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Study on response of AlphaGUARD PQ2000 radon monitor to ^{220}Rn and its long-lived progeny in diffusion mode

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Abstract

Owing to the inherent limitation of the internal pulse ionization chamber within the AlphaGUARD PQ2000 radon monitor, that is, its inability to discriminate the energy levels of α particles, the ingress of ^{220}Rn from the surrounding environment, along with its decay progeny, poses a substantive challenge in accurately determining the ^{222}Rn concentration in the measurement outcomes. Among these, the protracted influence primarily stems from the two enduring decay progenies, namely ^{212}Pb with a half-life of 10.64 h and ^{212}Bi with a half-life of 60.54 min. This study explored the influence of ^{220}Rn progeny on the measurement results of an AlphaGUARD PQ2000 radon monitor by developing a theoretical calculation model. The response coefficient related to the residual ^{220}Rn progeny within the AlphaGUARD PQ2000 radon monitor was experimentally validated. In addition, this study investigated the effects of temperature and wind speed on the sensitivity of the instrument to ^{220}Rn gas. The research findings revealed commendable agreement between the experimentally measured response coefficients of the residual ^{220}Rn progeny and the corresponding values derived from the theoretical model. Notably, both the response coefficients of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas and its internal residual ^{220}Rn progeny increased with elevated temperatures and increased wind speeds, providing a reference for correcting the impact of ^{220}Rn and its progeny on the measurement results of ^{222}Rn concentration obtained using the AlphaGUARD PQ2000 radon monitor.

Keywords ^{220}Rn progeny · ^{222}Rn · AlphaGUARD PQ2000 · Long-term decay · Response coefficient · ^{220}Rn gas · Temperature effects · Wind speed effects

1 Introduction

^{222}Rn and its progeny are ubiquitously present in both indoor and outdoor environmental air, constituting the predominant source of natural radiation exposure for the general public [1–3]. Airborne ^{222}Rn is a leading cause of lung cancer [4–6]. Recent investigations have revealed elevated concentrations of ^{220}Rn in specific regions [7], with instances where the concentration surpassed that of ^{222}Rn and its progeny [8–11]. The existence of ^{220}Rn and its progeny poses a potential challenge for instruments designed to measure ^{222}Rn concentrations, affecting the precision of their results [12]. Consequently, to accurately assess the environmental hazards associated with ^{222}Rn, the precise monitoring of its concentration levels is important. To address this requirement, various instruments have been developed to measure the ^{222}Rn concentration.

The methods used to quantify the concentration of ^{222}Rn in an environment generally fall into three distinct categories: spot (grab) measurements, continuous measurements, and integrated (cumulative) measurements [13]. The AlphaGUARD PQ2000 radon monitor, which uses a typical continuous measurement approach, has been widely adopted as a prominent instrument for environmental ^{222}Rn measurements. The primary challenge in

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precisely monitoring the concentration of ^{222}Rn in the environment is effectively distinguishing between ^{222}Rn and ^{220}Rn [14]. Owing to the inherent characteristics of the pulse ionization chamber, the AlphaGUARD PQ2000 radon monitor lacks the capability to differentiate the energies of α particles, rendering it unable to distinguish between ^{222}Rn and ^{220}Rn [15]. Consequently, when the instrument continuously monitors the concentration of ^{222}Rn in an environment containing ^{220}Rn, the short-lived progeny ^{216}Po (half-life: 0.15 s), produced through the decay of ^{220}Rn, introduces interference, thereby affecting the precision of the ^{222}Rn measurement results. This challenge is further exacerbated by the presence of long-lived progeny, ^{212}Pb (half-life: 10.64 h) and ^{212}Bi (half-life: 60.05 min), resulting from the decay of ^{220}Rn. These long-lived progeny persisted within the ionization chamber of the AlphaGUARD PQ2000 radon monitor for an extended period, exerting a sustained influence on the accuracy of the ^{222}Rn measurement results over subsequent periods. This interference phenomenon aligns with the observations reported in the research conducted by Michielsen [16]. As outlined in the MetroRadon WP 2 report [17], several experimental investigations on the response of ^{222}Rn detectors to ^{220}Rn gas have been documented (Tokonami et al., 2001; Ishikawa, 2004; Bochicchio, 2009; Chen, 2009; Chen and Moir, 2012; Sumesh et al., 2012; Bondelsen and Bondiffel, 2015). In particular, for ionization chambers or semiconductor detectors used as ^{222}Rn monitors, the observed interference from ^{220}Rn gas typically ranges from 4% to 66% [17]. The modest response coefficient of the AlphaGUARD PQ2000 radon monitor toward ^{220}Rn necessitates careful consideration of the interference arising from residual ^{220}Rn progeny within the instrument, especially in environments with low ^{222}Rn and high ^{220}Rn concentrations [4]. Moreover, the response coefficient of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn does not vary with changes in the absolute concentration of ^{220}Rn or with the ratio of ^{222}Rn to ^{220}Rn [14]. Notably, a research gap remains regarding the influence of residual ^{220}Rn progeny within the instrument on ^{222}Rn measurement outcomes. Consequently, investigating the response coefficient of the instrument to its internal residual ^{220}Rn progeny is of paramount importance to ensure the accuracy of ^{222}Rn measurements obtained using the AlphaGUARD PQ2000 radon monitor.

In 2000, Fleischer et al. [18] demonstrated that the diffusion coefficients of various polymer materials were highly sensitive to temperature fluctuations, leading to significant variations in the permeation rate of ^{222}Rn as the temperature changed. The diffusion chamber of the AlphaGUARD PQ2000 radon monitor employs a glass fiber filter membrane as a diffusion barrier, which is insufficient to prevent ^{220}Rn gas from entering the ionization chamber [19]. During the initial phases of utilizing the AlphaGUARD PQ2000 radon monitor for the measurements, ^{220}Rn gas permeated the glass fiber filter membrane and entered the instrument's effective volume. The diffusion characteristics of the glass fiber filter membrane are temperature dependent, affecting the concentration penetration ratio of ^{220}Rn gas. Additionally, Omori et al. [20] observed that the response of diffusive detectors to ^{220}Rn gas varies depending on the ventilation status of the ambient air surrounding the detector. Therefore, it is crucial to investigate the impact of temperature on the response coefficient of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas.

This study was conducted under high ^{220}Rn concentrations. Experimental measurements and theoretical calculations were combined to investigate the response coefficients of the residual ^{220}Rn progeny within the AlphaGUARD PQ2000 radon monitor. The primary objective is to develop an innovative predictive model for estimating the concentration of the residual ^{220}Rn progeny with the aim of minimizing interference and enabling precise measurements of ^{222}Rn concentrations. In addition, the research explores the impact of temperature and wind speed on the response coefficients of the AlphaGUARD PQ2000 radon monitor for ^{220}Rn gas and its progeny.

2 Materials and methods

2.1 AlphaGUARD PQ2000 radon monitor

The AlphaGUARD PQ2000 radon monitor is a portable radon-monitoring device well-known for its high detection efficiency, broad measurement range, rapid response, and sustained long-term stability [21]. Consequently, it is widely used for radon monitoring. The measurement chamber has a volume of 0.62 ls, an effective detection volume of 0.56 ls, and a sensitivity of $50\,\mathrm{cpm} \cdot \mathrm{kBq}^{-1} \cdot \mathrm{m}^3$ [14]. The AlphaGUARD PQ2000 radon monitor primarily operates in two distinct measurement modes: flow and diffusion [21]. In flow mode, the gas was drawn into the ionization chamber through an external pump. In contrast, the diffusion mode involves the permeation of ^{222}Rn gas through a glass fiber filter covering the inlet to the ionization chamber, while simultaneously trapping the ^{222}Rn progeny on the filter [7]. The air inlet of the diffusion chamber is characterized by a circular opening with a diameter of 6.5 cm. According to the manufacturer's specifications, the glass fiber filter had a surface density of $70\,\mathrm{g} \cdot \mathrm{m}^{-2}$, a thickness of 0.35 mm, and an average particle size retention capability of 0.6 μm [22].

In an environment with a mixture of ^{222}Rn and ^{220}Rn, the instrument utilizes the detected α particles to calculate the ^{222}Rn concentration, leading to an overestimation of the actual environmental ^{222}Rn concentration levels. Consequently, the ^{222}Rn concentrations displayed by the AlphaGUARD PQ2000 radon monitor in these environments are inaccurate. Figure 1 shows a schematic diagram of ^{222}Rn collection principle by the AlphaGUARD PQ2000 radon monitor.

2.2 Establishment of the experiment for measuring the response coefficient of the AlphaGUARD PQ2000 radon monitor

An experiment was conducted in ^{220}Rn progeny during prolonged measurements using an AlphaGUARD PQ2000 radon monitor in a ^{220}Rn chamber, as shown in Fig. 2. The rectangular chamber had a volume of 125 ls and used a fan-driven solid-state ^{220}Rn source with an activity of 6×10^4 Bq. The ^{220}Rn concentration was measured using a single scintillation cell flow-static method [23]. The concentration from the LM2 ST-203 scintillation cell was decay-corrected to determine the true ^{220}Rn concentration in the thoron chamber as follows:

$$C_{\text{LM-Tn}} = \frac{C}{e^{-\lambda t}}, \tag{1}$$

where C represents the ^{220}Rn concentration measured using the LM2 ST-203 scintillation cell, λ is the decay constant of ^{220}Rn gas, and t is the pipeline correction time, defined as the ratio of the pipeline volume V connecting the ^{220}Rn chamber and scintillation cell to the air flow rate L.

Owing to the long half-life of ^{212}Pb, measurements were conducted for at least three days at high ^{220}Rn concentrations ($\geq 10\,\text{kBq} \cdot \text{m}^{-3}$) to determine the residual ^{220}Rn progeny response coefficient. The procedure was as follows: Valves 1

Fig. 1 AlphaGUARD PQ2000 radon monitor

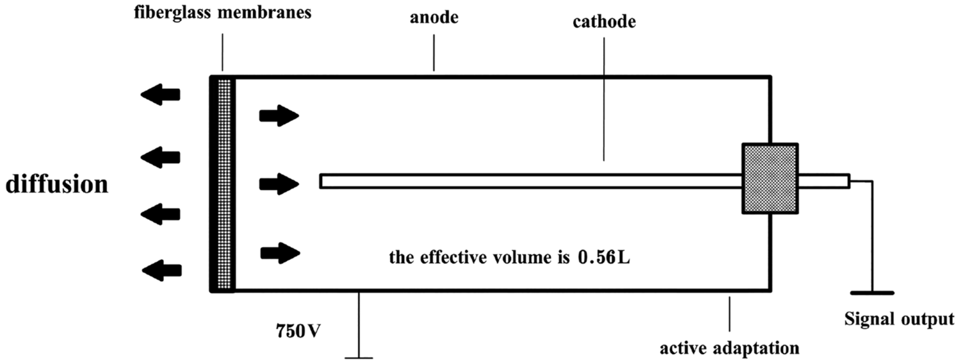
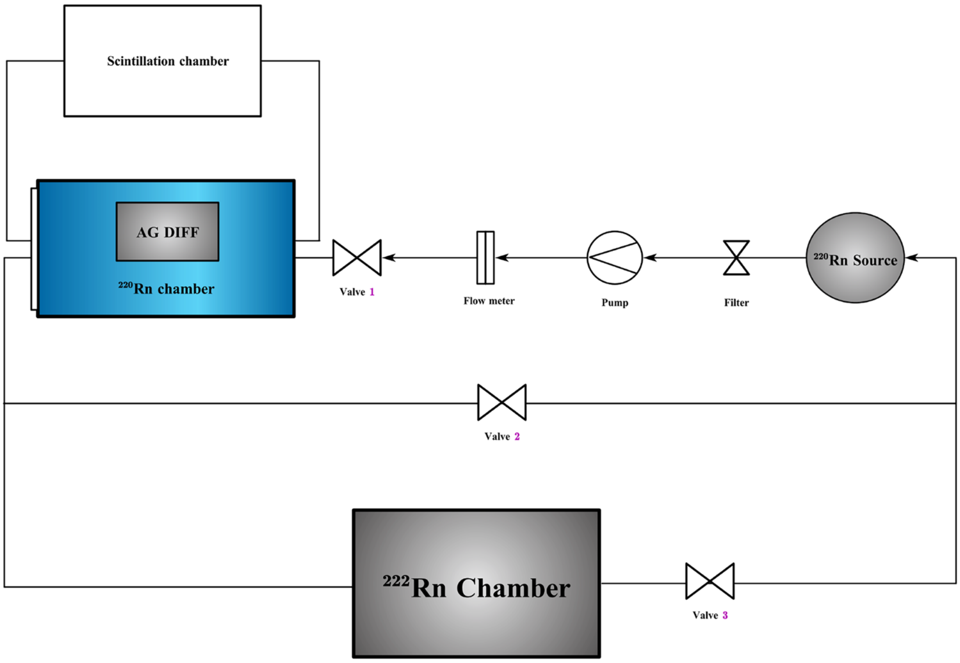


Fig. 2 (Color online) Experimental flowcharts illustrating the response measurement and validation procedures for the AlphaGUARD PQ2000 radon monitor with respect to residual ^{220}Rn progeny. “AG DIFF” denotes operation of the AlphaGUARD PQ2000 in diffusion mode



and 2 were opened, while valve 3 was closed. Subsequently, the AlphaGUARD PQ2000 radon monitor, operating in diffusion mode with a 10 min measurement interval, was placed in the small ^{220}Rn chamber and exposed until diffusion equilibrium was reached over a period of three days. Afterward, the ^{220}Rn source was disconnected, allowing the accumulated ^{220}Rn and its progeny to decay within the monitor in a low-radon background environment. Changes in the counting window data recorded by the AlphaGUARD PQ2000 radon monitor were monitored, and the background values of the environmental ^{222}Rn concentrations were subtracted; the resulting values were denoted as C_{PQ2000}.

The ratio of C_{PQ2000} to $C_{\text{LM-Tn}}$ represents the actual value of the response coefficient R_1 of the AlphaGUARD PQ2000 radon monitor relative to its internal residual ^{220}Rn progeny. The response coefficient R_1 of the instrument's response to the residual ^{220}Rn progeny is expressed as follows:

$$R_1 = \frac{C_{\text{PQ2000}}}{C_{\text{LM-Tn}}}. \tag{2}$$

To validate the theoretical model of the residual ^{220}Rn progeny response coefficient in a mixed ^{222}Rn and ^{220}Rn environment, an AlphaGUARD PQ2000 radon monitor was placed (as illustrated in Fig. 2). This experiment required valves 1 and 3 to be opened while valve 2 was closed. The vacuum pump was activated to draw ^{222}Rn gas from the ^{222}Rn chamber (maintained at a stable concentration of approximately 1600 $\text{Bq} \cdot \text{m}^{-3}$) into the small chamber containing ^{220}Rn gas, thereby ensuring uniform mixing and establishing a stable ^{222}Rn and ^{220}Rn mixed environment.

The concentrations of ^{222}Rn and ^{220}Rn were evaluated using various ST-203 scintillation cell models. The calibration coefficients for these scintillation cells were determined using standard flow-type solid-state ^{220}Rn sources with known activities and standard ^{222}Rn chambers with known concentrations. The mixed gas containing ^{222}Rn and ^{220}Rn was passed through a high-efficiency filter at a flow rate of approximately 3 $\text{L} \cdot \text{min}^{-1}$ before entering the scintillation cell. After a circulation period of 2 min, the initial counting session began at a counting time of 5 min. The sampling pump was then turned off and the scintillation cell was sealed. Following a 10-min waiting period, the second counting session was conducted, which lasted 5 min. The concentrations of ^{222}Rn and ^{220}Rn entering the scintillation cell can be determined using Eqs. [23]:

$$C_{\text{LM-Tn}} = K_{\text{Tn},1}(N_1 - C_{\text{Rn}}/K_{\text{Rn},1}), \tag{3}$$

$$C_{\text{Rn}} = K_{\text{Rn},2}(N_2 - q \cdot C_{\text{LM-Tn}}), \tag{4}$$

where C_{Rn} and $C_{\text{LM-Tn}}$ represent the concentrations of ^{222}Rn and ^{220}Rn, respectively. N_1 and N_2 denote the first and second counting rates, respectively. $K_{\text{Tn},1}$ is the calibration coefficient for ^{220}Rn, valued at 21.69 $\text{Bq} \cdot \text{m}^{-3} \cdot \text{cpm}^{-1}$, with a relative standard deviation of 2.00%. $K_{\text{Rn},1}$ is the calibration coefficient for ^{222}Rn during the flow measurement period, which is valued at 24.60 $\text{Bq} \cdot \text{m}^{-3} \cdot \text{cpm}^{-1}$ with a relative standard deviation of 2.51%. $K_{\text{Rn},2}$ is the calibration coefficient for ^{222}Rn during the static measurement period, valued at 20.32 $\text{Bq} \cdot \text{m}^{-3} \cdot \text{cpm}^{-1}$, with a relative standard deviation of 2.70%. The symbol q denotes the counting rate generated per unit concentration of ^{220}Rn during the second counting period, with a value of $8.61 \times 10^{-5} \text{Bq} \cdot \text{m}^{-3} \cdot \text{cpm}^{-1}$. This methodology achieved a combined uncertainty in the measured ^{220}Rn concentration, which was controlled within 5% [23].

Consequently, within a mixed environment of ^{222}Rn and ^{220}Rn, the modification of the AlphaGUARD PQ2000 radon monitor's measurement results using the theoretical model is expressed as the corrected result $C_{\text{Model-Rn}}$, as:

$$C_{\text{Model-Rn}} = C_{\text{PQ2000}} - R_2 \cdot C_{\text{LM-Tn}}. \tag{5}$$

Here, R_2 represents the response of the AlphaGUARD PQ2000 radon monitor to the residual ^{220}Rn progeny derived from the theoretical model. The calculation of R_2 is described in detail in Sect. 2.3.

2.3 Theoretical model for evaluating the response of AlphaGUARD PQ2000 radon monitor to its internal residual ^{220}Rn progeny in long-term measurements

In diffusion mode, the AlphaGUARD PQ2000 radon monitor allows gas from a ^{220}Rn environment to diffuse through its filter membrane and enter the pulse ionization chamber. According to Fick's first law, the rate at which molecules cross a unit area per unit time, denoted by J, is directly proportional to the concentration gradient of particles perpendicular to that unit area. In simpler terms [24]:

$$J = -D\frac{\partial C}{\partial x} = -\frac{D}{d}(C_{\text{in}} - C_{\text{out}}). \tag{6}$$

Hence, the gas diffusion process occurring in the pulse ionization chamber of the AlphaGUARD PQ2000 radon monitor that involves a time-dependent evolution of the ^{220}Rn concentration can be expressed as follows [25–27]:

$$\frac{\mathrm{d}C_{\text{in}}}{\mathrm{d}t} = -\lambda C_{\text{in}} + \gamma(C_{\text{out}} - C_{\text{in}}), \tag{7}$$

where J denotes the flux of flow, D is the diffusion coefficient of ^{220}Rn gas in the glass fiber filter, and d represents the thickness of the filter membrane, which is assumed to be very thin. C_{in} and C_{out} represent the theoretical ^{220}Rn concentrations inside the pulse ionization chamber of the

AlphaGUARD PQ2000 radon monitor and in the ^{220}Rn chamber, respectively. λ is the decay constant of ^{220}Rn, and γ denotes the air exchange rate.

In accordance with the differential Eq. (7) and under the initial condition $C_{\text{in}}(0) = 0$, we derive the expression that delineates the temporal evolution of C_{in}:

$$C_{\text{in}} = \frac{\gamma}{\gamma + \lambda}[1 - e^{-(\gamma+\lambda)t}]C_{\text{out}}. \tag{8}$$

After a long measurement period, the concentrations on both sides of the filter, specifically, the ^{220}Rn concentration in the pulse ionization chamber of the AlphaGUARD PQ2000 radon monitor and the ^{220}Rn concentration in the ^{220}Rn chamber reached a stable state and formed a ratio termed the concentration penetration ratio (ξ):

$$\xi = \frac{C_{\text{in}}}{C_{\text{out}}} = \frac{\gamma}{\gamma + \lambda}. \tag{9}$$

In the given equation, as deduced from Eq. (9), it is evident that ξ is related to γ and λ: ξ value of ^{220}Rn inside and outside the glass fiber filter in equilibrium on the AlphaGUARD PQ2000 radon monitor was 0.14 [28, 29], which was used to calculate the theoretical response coefficient value.

After exposing the AlphaGUARD PQ2000 radon monitor to the ^{220}Rn chamber for a duration of 3 d, and upon reaching diffusion equilibrium, the internal concentration, denoted as ($C_{\text{in}}(0)$) within the AlphaGUARD PQ2000 radon monitor, is described as:

$$C_{\text{in}}(0) = \xi \cdot C_{\text{out}}. \tag{10}$$

Assuming C_{out} remains constant, after three days, the internal ^{220}Rn and its progeny within the AlphaGUARD PQ2000 radon monitor can attain long-term equilibrium:

$$\begin{aligned} C_{^{220}\text{Rn}}(0) &= C_{^{216}\text{Po}}(0) = C_{^{212}\text{Pb}}(0) \\ &= C_{^{212}\text{Bi}}(0) = \frac{C_{^{212}\text{Po}}(0)}{0.64}. \end{aligned} \tag{11}$$

In accordance with the series of cascade decays involving ^{220}Rn and its progeny, the change in the overall radioactive concentration resulting from total α decay within the instrument can be expressed as follows:

$$C_R(T) = [C_{^{220}\text{Rn}}(T) + C_{^{216}\text{Po}}(T) + C_{^{212}\text{Bi}}(T)] \cdot E. \tag{12}$$

In the given expression, $C_{^{220}\text{Rn}}(T)$, $C_{^{216}\text{Po}}(T)$, and $C_{^{212}\text{Bi}}(T)$ represent the radioactive concentrations resulting from the α decay of ^{220}Rn gas, ^{216}Po, and ^{212}Bi, respectively. E denotes the average detection efficiency of the internal detector for α particles in the instrument, and T represents the decay time elapsed after the instrument's exposure. The sum of the radioactive concentrations of ^{220}Rn, ^{216}Po, and ^{212}Bi is detailed in Appendix A.

In fact, the instrument's detection efficiency for α particles from the decay of ^{220}Rn gas is nearly equal to α particles from the decay of ^{222}Rn gas. Based on the sensitivity of the instrument, the average theoretical E of the α particles measured using the pulse ionization chamber detector inside the AlphaGUARD PQ2000 radon monitor was determined to be 0.496. This value closely matched the simulated detection efficiency obtained by Zhang et al. [30] using Geant4 simulations.

Based on the theoretical model of the residual ^{220}Rn progeny in the diffusion mode of the AlphaGUARD PQ2000 radon monitor, the response coefficient R_2 of the instrument to its internal residual ^{220}Rn progeny is intricately linked to ξ. The theoretical expression for the response coefficient R_2 is given as:

$$R_2 = \frac{C_{\text{R}}}{C_{\text{out}}}. \tag{13}$$

This formulation embodies a theoretical model describing the instrument's response to the decay of the residual ^{220}Rn progeny.

3 Results and discussion

3.1 Comparison of theoretical and experimental values for the response coefficient of residual ^{220}Rn progeny in long-term measurements

AlphaGUARD PQ2000 radon monitor was exposed to a high concentration of ^{220}Rn in an environment where the ambient temperature was stabilized between 21 °C and 28 °C throughout each exposure period. During exposure, the relative humidity was maintained at 59% ±0.71%, the average pressure at 1006 ± 8.49 mbar. The response coefficient was theoretically calculated from a theoretical model describing the instrument's response to the residual ^{220}Rn progeny, as established in Sect. 2.3. The response coefficient was obtained via algorithmic fitting. The instrument was placed in a low-radon background environment with a ^{222}Rn concentration of 42 ±15 Bq·cm^{-3}. As the ^{220}Rn progeny decayed inside the instrument, three experiments were conducted to measure the response coefficients of residual ^{220}Rn. The C_{PQ2000} values were averaged, and C_{R} were determined. The theoretical and experimental response coefficients of the residual ^{220}Rn progeny are presented in Table 1.

The results in Table 1 indicate that, in an environment exposed to high ^{220}Rn gas concentrations of 4.65×10^5 Bq $\cdot$ m^{-3}, as measured by ST-203 scintillation cell, the influence of the residual ^{220}Rn progeny on radon measurements by the instrument cannot be overlooked. In this experiment, data were recorded every 10 min and

Table 1 Comparison of the experimental and theoretical values of the response coefficient of the AlphaGUARD PQ2000 radon monitor to residual ^{220}Rn progeny

Elapse time (h)	Radon concentration (Bq·m^{-3})		Response coefficient (%)		RD[a] (%)
	C_{PQ2000}	C_R	Experimental value	Theoretical value	
0	45413 ± 634	43689	9.78 ± 0.51	16.42	−40.43
2	9958 ± 287	11468	2.26 ± 0.03	2.39	−5.23
3	9563 ± 563	10887	2.17 ± 0.04	2.27	−4.19
4	9508 ± 123	10275	2.16 ± 0.11	2.14	1.07
5	8913 ± 337	9667	2.03 ± 0.00	2.01	0.60
6	8923 ± 379	9081	2.03 ± 0.00	1.89	7.19
7	8793 ± 195	8524	1.89 ± 0.12	1.78	6.64
8	7618 ± 236	7997	1.73 ± 0.12	1.67	4.02
9	7513 ± 54	7502	1.71 ± 0.06	1.56	9.34
10	7058 ± 429	7037	1.60 ± 0.03	1.47	9.41
11	6568 ± 202	6601	1.49 ± 0.013	1.38	8.58
12	6788 ± 1136	6192	1.54 ± 0.20	1.29	19.30
13	5778 ± 10	5809	1.32 ± 0.05	1.21	8.68
14	5703 ± 266	5450	1.30 ± 0.00	1.14	14.19
15	5597 ± 387	5114	1.27 ± 0.04	1.07	19.44
16	5248 ± 443	4799	1.19 ± 0.05	1.00	19.20
17	4988 ± 471	4504	1.03 ± 0.06	0.94	10.13
18	4628 ± 24	3925	0.95 ± 0.05	0.82	16.36

[a] RD is the relative deviation between the actual value and the theoretical value of the response coefficient

subsequently averaged over each 60-min period, as recommended. After the three-day exposure period, the instrument exhibited a response coefficient of 9.78% for the residual ^{220}Rn progeny within its internal components, consistent with results reported by national agencies such as STUK, SUBG, and IRSN [17]. The relative deviation between the experimental and theoretical values of the response coefficient was at its maximum immediately after the conclusion of the exposure period, exhibiting a deviation of 40.43%. This substantial discrepancy may be attributed to overestimation of the theoretical value. Conversely, the minimum relative deviation is 0.60%. The experimental response coefficient values for the residual ^{220}Rn progeny ranged from 0.95% to 9.78%, whereas the theoretical values range from 0.82% to 9.10%. All the response coefficient values for the residual ^{220}Rn progeny within the instrument were below 20%, aligned with the stipulations of the IEC 61577-2 standard.

Figure 3 shows a plot of the experimental and theoretical values of the response coefficients of the residual ^{220}Rn progeny. The observations suggest that at the 0-min mark, both the fitting results of the theoretical model and the experimental values after 120 min are higher. This discrepancy may be owing to the large uncertainty in the parameter values used in the model. However, after 120 min, the experimental values converged with the theoretical values. The response to residual ^{220}Rn progeny can be effectively predicted using the theoretical model developed in this study for the AlphaGUARD PQ2000 radon monitor, offering robust technical support for managing residual ^{220}Rn progeny interference in future applications.

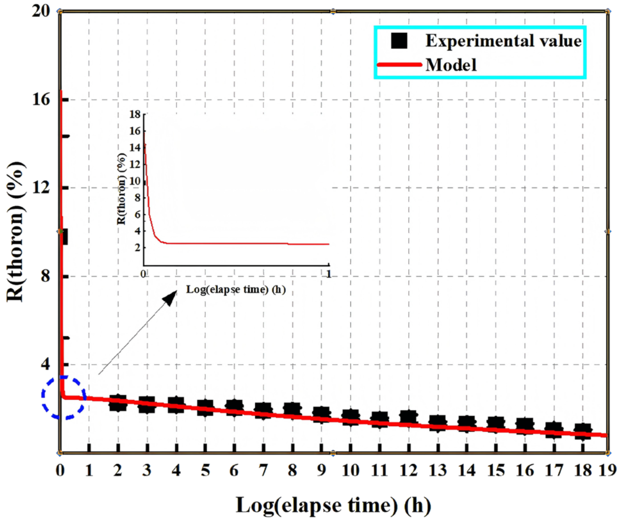


Fig. 3 (Color online) A comparative analysis was conducted between the experimental and theoretical response coefficient values for residual ^{220}Rn progeny within the instrument. The theoretical model was developed based on curve fitting using experimental data to estimate the relationship between the residual progeny concentration and the instrument's response $R = \frac{C_R}{C_{out}}$

3.2 Validation of the theoretical model for the response coefficient of residual ^{220}Rn progeny during long-term measurements

An AlphaGUARD PQ2000 radon monitor was used to measure the ^{222}Rn concentration in a mixed environment with low ^{222}Rn and high ^{220}Rn levels, as part of a validation experiment to evaluate its response to the residual ^{220}Rn progeny. Various models of ST-203 scintillation cells were deployed to determine the concentrations of both ^{222}Rn and ^{220}Rn within a small blue chamber with low ^{220}Rn levels. Initial measurements indicated a ^{220}Rn concentrations of 473502 ± 12666 Bq·m^{-3}. Subsequently, the AlphaGUARD PQ2000 radon monitor was exposed to the ^{220}Rn chamber for three days, maintaining a stable temperature between 20 °C and 24 °C. After disconnecting the ^{220}Rn source, the monitor initiated hourly measurements of ^{222}Rn concentration within the chamber. Following the methodology outlined in Sect. 2.2 of this paper for the validation experiment, readings from the AlphaGUARD PQ2000 radon monitor were corrected using the theoretical model for residual ^{220}Rn progeny. The corrected results were then compared with the experimental ^{222}Rn concentration values for analysis.

Figure 4 compares the corrected values from the theoretical model for the AlphaGUARD PQ2000 radon monitor in a mixed environment of ^{222}Rn and ^{220}Rn with the actual ^{222}Rn concentration values. The theoretical values closely matched the experimental data with minor deviations observed at certain points. These deviations may arise because the AlphaGUARD PQ2000 radon monitor primarily detects α decay energy from ^{222}Rn gas, typically around 5.49 MeV, while ^{212}Bi—a progeny of ^{220}Rn emits α particles within a similar energy range [17], potentially causing signal overlap at higher concentrations. In this mixed environment, the theoretical model was applied to correct the ^{222}Rn concentration values measured by the AlphaGUARD PQ2000 radon monitor. Despite slight fluctuations, the experimental measurements yielded an average ^{222}Rn concentration of 1648 ± 41 Bq·m^{-3} over 18 cycles. After correction, the theoretical model produced an average concentration of 1631 ± 112 Bq·m^{-3} for the same 18 cycles. The close agreement between these values highlights the practical utility of the theoretical model in reducing the influence of residual ^{220}Rn progeny on the monitor's performance, thereby enhancing the precision of ^{222}Rn concentration measurements.

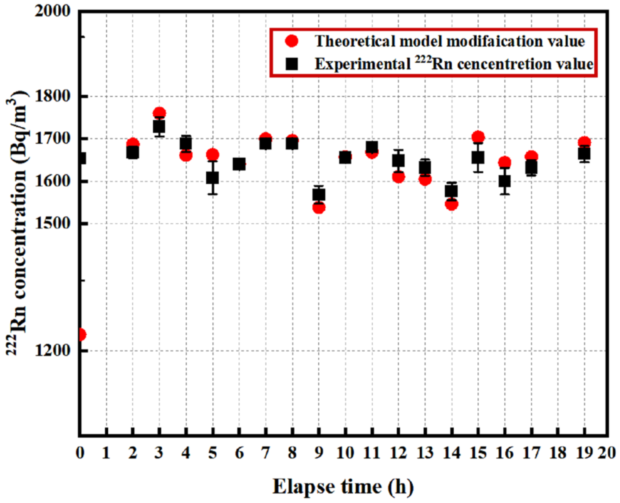


Fig. 4 (Color online) Comparison between the corrected ^{222}Rn concentration results obtained from the validation experiment and the corresponding experimental ^{222}Rn concentration values

3.3 Influence of temperature on the response of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas

Some radon monitors, such as those employing activated charcoal detectors [31], solid-state nuclear track detectors such as CR-39 [32] and instruments with membrane-covered diffusion chambers, where ξ for ^{222}Rn gas increases with temperature [19], show decreased sensitivity with increasing temperature. It is essential to account for temperature-induced biases during long-term monitoring using these instruments, particularly in environments with significant temperature fluctuations.

Furthermore, based on previous research findings, γ for the diffusion mode of the AlphaGUARD PQ2000 radon monitor can be mathematically expressed as [33]

$$\gamma = \frac{S \times D}{V \times d}. \tag{14}$$

Therefore, for the glass fiber filter, when $d \gg L_D$ (where L_D is the diffusion length of ^{220}Rn gas), combined with Eq. (7), ξ for the AlphaGUARD PQ2000 radon monitor can be expressed as

$$\xi = \frac{1}{1 + \lambda \frac{dV}{PS}}. \tag{15}$$

In this equation, S represents the effective area of the diffusion window filter in the AlphaGUARD PQ2000 radon monitor; D is the diffusion coefficient of ^{220}Rn gas in the glass fiber filter, which depends on the air temperature, porosity, and curvature of the glass fiber filter; V is the effective volume of the pulse ionization chamber; d is the thickness of the glass fiber; and P is the permeability of the ^{220}Rn gas through the glass fiber filter by diffusion. In fact, the temperature effect of ξ of the instrument is caused by the temperature effect of P of the glass fiber membrane on the ^{220}Rn gas [19].

In this study, under a consistent airflow velocity ($v = 1\ \mathrm{m} \cdot \mathrm{s}^{-1}$) within a disturbed environment, the concentration of the ^{220}Rn gas diffusing into the instrument was linked to ξ. After exposing the instrument to a stable ^{220}Rn concentration 255731 ± 9541 Bq·m^{-3} at temperatures of 9 °C, 28 °C, and 46 °C for 6 h, the ^{220}Rn source was then turned off. Measurements were then performed in a low ^{222}Rn background to determine the response coefficients of the ^{220}Rn gas and its internal residual ^{220}Rn progeny. The relationship between the response coefficient and temperature during short-term measurements was derived using the formula $R = signal/C_{\mathrm{out}}$. Based on the typical operating temperature range of 0–45 °C for the instrument, the variation in the response coefficient with temperature is shown in Fig. 5(a). Figure 5(b) presents a box plot of the temperature-related response coefficient to the internal residual ^{220}Rn progeny, where the square indicates the mean and the whiskers show the range from minimum to maximum. Across the three distinct temperature conditions, the median response coefficients of the instrument to its internal residual ^{220}Rn progeny were 0.685%, 1.038%, and 1.124%, respectively.

As depicted in Fig. 5(a), as the temperature increases, the instrument response to ^{220}Rn gas shows an increasing trend because the concentration of ^{220}Rn gas entering the instrument is affected by different temperatures, leading to different quantities of residual ^{220}Rn progeny. A box plot illustrating the relationship between the response coefficient of the AlphaGUARD PQ2000 radon monitor and the residual ^{220}Rn progeny with temperature (see Fig. 5b), discernible changes in the instrument response to the residual ^{220}Rn progeny at varying temperatures were observed. However, the response coefficient values obtained in this study were more than twice those reported by Liu et al. [14] under static conditions in 2010. In the present study, a fan-based thorium source was used to generate ^{220}Rn gas, and the exposure chamber volume was relatively small, which may have contributed to the higher response values. Consequently, the observed response pattern of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas in this experiment was higher than the response coefficient values reported in other studies that utilized membrane-covered diffusion chambers [7].

3.4 The impact of wind speed on the responsiveness of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas

Air exchange through a glass fiber filter (porous medium) depends partly on the pressure difference from the external air. Consequently, the response of diffusion-type detectors to ^{222}Rn and ^{220}Rn gases may vary with changes in the surrounding wind speed intensity [22]. During the extended environmental monitoring of the ^{222}Rn concentration using the diffusion mode of the AlphaGUARD PQ2000 radon monitor, the response coefficient to ^{220}Rn gas within the monitor may be affected by wind speed.

To scrutinize the effect of wind speed on the response of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas, the instrument was placed in a controlled 2700 L ^{220}Rn chamber containing consistent ^{220}Rn levels. Environmental temperatures during each exposure were maintained between 15 °C and 19 °C, whereas humidity was carefully controlled between 66% and 80%. Within the temperature and

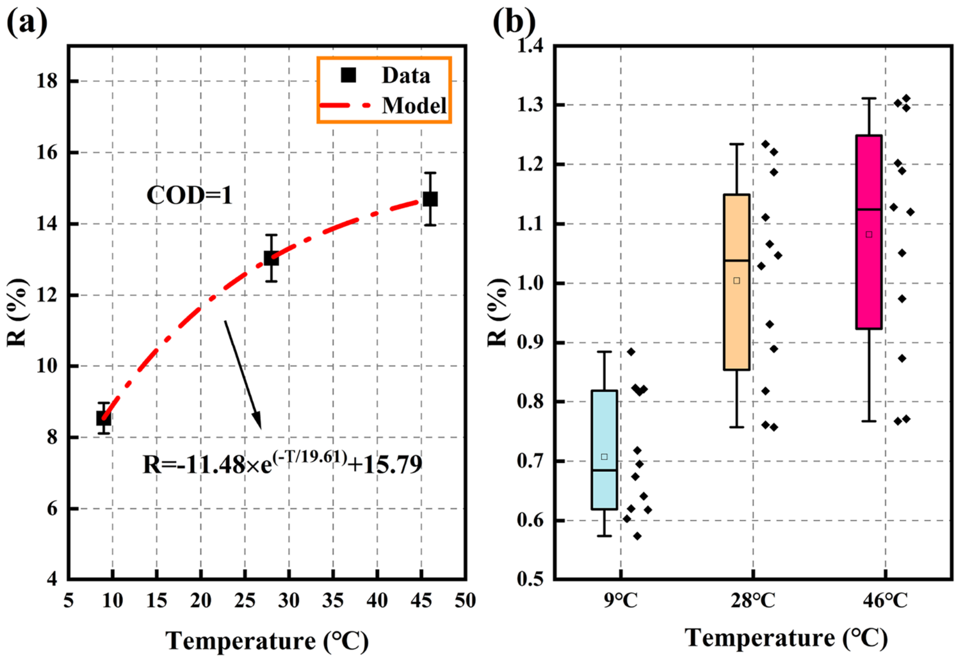


Fig. 5 (Color online) **a** Response coefficient of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas at different temperatures, with the fitted curve described by the equation: $y = -11.48 \times e^{(-T/19.61)} + 15.79$. **b** Box plot illustrating the instrument's response coefficient to residual ^{220}Rn progeny as a function of temperature

Table 2 Response coefficients of AlphaGUARD PQ2000 to ^{220}Rn gas at various wind speeds

Wind speed ($\mathrm{m \cdot s^{-1}}$)	C_{PQ2000} ($\mathrm{Bq{\cdot}m^{-3}}$)	C_{out} ($\mathrm{Bq{\cdot}m^{-3}}$)	Response coefficient (%)
0.00	567	11312	4.90
0.24	775	14376	5.48
0.50	939	14251	6.62
1.00	1572	14299	10.90
1.50	1681	14383	11.76
2.00	1797	14274	12.50
2.50	1804	14327	13.00
3.00	1762	14218	12.30

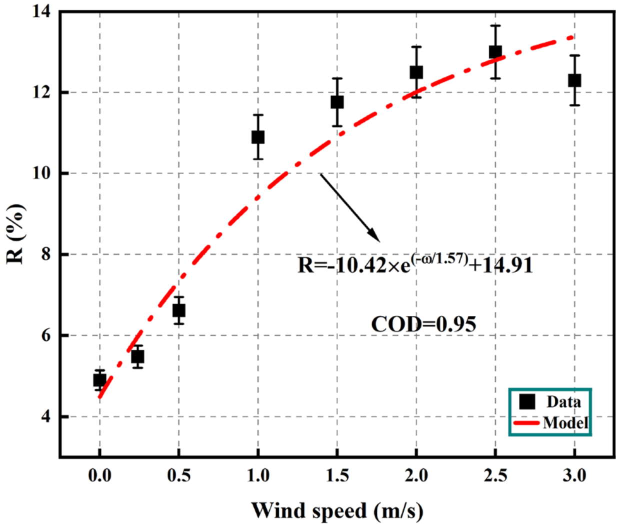


Fig. 6 (Color online) Response coefficient of AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas at different wind speeds

humidity range considered in this study, the potential influence of these environmental factors was deemed negligible [34]. The instrument was exposed for 6 h to a constant ^{220}Rn concentration of 14501 $\mathrm{Bq \cdot m^{-3}}$, under varying wind speeds of 0 $\mathrm{m \cdot s^{-1}}$, 1 $\mathrm{m \cdot s^{-1}}$, 2 $\mathrm{m \cdot s^{-1}}$, and 3 $\mathrm{m \cdot s^{-1}}$. The measurements were conducted over a fixed period of 60 min, and the changes in the response coefficient at different wind speeds are listed in Table 2.

Figure 6 shows how the AlphaGUARD PQ2000 radon monitor's response coefficient to ^{220}Rn gas related to wind speed. The figure indicates that the wind speed increases, similar to the response coefficient. Through a linear regression of the data within this range of wind speeds, the linear relationship between the response coefficient and wind speed was determined to be $R = -10.42 \times e^{(-\omega/1.57)} + 14.91$. Specifically, as wind speed increased from 0 to 1 $\mathrm{m \cdot s^{-1}}$, the response coefficient rose sharply from 4.90 to 10.90%, approximately doubling. This helps explain the higher response coefficient observed in this study compared to previous findings [14], as discussed in Sect. 3.3, which used a fan-driven diffusion-type ^{220}Rn source in a small-volume ^{220}Rn chamber. However, as wind speed increased further from 1 to 3 $\mathrm{m \cdot s^{-1}}$, the increase in the response coefficient became more gradual, rising from 10.90% to 12.30%. This reduced rate of increase at higher wind speeds can be explained by the principles of Darcy's law, which governs gas flow through porous media [35–38]. According to Darcy's law, when the Reynolds number is below a critical threshold, fluid velocity through a porous medium is linearly proportional to its permeability, cross-sectional area, and pressure gradient. However, once the Reynolds number exceeds this critical value, the flow transitions from laminar (Darcy flow) to turbulent (non-Darcy flow), where inertial forces dominate. In this experiment, below a wind speed of 1 $\mathrm{m \cdot s^{-1}}$, the response coefficient for ^{220}Rn gas was nearly proportional to wind speed, showing a sharp increase. As the wind speed exceeded 1 $\mathrm{m \cdot s^{-1}}$, the rate of increase in the response coefficient slowed and eventually stabilized, corresponding to a critical Reynolds number of approximately 1 $\mathrm{m \cdot s^{-1}}$.

4 Conclusion

This study establishes a theoretical model to explain the residual ^{220}Rn progeny response during long-term ^{222}Rn concentration measurements. The experimental data on the response coefficients of the residual ^{220}Rn progeny in a controlled ^{220}Rn environment were collected. The theoretical model is validated in an environment containing both ^{222}Rn and ^{220}Rn. Furthermore, we investigated and analyzed the effects of temperature and wind speed on the response of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas. The conclusions drawn are as follows:

1. The response coefficients of the residual ^{220}Rn progeny within the AlphaGUARD PQ2000 radon monitor consistently remained below 10% and aligning well with the simulated values from the theoretical model.

2. The response coefficient of the AlphaGUARD PQ2000 radon monitor to the ^{220}Rn gas increased with temperature. Similarly, its response to the internal residual ^{220}Rn progeny increases with temperature.

3. The response coefficient of the AlphaGUARD PQ2000 radon monitor to ^{220}Rn gas increased with wind speed. The critical Reynolds number was reached at a wind speed of 1 $\mathrm{m \cdot s^{-1}}$. Beyond this point, the rate of response increase slowed and stabilized.

Based on the above findings, the theoretical model used in this study effectively predicted the impact of the residual

^{220}Rn progeny within the AlphaGUARD PQ2000 radon monitor in mixed ^{222}Rn and ^{220}Rn environments. Additionally, it can assess the impact of the ^{220}Rn progeny on long-term monitoring of the ^{222}Rn concentration, significantly broadening its range of applications. It is important to emphasize that when using the AlphaGUARD PQ2000 radon monitor, appropriate precautions should be taken to minimize interference from environmental fluctuations that may affect ambient ^{222}Rn concentration measurements.

Appendix A: Internal decay of ^{220}Rn and its progeny in AlphaGUARD PQ2000 radon monitor

To ensure accurate measurement of ^{222}Rn concentration using the AlphaGUARD PQ2000 radon monitor in a mixed ^{222}Rn and ^{220}Rn environment, it is essential to understand the impact of ^{220}Rn and its progeny on the instrument. Although ^{220}Rn has a short half-life, a portion of the gas can diffuse into the detector chamber during long-term environmental monitoring, leading to the accumulation of its decay progeny. As illustrated in Fig. 7, which shows the ^{220}Rn decay chain, both ^{220}Rn and ^{216}Po present in the chamber can cause short-term interference with ^{222}Rn concentration measurements. In addition, the long-lived progeny of ^{220}Rn can result in sustained interference, potentially causing false counts in the AlphaGUARD PQ2000 ^{222}Rn concentration readings.

AlphaGUARD PQ2000 radon monitor was removed after being placed in the ^{220}Rn chamber for 3 days to establish equilibrium. Assume decay constants for ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi, and ^{212}Po are denoted as $\lambda_1 = 0.750\ \mathrm{min}^{-1}$, $\lambda_2 = 277.259\ \mathrm{min}^{-1}$, $\lambda_3 = 0.001\ \mathrm{min}^{-1}$, $\lambda_4 = 0.012\ \mathrm{min}^{-1}$, $\lambda_5 = 5 \times 10^{-9}\ \mathrm{min}^{-1}$, respectively. The decay of ^{212}Pb involves β decay; however, the pulse ionization chamber inside AlphaGUARD PQ2000 radon monitor detects only α particles and is insensitive to β particles. Based on the internal decay chain of ^{220}Rn and its progeny within the instrument, it was observed that, upon reaching long-term equilibrium, the primary contribution to the instrument's counts arises from the decay of the long-lived progeny ^{212}Bi of ^{220}Rn.

Because the decay of the progeny nuclei does not affect the decay of the ^{220}Rn gas, the change in $N_{^{220}\mathrm{Rn}}(T)$ with time follows the exponential decay law, which is expressed as

$$N_{^{220}\mathrm{Rn}}(T) = N_{^{220}\mathrm{Rn}}(0)e^{-\lambda_1 T}. \tag{A1}$$

For the progeny nuclei, the decay process is as follows:

$$\frac{\mathrm{d}N_i(T)}{\mathrm{d}T} = \lambda_{i-1}N_{i-1}(T) - \lambda_i N_i(\mathrm{T}). \tag{A2}$$

The equation describing the variation in ^{220}Rn progeny nuclei undergoing α decay can be derived according to the formula (A2):

$$\begin{cases} \frac{\mathrm{d}N_{^{216}\mathrm{Po}}(T)}{\mathrm{d}T} = \lambda_1 N_{^{220}\mathrm{Rn}(T)} - \lambda_2 N_{^{216}\mathrm{Po}}(T) \\ \frac{\mathrm{d}N_{^{212}\mathrm{Pb}(T)}}{\mathrm{d}T} = \lambda_2 N_{^{216}\mathrm{Po}}(T) - \lambda_3 N_{^{212}\mathrm{Pb}}(T) \\ \frac{\mathrm{d}N_{^{212}\mathrm{Bi}}(T)}{\mathrm{d}T} = \lambda_3 N_{^{212}\mathrm{Pb}}(T) - \lambda_4 N_{^{212}\mathrm{Bi}}(T) \end{cases}. \tag{A3}$$

Therefore, the concentration of radioactive nuclides can be expressed as

$$C = \frac{\lambda_i N_i}{V}. \tag{A4}$$

The internal concentration change in AlphaGUARD PQ2000 radon monitor is as:

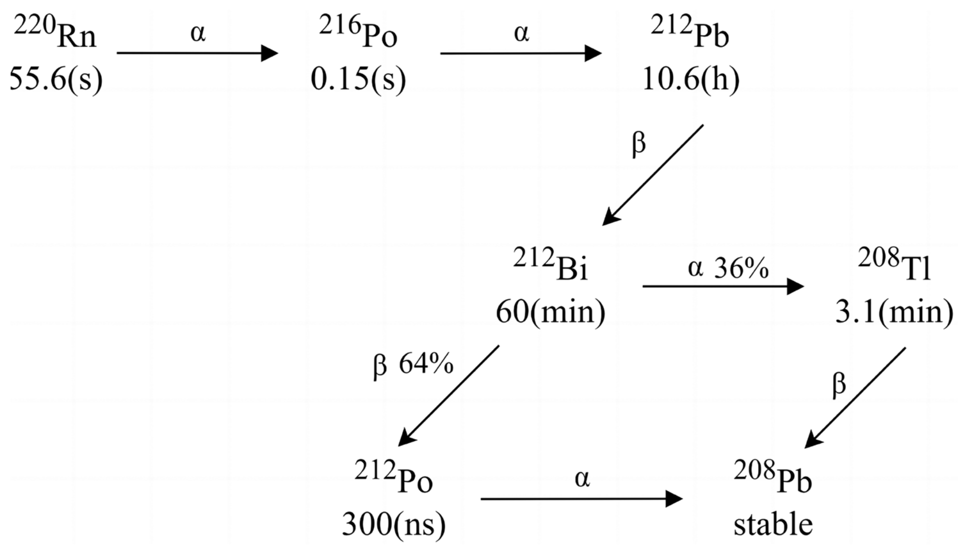


Fig. 7 ^{220}Rn decay chain

$$C_{^{220}\mathrm{Rn}}(T) = C_{^{220}\mathrm{Rn}}(0)\mathrm{e}^{-\lambda_1 T}. \tag{A5}$$

Equation (A5) represents the radioactive activity generated by the decay of ^{220}Rn, which indicates the total radioactive concentration of the ^{220}Rn gas within the instrument.

$$\begin{aligned} C_{^{216}\mathrm{Po}}(T) = {} & \frac{\lambda_2}{\lambda_2 - \lambda_1} C_{^{220}\mathrm{Rn}}(0)\mathrm{e}^{-\lambda_1 T} \\ & + \left[C_{^{216}\mathrm{Po}}(0) - \frac{\lambda_2}{\lambda_2 - \lambda_1} C_{^{220}\mathrm{Rn}}(0) \right] \mathrm{e}^{-\lambda_2 T}. \end{aligned} \tag{A6}$$

Equation (A6) represents the total radioactive concentration of ^{216}Po within the instrument, which is denoted by $C_{^{216}\mathrm{Po}}(T)$.

Considering that the internal pulsed ionization chamber of the AlphaGUARD PQ2000 radon monitor cannot distinguish between α particles with similar energies, but may exclude those with an energy of 8.78 MeV, the decay of the residual ^{212}Bi progeny within the instrument is represented as:

$$\begin{aligned} C_{^{212}\mathrm{Bi}}(T) = 0.36 \times \Bigg\{ & \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_1)(\lambda_3-\lambda_1)(\lambda_2-\lambda_1)} C_{^{220}\mathrm{Rn}}(0)\mathrm{e}^{-\lambda_1 T} \\ & - \left[\frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_2)(\lambda_3-\lambda_2)(\lambda_2-\lambda_1)} C_{^{220}\mathrm{Rn}}(0) - \frac{\lambda_3\lambda_4}{(\lambda_4-\lambda_2)(\lambda_3-\lambda_2)} C_{^{216}\mathrm{Po}}(0) \right] \mathrm{e}^{-\lambda_2 T} \\ & + \left[\frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_3)(\lambda_3-\lambda_2)(\lambda_3-\lambda_1)} C_{^{220}\mathrm{Rn}}(0) - \frac{\lambda_3\lambda_4}{(\lambda_4-\lambda_3)(\lambda_3-\lambda_2)} C_{^{216}\mathrm{Po}}(0) + \frac{\lambda_4}{(\lambda_4-\lambda_3)} C_{^{212}\mathrm{Pb}}(0) \right] \mathrm{e}^{-\lambda_3 T} \\ & + \Bigg[\left(\frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_2)(\lambda_3-\lambda_2)(\lambda_2-\lambda_1)} - \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_1)(\lambda_3-\lambda_1)(\lambda_2-\lambda_1)} - \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_4-\lambda_3)(\lambda_3-\lambda_2)(\lambda_3-\lambda_1)} \right) C_{^{220}\mathrm{Rn}}(0) \\ & + \left(\frac{\lambda_3\lambda_4}{(\lambda_4-\lambda_3)(\lambda_3-\lambda_2)} - \frac{\lambda_3\lambda_4}{(\lambda_4-\lambda_2)(\lambda_3-\lambda_2)} \right) C_{^{216}\mathrm{Po}}(0) - \frac{\lambda_4}{(\lambda_4-\lambda_3)} C_{^{212}\mathrm{Pb}}(0) + C_{^{212}\mathrm{Bi}}(0) \Bigg] \mathrm{e}^{-\lambda_4 T} \Bigg\}. \end{aligned} \tag{A7}$$

The total radioactive concentration of the ^{212}Bi progeny is obtained by summing the activities described in Eq. (A7) and is represented by $C_{^{212}\mathrm{Bi}}(T)$.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Ke-Xin Wang, Ya-Song Xiao, Yan-Bing Lin, and Wen-Jie Xu. The first draft of the manuscript was written by Ke-Xin Wang, and all authors commented on previous versions of the manuscript. Zheng-Zhong He supervised the project and provided critical intellectual input throughout the study. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are openly available in Science Data Bank at https://cstr.cn/31253.11.sciencedb.j00186.00810 and https://doi.org/10.57760/sciencedb.j00186.00810.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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