3\}\$$, respectively. Uncertainties are synthetic, dominated by detection efficiency uncertainty and gamma-ray statistical fluctuations. Table 5 lists estimated MDACs for common atmospheric radionuclides based on Table 4, Eq. (5), Eq. (6), Eq. (13), and the background spectrum.

V. Preliminary Application Results and Analysis

The NSAROMS was deployed in Mianyang, Leshan, Yibin, and Guangyuan, Sichuan Province, to measure atmospheric radionuclides under natural conditions. Fig. 16 [Figure 16: see original paper] shows measured gamma energy spectra, demonstrating the system' s capability to detect radon progeny ^{214}Pb (0.351 MeV) and ^{214}Bi (0.609 MeV, 1.764 MeV). We applied the system to atmospheric radon concentration measurements to evaluate accuracy and stability.

Atmospheric radon concentration can be expressed through ^{214}Pb and ^{214}Bi activity concentrations [46, 47]:

$$C_{Rn} = m(0.515C_{^{214}Pb} + 0.380C_{^{214}Bi}) + n$$

where C_{Rn} is atmospheric radon concentration, $C_{^{214}Pb}$ and $C_{^{214}Bi}$ are progeny activity concentrations, and m and n are calibration factors. Calibration against a Durridge RDA7 radon monitor yielded:

$$C_{Rn} = 1.15(0.515C_{^{214}Pb} + 0.380C_{^{214}Bi}) + 1.25 \quad (R^2 = 0.74)$$

Fig. 17 [Figure 17: see original paper] shows 30-minute interval radon concentration measurements from September 7 to October 7, 2024. On non-rainy days, all four sites exhibited diurnal periodicity. From September 23–25, concentrations peaked at sunrise (minimum temperature), decreased to afternoon minima (maximum temperature), then rose again. This pattern primarily reflects temperature inversion dynamics: nighttime inversions suppress turbulence, allowing radon accumulation until sunrise, while daytime surface heating disrupts inversions, enhancing vertical mixing and dispersion [48, 49].

Rainfall and strong winds disrupt this pattern. At Guangyuan, rainfall scavenging increased measured radon concentrations as progeny entered the detection volume with precipitation or deposited on system surfaces (Fig. 18 [Figure 18: see original paper]) [50]. On September 11, elevated radon occurred without optical rainfall detection because precipitation remained below the weather station' s 0.01 mm/min detection limit. Strong winds dispersing radon over larger areas and greater heights produced concentration minima, as observed on September 22 (Fig. 19 [Figure 19: see original paper]) [48].

The diurnal variation and wind effects measured by NSAROMS agree with Kumar K. C. et al. [49], while rainfall caused overestimation due to wet deposition of radon progeny. The overestimation magnitude depends on aerosol concentration, rainfall intensity, and duration. Future work will integrate NSAROMS radionuclide data with PM2.5, PM10, and optical rainfall measurements to develop deposition models correcting rainfall effects on measured concentrations.

After excluding rainfall periods, radon concentration ranges were <3.91-13.67 Bq/m^3 (Mianyang), <3.91-9.91 Bq/m^3 (Leshan), <3.91-9.90 Bq/m^3 (Yibin), and <3.91-19.95 Bq/m^3 (Guangyuan). Minimum values were below the NSAROMS radon MDAC (3.91 Bq/m^3). Average concentrations were $7.87\$\pm0.23, 4.48\pm0.15, 4.30\pm0.13, and 9.90\pm0.29 Bq/m^{\{3\}, respectively—all below the 10 Bq/m}\{3\}\$$ typical outdoor value reported by UNSCEAR 2000 [51]. The lower values reflect suburban measurement locations distant from major radon-emitting structures. The NSAROMS accurately measures atmospheric radon concentrations, reflecting variation patterns without enrichment or sampling steps, with minimal humidity effects, enabling long-term continuous online monitoring. The system also measures other atmospheric radionuclides, providing reliable data for routine facility monitoring and emergency early warning.

VI. Conclusions

We developed a NaI(Tl)-based nonsampling atmospheric radionuclide online measurement system for routine and emergency monitoring around nuclear facilities, establishing a calibration model and method for detection efficiency determination. Experimental results show relative errors within $\pm$5% between measured, calculated, and simulated detection efficiencies across all layers and depths, demonstrating high feasibility and accuracy. Analysis reveals that detector shape effects become negligible beyond 300 cm measurement distance.

The 30-minute MDACs from calibration experiments are $2.74\$\pm0.08 Bq/m\hat{}\{3\}\$$ (0.351 MeV ^{214}Pb), $2.85\$\pm0.09 Bq/m\hat{}\{3\}\$$ (0.609 MeV ^{214}Bi), and $8.94\$\pm0.27 Bq/m\hat{}\{3\}\$$ (1.764 MeV ^{214}Bi). Based on these results, 30-minute MDACs were calculated for common radionuclides including ^{7}Be, ^{22}Na, ^{134}Cs, ^{137}Cs, ^{131}I, and ^{40}K, with most meeting public dose constraint DACs. One-month continuous measurements at four locations yielded average radon concentrations of $7.87\$\pm0.23, 4.48\pm0.15, 4.30\pm0.13, and 9.90\pm0.29 Bq/m\hat{}\{3\}\$$— all below the UNSCEAR 2000 typical outdoor value.

The NSAROMS satisfies requirements for routine and emergency monitoring at nuclear facilities and is suitable for daily atmospheric radon monitoring. Compared to traditional methods, it significantly improves surveillance timeliness, providing rapid, reliable data for both routine operations and emergency response.

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