Measurement of radon concentration in the air by PicoRad detectors

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Abstract. The paper presents the theory and methodology of radon concentration measurement in the air by PicoRad detector, which consists of a porous canister held securely near the top of a plastic vial. The porous canister contains a bed of a controlled mass of charcoal (1.3 g) and silica desiccant (0.9 g). To measure the radon concentration, the vial detector is exposed in the radon laden air for a certain interval of time (24, 48 or 72 h or longer), then the liquid scintillation cocktail is added into the vial and measured by the help of a liquid scintillation counter. In this paper both radon adsorption by the charcoal detector, while it is being exposed in the radon laden air, and desorption of radon from the charcoal into the liquid scintillation cocktail were investigated. As a result, some conclusions concerning the methodology of radon measurement by PicoRad detectors have been done. The desorption factor of radon from the charcoal into the liquid scintillation cocktail was determined. The radon concentration values in the air measured by PicoRad detectors were in good agreement with those obtained by an AlphaGuard radon monitor.

Key words: radon • PicoRad detectors • charcoal • adsorption • desorption • liquid scintillation

Introduction

The fraction of radon and it progenies in the annual dose caused by natural radiation and X-ray medical examination is higher than 50% [8]. The proper estimation of the dose rate demands precise measurements of all the radiation sources, therefore the methods and devices for radon and its progenies measurements are constantly investigated. The radon measurement devices can be classified into two groups, the first is the active group and the second – passive one. The instruments which need electric power during measurement belong to the active group and the other to the passive one. The active devices such as AlphaGuard®, Pylon AB-5® etc. are often used to measure the current radon concentration in air. The PicoRad and track foil detectors belong to passive group. The track method consists in the exposure of plastic foil detectors CR-39® or a Kodak® foil in the radon laden air, the alpha particles emitted by the decay of the radon and its progenies act upon the foil and remain tracks. After chemical etching, the tracks became larger. The number of tracks in the area unit of foil is proportional to the average radon concentration of the investigated air and the exposure time of the track detectors [4, 6, 10]. In the method, the occurring radioactive equilibrium between radon and its progenies in the investigated air should be assumed.

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The PicoRad detector consists of the charcoal bed (1.3 g) placed near the top of a plastic vial (22 cm³) and hermetically closed [7]. To measure the radon concentration, the PicoRad vial is opened and exposed in the investigated air for a time interval of a few dozen hours to a few days depending on the measurement aims [2, 7]. After exposure, 10 cm³ of the scintillation cocktail (Hisafe 3® or Insta-Fluor Packard®) is added to the vial and measured by the liquid scintillation counter. Some explanations of the radon adsorption onto the particles of the charcoal by the diffusion effect and measurement methodologies can be found in many works, for instance in Refs. [1, 3, 9]. In some cases of the comparison measurements of radon concentrations the results from different participants often significantly differ, even between the labs using the active charcoal detectors [5, 11].

This work presents a simple theoretical background of radon adsorption onto the active charcoal during the detector exposure and desorption of the radon from the charcoal into the scintillation cocktail after its adding into the vial. As a result, the procedures of measurement and estimation of radon concentration by PicoRad detectors are proposed.

Theoretical background

Adsorption of radon onto particles of charcoal bed

Since the charcoal detector was exposed in the radon laden air, the change of radon content in the charcoal bed as a function of time can be described by the differential equation as follows:

$$(1) \qquad \frac{dN_W}{dt} = a_s \cdot S \cdot C_{Rn}(t) - \lambda \cdot N_W$$

where: N_W – radon content in the charcoal; a_s – adsorption factor of the charcoal (assumed that during the exposure a_s is constant); S – total area of all charcoal particles of the detector; λ – decay constant of radon isotope ^{222}Rn equal to 0.00756 h^{-1}; $C_{Rn}(t)$ – radon concentration in the air at the moment t.

Solving Eq. (1) we have:

$$(2) \qquad N_W^T = \frac{a_s \cdot S \cdot C_{Rn}}{\lambda} \cdot (1 - e^{-\lambda \cdot T})$$

where: T – time interval of detector exposure in the radon air; C_{Rn} – average radon concentration of the investigated air in the interval of T,

$$(3) \qquad C_{Rn} = \frac{\int_0^T C_{Rn}(t)}{T}$$

The charcoal detectors have been manufactured, so one can assume that the area S is proportional to the mass (M) of the charcoal detector, and Eq. (2) can be rewritten as follows:
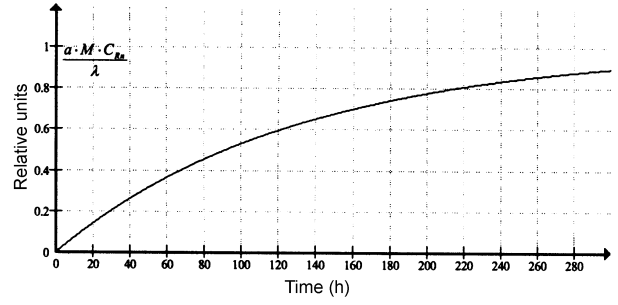

Fig. 1. The growing up of radon content in the PicoRad charcoal as a function of exposure time in the radon laden air.

$$(4) \qquad N_W^T = \frac{a_s \cdot M \cdot C_{Rn}}{\lambda} \cdot (1 - e^{-\lambda \cdot T})$$

The shape of the curve describing Eq. (4) is presented in Fig. 1, and the relative values of radon content in the charcoal during 24, 48 and 72 h of detector exposure are equal to 16.6, 30.4 and 42% of the maximum stable value, respectively. So, the calibration curve of the relation between the radon content in charcoal and radon concentration in the air should be done for a given interval of time (T) of detector exposure.

After exposure, the scintillation cocktail is added into the vial of PicoRad detector as soon as possible. Nevertheless, the time interval from the moment of exposure ending to the moment of cocktail adding always is different than zero, and the radon concentration in the charcoal detector decreases due to radon decay. So, the radon content in the charcoal at the moment of adding the scintillation cocktail can be expressed by the formula:

$$(5) \qquad N_W^{\Delta T} = N_W^T \cdot e^{-\lambda \cdot \Delta T}$$

where ΔT is the interval of time between the exposure ending to the scintillator adding.

Desorption of radon from charcoal into liquid scintillation cocktail

The radon content N_{SC} in the liquid scintillation cocktail can be expressed by the differential equation:

$$(6) \qquad \frac{dN_{SC}}{dt} = k \cdot N_W - \lambda \cdot N_{SC}$$

where: k – desorption factor; N_W – radon content in the active charcoal at the moment t which can be expressed as follows:

$$(7) \qquad \frac{dN_W}{dt} = -k \cdot N_W - \lambda \cdot N_W$$

The solution of this equation is:

$$(8) \qquad N_W(t) = N_W^{\Delta T} \cdot e^{-(k+\lambda) \cdot t}$$

where: t – time counted from the moment of the adding of the liquid scintillation cocktail into the vial detector.
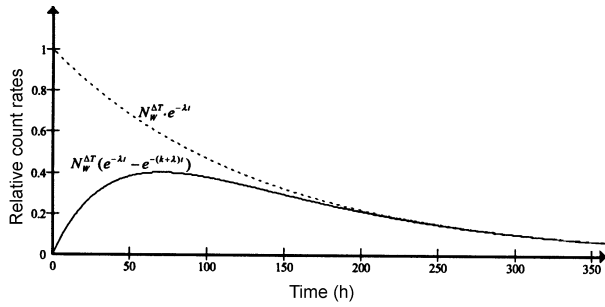
Fig. 2. Continue line – the radon content in the liquid scintillation cocktail in the PicoRad vial as a function of time (time is counted from the moment of the addition of the scintillator); dashed line – the curve describing the function fitting the declining part of the mentioned continuous line.

Replacing Eq. (8) into Eq. (6) and to resolve this equation, one can have the radon content in the scintillation cocktail in the vial as a function of time as follows:

$$(9) \qquad N_{SC}(t) = N_W^{\Delta T} \cdot (e^{-\lambda \cdot t} - e^{-(k+\lambda) \cdot t})$$

The shape of the $N_{SC}(t)$ is presented in Fig. 2. At a certain moment after adding of scintillation cocktail, the N_{SC} reaches a maximum value, then the N_{SC} decreases. Because the desorption factor k is positive, so the declining part of the curve $N_{SC}(t)$ can fit as a function of $N_W^{\Delta T} \cdot e^{-\lambda \cdot t}$. On the basis of this relation, one can determine the $N_W^{\Delta T}$ by extrapolation of the curve $N_{SC}(t)$ to $t = 0$ (the moment of scintillator adding). Having the $N_W^{\Delta T}$, the N_W^T can be calculated by Eq. (2).

The desorption factor k can be determined on the basis of Eq. (9), for instance, the moment t_{max}, at which the value of N_{SC} is at a maximum, and the desorption factor k is expressed as follows:

$$k = \frac{\ln \dfrac{\lambda}{k + \lambda}}{t_{max}}$$

Measurements

To measure the radon concentration in air, the PicoRad detector was exposed in it at a certain interval of time T, then 10 ml of the scintillation cocktail (in the case HiSafe 3®) was added to the detector vial. The radioactivity was measured by a liquid scintillation counter according to the programed device software protocol, usually one measurement lasted 1 h for 1 vial. The output signals are given in the unit of counts per minute (cpm). To follow the output signals as a function of time, the measurement was performed once per 24 h or so. The total number of measurements for one vial should amount to about 10. Figure 3 presents the typical empirical curve of the net count rates (gross count rate minus count rate of background) as a function of time. The time is counted starting from the moment of addition of the scintillation cocktail to the PicoRad detector. In Fig. 3, there is also shown the dashed line fitting the last part of the line of $I_W(t)$ as an exponential function similar to $N_W^{\Delta T} \cdot e^{-\lambda \cdot t}$. The count rate $I_W^{\Delta T}$ determined on the vertical axis at the intersection point with the fitting line is exactly adequate for the $N_W^{\Delta T}$ of Eq. (5).
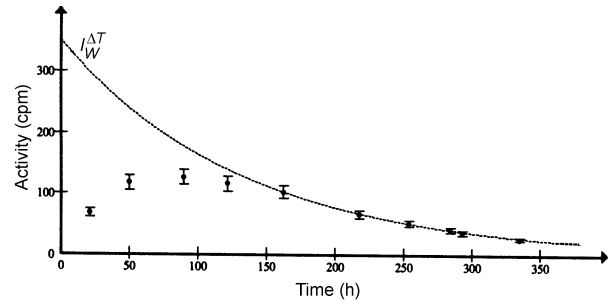

Fig. 3. Dotted line – the measured net count rates (gross count rate minus count rate of background) as a function of time starting from the moment of the addition of the scintillation cocktail to the PicoRad detector; dashed line – the curve describing the function fitting the declining part of the mentioned dotted line.

Using this equation and ΔT, one can calculate I_W^T, which correspondents to N_W^T. The radon concentration in the investigated air can be determined using the calibration curve describing the relation between I_W^T and the radon concentration C_{Rn}.

Results and conclusions

Results

Figure 4 presents the calibration curve – I_W^T as a function of radon concentration of the radon laden air – C_{Rn}, T is the exposure time, in this case T amounts to 48 h. The calibration curve was constructed on the basis of comparative measurements held at the Central Laboratory for Radiological Protection in Warsaw, Poland.

Table 1 presents the radon concentrations and the values of radon desorption factor k obtained by the PicoRad detectors exposed from 9:21 October 21 to 12:43 October 23, 2007 in a radon chamber of the National Institute of Radiological Sciences Anagawa, Japan. During exposure of the PicoRad detectors, the radon concentration in the chamber was measured constantly by AlphaGuard. The radon concentrations obtained by AlphaGuard varied from time to time and were contained in the range of 6.26 kBq/m³ to 8.79 kBq/m³ with 7.70 kBq/m³ on the average. The difference between the average concentrations obtained by the PicoRad detectors and AlphaGuard was equal to 0.30 Bq/m³. The value of desorption factor varied from 0.0134 to 0.0192 h⁻¹, while the decay constant of ²²²Rn amounts to 0.0076 h⁻¹. So, the desorption factor is larger about twice than the radon decay constant.
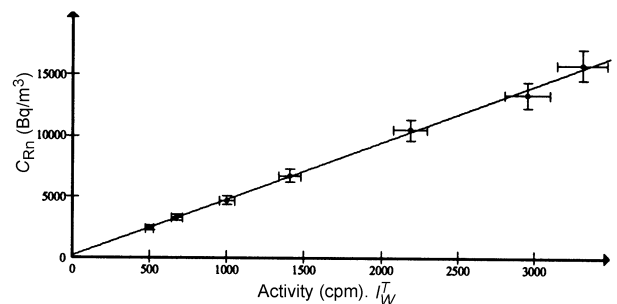

Fig. 4. The calibration curve describing the relation between the extrapolated count rates I_W^T, at the moment of exposure ending, and radon concentration in the air C_{Rn}; T – exposure time.

Table 1. The values of desorption factor and radon concentrations measured in the radon chamber of the National Institute of Radiological Sciences Anagawa, Japan, the average radon concentration after AlphaGuard amounted to 7.70 kBq/m^3

Name of PicoRad detector	Desorption factor k (h^{-1})	Average radon concentration ± standard variation σ* (kBq/m^3)
AGH1	0.0192	6.97 ± 0.32
AGH2	0.0198	8.36 ± 0.38
AGH3	0.0134	8.15 ± 0.37
AGH4	0.0142	8.00 ± 0.36
AGH5	0.0153	8.54 ± 0.38
Average	0.0164 ± 0.0026	8.00 ± 0.30

* The cover coefficient is equal to 1.

Conclusion

– The radon concentrations in the air samples measured by the PicoRad detectors, following the procedure described in this work for the measurement and estimation were in good agreement with those obtained by the AlphaGuard radon monitor.
– The interval of the estimated values of radon desorption factor was broad enough, the fact could be connected with the empirical determinations of the maximum points on the curves describing the measured count rates as a function of time.
– The calibration curve of the relation between the radon concentrations in the air samples C_{Rn} and I_W^T should be performed for exposure during a given interval of time (T).

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