Radon collectors (e.g., PicoRad collectors) based on activated-charcoal have been used for screening and measuring radon. However, researchers at the U.S. Environmental Protection Agency reported that they could not verify the proper functioning of some commercially available radon detectors, including PicoRad collectors. In this study, we exposed two lots (with different expiration dates) of PicoRad collectors to the reference conditions at a controlled radon concentration within a radon chamber because the calibration factors were derived for use by a semi-empirical equation. Further, we exposed the PicoRad collectors to an uncontrolled radon atmosphere for conducting validity evaluation. The radon concentration results obtained by the PicoRad collectors using the semi-empirical equation were observed to be in good agreement with the conventional true radon concentration value. It denoted the optimal value of a quantity determined using a reference instrument. These experiments revealed that different values were required for the factors of the conversion equation of each radon collector lot with a different expiration date.

Key Words: radon ($^{222}\text{Rn}$), PicoRad collector, activated-charcoal radon collector, calibration factor, validity evaluation, radon chamber

1. Introduction

Radon ($^{222}\text{Rn}$) is a radioactive noble gas released by the normal decay of radium atoms within rocks and soil. Long-term exposure to radon can lead to lung cancer. In 2007, the International Commission on Radiological Protection recommended an upper reference level value of 300 Bq m$^{-3}$ for radon gas.
within dwellings.\(^1\)

In the present study, radon concentrations were measured using PicoRad collectors provided by AccuStar Labs (formerly Packard Instrument Company), USA.\(^2\) These collectors rely on radon adsorption onto activated-charcoal surfaces. In addition to activated carbon, the collectors contain silica as a desiccant. According to AccuStar Labs, the activated carbon can adsorb radon for 0.33 (8 h) to 3.25 d, which conforms with the 2 d minimum exposure time required by the American National Standards.\(^3\)

PicoRad collector is a short-term test device for radon. The U.S. Environmental Protection Agency (U.S. EPA) proposes that short-term tests should be performed under closed conditions,\(^4\) within which the radon concentration exhibits an increasing trend. It was our goal to identify an enclosed space with the potential to maintain an elevated radon level (e.g., levels of 300 Bq m\(^{-3}\) or greater). If a short-term test device reflects the value at the end of its exposure period, this type of device is considered ideal. Stawarz et al. reported that the radon concentration measured by PicoRad collectors is close to the mean radon concentration over the last 0.25 d exposure interval.\(^5\)

Radon measurements in previous studies (Table 1) have been out with a liquid scintillation counter (LSC, PerkinElmer Inc.), using PicoRad collectors, where the user interface is provided through dedicated PicoRad software.\(^6\) In such cases, the software contains a semi empirical equation to allow for conversion from the LSC counting ratio to the radon concentration.\(^6\) However, the U.S. EPA has been unable to verify the proper functioning of some commercially available radon detectors, including activated-charcoal radon collectors.\(^7,8\) Moreover, the measurement procedure recommended by the former Packard Instrument Company is obsolete because it specifies Insta-Fluor (PerkinElmer Inc.),\(^2,6\) which is mostly xylene (flash point 28°C) and is unavailable on the market, as the liquid organic scintillator. In our study, we used Insta-Fluor Plus (PerkinElmer Inc.) instead of Insta-Fluor. Our

Table 1 Calibration constants and factors for the PicoRad collectors. I: Passo and Cook (1994),\(^2\) II: Mamont-Cieśla et al. (1996),\(^14\) III: Koga et al. (1996),\(^15\) IV: Shefsky (1998),\(^16\) V: Stawarz et al. (2006),\(^5\) VI: Mori et al. (2013),\(^17\) VII: Iimoto et al. (2005),\(^12\) VIII: Cooper et al. (2011)\(^18\)

| LS | I | II | III | IV | V | VI | VII | VIII |
|----|---|----|-----|----|---|----|-----|------|
| Volume of LS | 10 | 10 | 10 | 10 | 10 | 15 | 20\(^7\) | 10 |
| Exposure time (days) | 2 | 1–3 | 1 | 2 | 2 | 4.2 | 1–2 | 0.1–1.7 |
| Elution time constant m (days) | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | – | – |
| Conversion coefficient f (cps m\(^{-3}\) kBq\(^{-1}\)) | 18.2 | 19.1 | 18.2 | 19.6 | 13.9 | 11.5 | – | – |
| Required elution time (days) | 0.33 | 0.33 | 0.83 | 0.33 | 0.33 | 0.83 | 0.15 | 0.33 |

\(^{*)}\) The PicoRad collector was full when 15 mL of LS was added.
previous investigations have shown that radon concentrations can be measured using a PicoRad collector with a conventional LSC (PerkinElmer Inc.) and a simplified LSC instrument (Thiathler LSC: Hidex Oy.) without using the PicoRad software. In the present paper, we focused on two calibration factors used in the conversion equation, i.e., a conversion coefficient that has a marked influence on the results and an elution time constant that has not yet been studied. The conversion coefficient directly affects the radon concentration conversion. Radon is eluted during PicoRad collector measurement. Therefore, when multiple PicoRad collectors are measured, the amount of radon eluted into the scintillator varies for each collector. Thus, the elution time constant and the required elution time are considered to be important parameters.

In Japan, radon detectors can be calibrated under reference conditions at a controlled radon concentration in a radon chamber at the National Institute of Radiological Sciences (NIRS). The standard procedure is based on a comparison of detectors tested using an AlphaGUARD reference instrument (NIRS AG), which is periodically calibrated in a certificated laboratory. PicoRad collectors exposed to radon for 2 d in the NIRS radon chamber were continuously measured using a LSC. The dedicated PicoRad software was not used.

We exposed two lots (with different expiration dates) of PicoRad collectors under reference conditions at a controlled radon concentration in the NIRS radon chamber. This enabled the derivation of calibration factors for use in the conversion equation of the PicoRad collectors. We determined the calibration factors (conversion coefficient and elution time constant) for the reference PicoRad collectors using the ratio that was obtained between the direct-reading counting rate of the PicoRad collectors and the conventional true radon concentration measured using the NIRS AG. The NIRS AG provided the optimal value of a quantity that was obtained using a reference instrument. Moreover, we tested whether the calibration factors are fixed values. We also exposed the PicoRad collectors to an uncontrolled radon atmosphere in an house-made radon exposition box to allow for a validity evaluation of these calibration factors. We assessed the validity evaluation based on the difference between the radon concentration measured by the PicoRad collectors and the conventional true radon concentration measured using the AlphaGUARD reference instrument.

2. Materials and methods

2.1 Reference PicoRad collector for the derivation of calibration factors

Two lots of PicoRad collectors, lots A and B, which had different expiration dates (different lot numbers) of 31 March, 2015 and 31 March, 2017, respectively, were used in the experiments. Six PicoRad collectors from each lot were simultaneously exposed under reference conditions at a controlled radon concentration in the NIRS radon chamber over 2 d (exposure time \( t_1 \) in Fig. 1) for the derivation of calibration factors, as shown in Fig. 2a. The spatial uniformity of the radon concentration inside the NIRS radon chamber was established with appropriate tests. The NIRS AG in the radon chamber was operated in diffusion mode and at a 10 min measurement interval. The conventional true radon concentration \( C_S \) kBq m\(^{-3} \) was determined using the optimal value of a quantity that was obtained using a reference instrument. Moreover, we tested whether the calibration factors are fixed values. We also exposed the PicoRad collectors to an uncontrolled radon atmosphere in a house-made radon exposition box to allow for a validity evaluation of these calibration factors. We assessed the validity evaluation based on the difference between the radon concentration measured by the PicoRad collectors and the conventional true radon concentration measured using the AlphaGUARD reference instrument.

Fig. 1 Measurement time schedule for the PicoRad collectors. The values of \( t, t_1, \) and \( t_2 \) are given in Eq. (1).
ing the NIRS AG, which was carried out using the NIRS AG within two years of its last calibration in a certified laboratory. A thermometer (TR-73U T&D Corp.) was used to determine the temperature at °C.

Exposure was terminated by closing the caps on the PicoRad collectors in the radon chamber. Data analyses were performed in the laboratory. Throughout this paper, these collectors are referred to as the “reference” PicoRad collectors.

2-2 Test PicoRad collectors for validity evaluation

In order to assess the validity evaluation of the conversion equation, we determined whether the conversion equation of a PicoRad collector that was determined using the NIRS radon chamber was effective for PicoRad collectors exposed to radon at varying concentrations in a laboratory at Kobe Pharmaceutical University (KPU). For this purpose, four PicoRad collectors from lot A (or lot B) were exposed for 2d (t₁ in Fig. 1) in an house-made radon exposition box (12 L polypropylene box) (Fig. 2b). Four PicoRad collectors from lot A were adhered to the inside lid of the box. Next, the caps of the PicoRad collectors were opened, the cover of the
case around the radon source was opened, and the lid of the box with the PicoRad collectors attached was closed. The collectors were then exposed to radon for 2 d before the lid on the box was opened and the caps on the PicoRad collectors were closed as quickly as possible. The high radon concentration air in the box was exchanged with air from the surrounding room. PicoRad collectors from lot B were subjected to the same procedure. Throughout this paper, these PicoRad collectors are referred to as the "test" PicoRad collectors.

The $C_S$ kBq m$^{-3}$ in the house-made radon exposition box was measured by the AG of KPU (KPU AG) under the same working regime that was used in the NIRS radon chamber (flow mode: 0.5 L min$^{-1}$, interval time: 10 min). A 50 g uranium ore sample was used as the radon source in the exposition box (Appendix A1). Further, a thermometer was used to determine $d^\circ$C.

2.3 PicoRad collector evaluations

After exposure, 15 mL of liquid scintillator (LS) Insta-Fluor Plus (PerkinElmer Inc.) was poured into each PicoRad collector, according to the Iimoto method (see Appendix A2).12 Radioactive equilibrium between radon and its short-lived decay products is established within 0.17 d (4 h). After radioactive equilibrium was established, the PicoRad collectors were measured with the LSC (Tri-Carb 2300TR, PerkinElmer Inc.). The PicoRad collectors were consecutively measured by the LSC for over 3 d. Fig. 1 shows a schematic of the experimental protocol. Each measurement was conducted for at least 10 min. Using the raw counting rates obtained from the LSC, the counting rates were calculated using the integral counting method. Approximately 100% of $\alpha$-rays were detected. However, $\beta$-rays required correction because of weak quenching; we therefore used the integral counting method. The lower limits of the energy windows were set in the $\beta$-ray regions (50–2000, 75–2000, and 100–2000 keV). The integral counting curves were extrapolated to intercept the vertical axis at 0 keV on the horizontal axis, and an integral counting rate of 0–2000 keV was obtained for $N$ cps (see Fig. 1–2 in Ref. 13).13 Similarly, a background integral counting rate of 0–2000 keV was obtained for $N_0$ cps.

3. Data analysis

We determined the calibration factors (conversion coefficient $f$ cps m$^3$ kBq$^{-1}$ and elution time constant $m$ d) for the reference PicoRad collectors using the ratio between the direct-reading counting rate of the PicoRad collectors and $C_S$ kBq m$^{-3}$ measured using the NIRS AG. The equation for converting from the counting rate of a PicoRad collector to the radon concentration ($C_i$ kBq m$^{-3}$) is given as Eq. (1).14 The uncertain two values expressed in $f$ cps m$^3$ kBq$^{-1}$ and $m$ d were determined using Eq. (2):

$$C_i = \frac{(N-N_0) \cdot \exp\left(\frac{d-d_0}{m_2}\right) \cdot \exp\left(\frac{t_1}{m_2}\right)}{f \cdot \left[1-\exp\left(-\frac{t}{m}\right)\right] \cdot \left[1-\exp\left(-\frac{t_1}{m_1}\right)\right]}$$

(1)

$$F(t)=\frac{(N-N_0) \cdot \exp\left(\frac{d-d_0}{m_2}\right) \cdot \exp\left(\frac{t_2}{m_3}\right)}{C_S \cdot \left[1-\exp\left(-\frac{h}{m_1}\right)\right]}$$

(2)

Terms used in the above equations were as follows:

- Actual measurement values:
  - $C_S$: Conventional true value of radon concentration measured using the NIRS AG or KPU AG (kBq m$^{-3}$)
  - $N$: Counting rate of the PicoRad collector using the LSC (cps)
  - $N_0$: Background counting rate of the PicoRad collector using the LSC (cps)
  - $d$: Exposure temperature ($^\circ$C)
  - $t$: Elution time (the elapsed time between the addition of the LS and the intermediate measuring time
of the LSC (d)

\( t_2 \): Elapsed time between cessation of radon exposure and the intermediate measuring time of the LSC (d)

Fixed values:

\( t_1 \): Exposure duration: 2 d

Constant values:

\( m_1 \): Adsorption time constant (d) (inverse exponential time constant at which the activated-charcoal of the PicoRad collector adsorbs radon from the air; the inverse exponential time constant is the time at which radon adsorption reaches \((1-e^{-1})=0.632\) of its maximum radon amount): 0.75 d

\( m_2 \): Exponential constant of temperature (°C) (with increasing temperature of \( m_2 \), radon adsorption is reduced to \( e^{-1}=0.368 \) times its initial value; the activated-charcoal adsorbs radon less effectively at higher temperatures and more effectively at lower temperatures): 27.78°C

\( m_3 \): Mean lifetime of radon (d): 5.5 d

\( d_0 \): Calibration temperature at which \( m_2 \) is determined: 22.22°C

Uncertain values:

\( f \): Conversion coefficient (cps m\(^{-3}\) kBq\(^{-1}\))

\( m \): Elution time constant (d) (an inverse exponential time constant at which radon elutes from the activated-charcoal to the LS in the PicoRad collector; the inverse exponential time constant is the time at which radon elution reaches \((1-e^{-1})=0.632\) of its maximum radon amount)

4. Results and discussion

4-1 Derivation of calibration factors

The mean \( C_s \) for the 2 d exposure, as determined using the NIRS AG, was 5.08±0.32 kBq m\(^{-3}\), as shown in Fig. 3. The exposure temperature (\( d °C \)) was 20.8±0.0°C.

Continuous measurements of the reference PicoRad collectors (both lots A and B) using the LSC

![Data](image)

**Fig. 3** Variation of the conventional true radon concentration (\( C_s \)) in the NIRS radon chamber, as measured using NIRS AG.

![Data](image)

**Fig. 4** Net counting rates as a function of elution time (\( t \)) for reference PicoRad collectors from a) lot A and b) lot B.
provided time-series data for the net counting rate 
\((N-N_0)\) cps, as shown in Fig. 4. The time-series data
for \(F(t)\) in Eq. (2) were then calculated. In Fig. 5, \(f\) in
Eq. (2) was determined to be 12.3±2.0 cps m\(^3\) kBq\(^{-1}\)
by fitting \(F(t)\) with 0.17 d (4 h)<\(t<3\) d (187 data
points) to a regression equation using KaleidaGraph

3.6 (HULINKS, Inc.). To obtain \(m\), data for 0.17 d
(4 h)<\(t<1.2\) d (71 data points) were also fitted to
a regression equation using KaleidaGraph. It takes
0.17 d (4 h) for radon and radon progeny nuclides
to reach a secular equilibrium. Ninety-five percent
of the radon was estimated to be eluted from the
PicoRad collector to the LS after 1.2 d (three times
the elution time constant). When the elution time
was determined using a fixed \(f=12.3\pm2.0\) cps m\(^3\)
kBq\(^{-1}\), \(m\) in Eq. (2) was 0.379±0.138 d. The relative
standard deviations (RSDs) of \(f\) and \(m\) were 17% and
36%, respectively. Since the RSD of \(m\) was
very high, it was considered that the regression was
invalid. We found that it was necessary to obtain a
separate regression analysis for each lot.

Similarly, regarding the reference PicoRad
collectors of lot A (Fig. 6a) and lot B (Fig. 6b), the \(f\)
and \(m\) values in Eq. (2) were determined. In the case
lot A, \(f=13.5\pm0.8\) cps m\(^3\) kBq\(^{-1}\) (91 data points)
and \(m=0.397\pm0.057\) d (35 data points), with RSDs
of 5.9% and 14%, respectively. In the case lot B,
\(f=10.6\pm0.6\) cps m\(^3\) kBq\(^{-1}\) (96 data points) and
\(m=0.399\pm0.077\) d (36 data points), with RSDs of
5.7% and 19%, respectively. The RSDs of \(m\) for lots
A and B were around 15%. We compensated for the

![Fig. 5 Correction factor \(F(t)\) as a function of elution time \(t\) for reference PicoRad collectors from both lots A and B. The regression line follows the exponential function given in Eq. (2) with \(f=12.3\pm2.0\) cps m\(^3\) kBq\(^{-1}\), \(m=0.379\pm0.138\) d, the correlation coefficient \(R=0.76\), and the number of PicoRad collectors \(n=12\).](image1)

![Fig. 6 Correction factor \(F(t)\) as a function of elution time \(t\) for reference PicoRad collectors from a) lot A. The regression line follows the exponential function given in Eq. (2) with \(f=13.5\pm0.8\) cps m\(^3\) kBq\(^{-1}\), \(m=0.397\pm0.057\) d, the correlation coefficient \(R=0.95\), and the number of PicoRad collectors \(n=6\). b) Lot B. The regression line follows the exponential function given in Eq. (2) with \(f=10.6\pm0.6\) cps m\(^3\) kBq\(^{-1}\), \(m=0.399\pm0.077\) d, \(R=0.96\), and \(n=6\).](image2)
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high relative standard deviation of \( m \) by making the elution time sufficiently long.

Fig. 7 shows the continuous measurement values of \( C_i \) for the reference PicoRad collectors, as obtained by substituting measurement data \( f \) and \( m \) into Eq. (1) for each lot. The mean \( C_i \) values of lot A and lot B were \( 5.00\pm0.27 \text{ kBq m}^{-3} \) and \( 4.92\pm0.12 \text{ kBq m}^{-3} \), respectively. After \( t \) of 0.4 d or more, the \( C_i \) values agreed with \( C_S \) (\( 5.08\pm0.32 \text{ kBq m}^{-3} \)) within a relative error of \( \pm15\% \) of \( C_S \). Considering (i) the influence of the fluctuation of \( m \) and (ii) the radioactive decay of radon, we decided to determine \( C_i \) using the data from 1.5 d to 3 d.

### 4.2 Validity evaluation

The results of the experiments are presented in Fig. 8a (lot A) and b (lot B). The variation curves (or the values of \( C_S \) \( \text{kBq m}^{-3} \)) differ between lot A and lot B. This phenomenon can be explained by the amount of radon released from the radon sources. The mean \( C_S \) \( \text{kBq m}^{-3} \) values for the various time (0.25 d, 0.5 d, 0.75 d, 1.0 d, 1.25 d, 1.5 d, 1.75 d, and 2 d) intervals of exposure are calculated and are indicated by the crosses in Fig. 8c (lot A) and d (lot B). In this paper, \( C_{S1} \) \( \text{kBq m}^{-3} \) (or \( C_{S2} \) \( \text{kBq m}^{-3} \)) in the house-made radon exposition box was defined as the conventional true radon concentration averaged for the last 0.25 d (or 2 d) interval of exposure. This was defined based on the work of Stawarz, who reported that the radon concentration measured by a PicoRad collector is close the mean radon concentration of the last 0.25 d interval of exposure. The 2d interval was the entire period of exposure. For PicoRad collectors from lot A, \( C_{S1}=9.68\pm0.40 \text{ kBq m}^{-3} \) and \( d=22.9\pm0.1 ^\circ \text{C} \). For PicoRad collectors from lot B, \( C_{S1}=13.10\pm0.44 \text{ kBq m}^{-3} \) and \( d=22.2\pm0.1 ^\circ \text{C} \).

While using the calibration factor shown in Fig. 6a and 6b, the \( C_i \) values of the test PicoRad collectors were determined using the measurement values of lot A and lot B, respectively, obtained between 1.5 d and 3 d. For PicoRad collectors from lot A and lot B values of \( C_i=9.72\pm0.38 \text{ kBq m}^{-3} \) and \( C_i=13.95\pm0.65 \text{ kBq m}^{-3} \), respectively, were calculated, as indicated by the circles in Fig. 8c and d (the primary vertical axis), respectively. The difference between \( C_i \) and \( C_{S1} \) (100(\( C_S-C_i \)/\( C_i \))\%), is shown on the secondary vertical axis. The difference between \( C_i \) and \( C_{S1} \) for each lot was less than 7\%, and the \( C_i \) results were in good agreement with the \( C_{S1} \) values. From Fig. 8d, the difference between \( C_i \) and \( C_{S2} \) for lot B was around 15\%, and the \( C_i \) values were closer to the \( C_{S1} \) values than to the \( C_{S2} \) values. Under conditions of increasingly fluctuating radon concentrations (Appendix 3), the difference between \( C_i \) and
C_{S1} for each lot was less than 12%, as shown in Fig. A2. The difference between C_i and C_{S2} was around 14%. The C_i values were closer to the C_{S1} values than to the C_{S2} values.

5. Conclusion

We exposed two lots (with different expiration dates) of PicoRad collectors to reference conditions at a controlled radon concentration in the NIRS radon chamber to enable the derivation of calibration factors for the collectors. We found that the calibration factors (elution time constant (m) and conversion coefficient (f) of the conversion equations) of the collectors should not be fixed; rather, they should be determined for each lot with a different expiration date. The m value was approximately 0.4 d, which is five times higher than the constants (0.08 d) reported in previous studies. The f value was approximately 10–14 cps m^3 kBq^{-1}, which was in agreement with the lower constants (11–19 cps m^3 kBq^{-1}) reported in previous studies. We exposed the two lots of PicoRad collectors to an uncontrolled radon atmosphere in an house-made radon exposition box to enable a validity evaluation of the PicoRad collectors. In accordance with a previous study, the conventional true radon concentration (C_S kBq m^{-3}) in the box was defined as the mean radon concentration of the last 0.25 d interval of exposure. The radon concentration results (C_i) obtained by the four PicoRad collectors using the above f and m values were in good agreement with the values of C_S. The values of C_i were closer to the values of C_S for the 0.25 d exposure interval than they were for the 2 d exposure interval. Even for an uncontrolled radon concentration, it was
possible to determine the radon concentration using four PicoRad collectors and the above calibration factors.

**Funding**

This work was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan under its Earthquake and Volcano Hazards Observation and Research Program [1207], and the network-type joint Usage/Research Center for Radiation Disaster Medical Science of Hiroshima University, Nagasaki University, and Fukushima Medical University.

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要 旨
活性炭ラドン収集器の校正係数の導出とその有効性評価
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2017 年 2 月 15 日 受付
2019 年 1 月 11 日 受理

活性炭を用いたラドン収集器 (PicoRad) は、ラドンのスクリーニングに用いられてきた。しかし、米国環境保護庁は、PicoRad を含む市販のラドン収集器について適切な測定結果が得られなかったことを指摘した。ラドン濃度を制御した標準ラドンチャンバで、2つのロット (有効期限が異なる) PicoRad を曝露し、その標準ラドンチャンバの基準と比較して、計数率からラドン濃度への変換式を決定した。さらに、有効性評価を行うために、PicoRad を、ラドン濃度が制御されていないラドン場で曝露し、この変換式を用いてラドン濃度を求めたところ、ラドン濃度基準値とよく一致した。この研究では、有効期限の異なるロットごとに PicoRad の変換式の係数が必要であることが明らかになった。
Appendix

A1. Trapping thoron emanating from the uranium ore sample

The uranium ore sample was placed into a hermetically sealed plastic bag to trap the thoron emanating from the sample. Using a RAD7 semiconductor α-detector (DURRIDGE Co. Inc., USA), which can measure radon concentrations and thoron concentrations discriminatively, we confirmed that no thoron was present in the house-made radon exposition box.

A2. Comparison of the conventional method with the method used in the present study

Using sensitivity experiments, we compared the \( f \) values obtained using 15 mL of Insta-Fluor Plus (type 1, the number of PicoRad collectors, \( n=11 \)) and 10 mL of Insta-Fluor Plus (type 2, \( n=4 \)). The Insta-Fluor Plus, which is mostly 1,2,4-trimethylbenzene, exhibits low volatility (flash point: 50°C). PicoRad collectors (lot C; expiration date of 31 January, 2020) were exposed in the NIRS radon chamber \( (C_S=8.00\pm0.5\text{ kBq m}^{-3}; \ d=24.5\pm0.2^\circ\text{C}; \ \text{entire period of exposure}) \). After exposure, LS was poured into each PicoRad collector. Continuous LSC measurements of the reference PicoRad collectors gave time-series data for the net counting rate \( (N-N_0) \text{ cps} \), and the time-series data for \( F(t) \) in Eq. (2) were subsequently calculated. In Fig. A1, the \( f \) values in Eq. (2) were 11.0±0.5 (type 1) and 9.79±0.37 (type 2). The regression lines follow the exponential function given in Eq. (2) with the following values. Type 1: \( f=11.0\pm0.5\text{ cps m}^3\text{ kBq}^{-1} \), \( m=0.39\pm0.05\text{ d} \), the correlation coefficient \( R=0.98 \), and the number of PicoRad collectors \( n=11 \). Type 2: \( f=9.79\pm0.37\text{ cps m}^3\text{ kBq}^{-1} \), \( m=0.22\pm0.04\text{ d} \), \( R=0.82 \), and \( n=4 \).

![Fig. A1](image1)

Correction factor \( F(t) \) as a function of elution time \( t \) for reference PicoRad collectors, as compared with the amount of Insta-Fluor Plus used. The regression lines follow the exponential function given in Eq. (2) with the following values. Type 1: \( f=11.0\pm0.5\text{ cps m}^3\text{ kBq}^{-1} \), \( m=0.39\pm0.05\text{ d} \), the correlation coefficient \( R=0.98 \), and the number of PicoRad collectors \( n=11 \). Type 2: \( f=9.79\pm0.37\text{ cps m}^3\text{ kBq}^{-1} \), \( m=0.22\pm0.04\text{ d} \), \( R=0.82 \), and \( n=4 \).

![Fig. A2](image2)

Evaluation of radon concentrations measured with the test PicoRad collectors. a) Variation in radon concentration in the house-made exposition radon box, as measured with an AlphaGUARD radon monitor for lot C. b) Comparison of the mean \( C_S \) over the last time interval exposure with the mean \( C_i \) of four PicoRad collectors from lot C.
and 9.79±0.37 cps m$^{-3}$ kBq$^{-1}$ (type 2). The $f'$ value of type 1 was significantly greater than that of type 2 because of the low volatility of the Insta-Fluor Plus; however, no marked difference was observed between the two types. We therefore used 15 mL of Insta-Fluor Plus as the LS.

A3. Validity evaluation under conditions of increasingly fluctuating radon concentrations

As with lots A and B, lot C ($n=4$) PicoRad collectors were exposed to radon in the house-made radon exposition box under conditions of increasingly fluctuating radon concentrations. The values of $C_S$ kBq m$^{-3}$ for these experiments are presented in Fig. A2a and can be explained by considering the amount of radon released from the radon sources. The mean $C_S$ kBq m$^{-3}$ values for the various time (0.25 d, 0.5 d, 0.75 d, 1.0 d, 1.25 d, 1.5 d, 1.75 d, and 2 d) intervals of exposure are calculated and are indicated by the crosses in Fig. A2b. In this paper, $C_{S1}$ kBq m$^{-3}$ (or $C_{S2}$ kBq m$^{-3}$) in the house-made radon exposition box was defined as the mean radon concentration over the last 0.25 d (2 d) interval of exposure. For the PicoRad collectors, $C_{S1}=5.51±0.22$ kBq m$^{-3}$ and $d=23.6±0.4°C$.

When using the factors for type 1 (Fig. A1), the $C_i$ values of the test PicoRad collectors were determined based on the measurement values for lots A and B obtained between 1.5 d and 3 d. PicoRad collectors from lot A gave $C_i=4.86±0.11$ kBq m$^{-3}$, as indicated by the circles in Fig. A2b (the primary vertical axis). The difference between $C_i$ and $C_S$, $(100(C_S-C_i)/C_i)$% is shown on the secondary vertical axis. The difference between $C_i$ and $C_{S1}$ was less than 12%, as shown in Fig. A2. The difference between $C_i$ and $C_{S2}$ was around 14%. The values of $C_i$ were closer to the values of $C_{S1}$ than to the values of $C_{S2}$.