Comparison of different methods of measuring the radon equilibrium factor

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Abstract. In this work, the radon equilibrium factor has been calculated and compared using three different methodologies. The first methodology studied consists of using a continuous air meter, the *SmartCam* (*Ultra Electronics*), which registers the alpha and beta radon descendant's particles deposited in a filter. The second methodology uses the same continuous air meter, but in this case the filter is analyzed by gamma spectrometry. The third technique is based on exposing several track-etch detectors, half of them with its corresponding chamber, that lets only radon nuclide pass through, and the other half in nude mode (detector without chamber). The comparison between track density obtained with and without chamber allows calculating the equilibrium factor. Equilibrium factor in steady laboratory conditions has been calculated using these methodologies and comparison between them show a good agreement.

1 INTRODUCTION

Radon is the largest source of radiation in nature. It comes from disintegration of Radium-226. When this radionuclide decays, radon appears as a noble gas and quickly diffuses into the air.
A closed room can accumulate radon from different sources: soil, building materials, water, etc. Depending on the greater or lower emission flow into the air from these sources, the radon concentration variates. The radon concentration is also influenced by the insulation of the room, ventilation, etc. [1].

Radon disintegrates into Po-218, Pb-214, Bi-214 and Po-214 with half-lives of 3.05, 26.8, 17.9 minutes and $1.6 \cdot 10^{-4}$ seconds, respectively. These descendants can be adhered to the aerosols, that once inhaled remain on the walls of the respiratory tract and continue disintegrating within the lungs (the most dangerous are Po-218, Po-214 because of its alpha particle emission) [2].

The knowledge of the radon equilibrium factor *(F)* value is essential to accurately determine the inhalation effective dose. The factor can vary between 0 and 1. The closer it is to 1, the higher the dose. UNSCEAR [3] and ICRP 65 [4] recommend a value for indoors equilibrium factor of 0.4, but this constant can vary between the mentioned margins. Among the factors that influence the equilibrium factor, the more important are the atmospheric pressure, the radon concentration, the ambient humidity, and the presence of aerosols in the air.

For a precise calculation of radon inhalation dose, it is important determining the equilibrium factor. There are several methods for equilibrium factor measuring. This paper in centered in the analysis and comparison of three of them:

- **Continuous *SmartCam* method**: By continuously monitoring the alpha and beta decays in a filter located after the air suction, carried out by the *SmartCam* air monitor, the equilibrium factor is calculated and obtained continuously [5].

- **Gamma radon descendants method**: This method uses also the *SmartCam* air continuous meter, but in this case, the fiberglass filter where the descendants are deposited after air suction, is measured in a germanium gamma spectrometer, analyzing Bi-214 and Pb-214 peaks [6]. In this case an averaged equilibrium factor during a short (about 40 minutes) exposition is obtained.

- **Track-etch detector method:** This method consists of exposing several long term track-etch detectors with and without chamber. Half of them are exposed with their chamber, so that only radon passes through and the other half are nakedly exposed (without the chamber). The relationship between the track density obtained after the exposition with these different

conditions allows calculating the equilibrium factor [7]. In this method, an average equilibrium factor during a long exposition term (several months) is obtained.

2 MEASUREMENT EQUIPMENT

2.1 Continuous *SmartCam* method

The *SmartCam* alpha-beta air detector, from *Ultra Electronics*, Fig 1, is a next generation continuous air monitor that continuously registers alpha and beta particles deposited in a filter with a high efficiency detector. To that, an external air pump drives the air through the high efficiency filter that is placed in the detector head. The pump flow velocity was adjusted to a value of $v = 1e^{-3}m^3/s$ (≈60 L/min). Air is drawn through the card-mounted filter by an external vacuum pump.
The detector head has two high resolution detectors (one for alphas and one for betas), which are solid state detectors (PIPS) with an active area of 450 mm^2. The filter is made of PTFE (Polytetrafluoroethylene) (5.0 μm, 35mm × 5m, Lab Impex Systems, USA) and the collection efficiency is higher than 99.8%.

Figure 1*:* *SmartCam* from Ultra Electronics

The *SmartCam* registers each minute the Rn-222, Po-216, total beta and Po-214 concentration in air. Other parameters registered are: air flow, temperature and atmospheric pressure. This information shows the evolution of these parameters in time and allows detecting deviations from expected values.

2.2 Gamma radon descendants method

The second method studied uses the same *SmartCam* monitor with the same filter. In this case, the pump flow velocity was also adjusted to 60 L/min approximately. The radon descendants are trapped in the filter and they are analyzed in a gamma spectrometer.
The gamma spectrometry measurements were performed in an *Ortec GMX 40* Germanium detector (Fig 2), with an extended range from 6 keV to 3 MeV in original lead shield with a wall thickness of 10 cm and 2 keV resolution (for 1.33 MeV of Co-60 peak). The net counts of the peaks of Bi-214 and Pb-214 were measured with the associated software Gammavision.

Figure 2 Ortec GMX 40 Germanium detector

2.3 Track-etch detector method

The CR39 track-etch detectors are rigid plastics ($C_{12}H_{18}O_7$) chips mounted in a specific cylindrical radon chamber. When alpha radiation hits them, a track is left on the material. Once the detector is exposed for long term period, it is brought under a NaOH chemical bath to widen tracks, so that they can be measured in a microscope. The track density measured allows estimating the radon concentration in air.

The detectors used are *Radosys* CR39 detectors chips (area of 100 mm^2) with its corresponding RSKS chamber, Fig 3.

Figure 3. *Radosys* CR39 detector chips (with and without chamber) (RADOSYS© User Manual)

The used microscope was *Radosys Radometer 2000*, which is able to read a detector chip in 20 seconds and has a CCD camera with 3 Mpx and an objective magnification of 4x/10x.

3 METHODS AND METHODOLOGY

The analysis of the equilibrium factor was carried out at the same conditions for the three methodologies studied, in the Nuclear Physics Laboratory of the Polytechnic University of Valencia. Moreover, the equilibrium factor was also measured at the underground bunker of this facility with the *SmartCam* detector.

The radon equilibrium factor is the relationship between the concentration of radon descendants in air and the concentration of radon in air. It can be calculated as Eq. (1):

$$F = \frac{0.105 \cdot C_{Po_{218}} + 0.515 \cdot C_{Pb_{214}} + 0.38 \cdot C_{Bi_{214}}}{C_{Rn_{222}}} \quad (1)$$

where, F is the equilibrium factor, and C_{Po218}, C_{Pb214} and C_{Bi214} is the concentration in air of Po-218, Pb-214 and Bi-214.

As the half-life of Po-214 is very short, it is considered to be in secular equilibrium with Bi-214, thus, the concentration of Bi-214 can be assumed to be equal to that of Po-214.

The atmospheric conditions in the laboratory (pressure, temperature, and humidity) and in the underground bunker, were registered for each measurement and not significant variations were detected during measurements.

3.1 F calculation by Continuous *SmartCam* method

During measurement *SmartCam* gives continuously the concentrations of Rn-222, Po-218, total betas and Po-214 per minute. These concentrations can be directly substituted in Eq. (1), to obtain the value of *F* per minute. With this methodology the evolution of *F* can be analyzed during the whole measure, which is an interesting feature to detect deviations and to analyze fluctuations.

3.2 F calculation by Gamma radon descendant method

In this method, once the *SmartCam* detector suction has finished, the filter is analyzed in a germanium detector spectrometer. This methodology was described in detail in a previous work [8].

After Bi-214 and Pb-214 gamma peaks are analyzed, an algorithm is applied to obtain the equilibrium factor. The algorithm begins with the two sets of the Bateman equations, one of them describes the decays that occur while the suction process is taking place. The second equation set describes the disintegrations that occur while the sample is transported to the spectrometer and the decays during the measurement in the spectrometer.

The number of decayed nuclei of Pb-214 and Bi-214 during the measurement (N_r) can be calculated with the gamma spectrometry detected results of measured filter paper.

$$N_r = \frac{N_d}{\epsilon_d p_\gamma} \tag{2}$$

Where N_d is the area under the photopeak, ε_d is photopeak detection efficiency and p_γ *is the* γ-ray emission probability.
The disintegrations detected in the spectrometer are the difference between the atoms that do not decay after transport and after the measurement time (1000 seconds):

$$N_r = N'(t = t_t) - N'(t = t_t + t_m) \tag{3}$$

The suction time, t_s, is 22 minutes in each measure, t_t is the time between the end of the suction and the filter is put into the spectrometer, in this case 2 minutes, and t_m is the time equal to t_s+t_t+*17* minutes. The initial conditions of the first group equations are created and those of the second are the solutions of the first group.

N' represents the solutions of the second system of the differential equations.

The Pb-214 detected decay is given by:

$$N_r(Pb-214) = e^{-\lambda_{Pb}t_t}\left[1-e^{-\lambda_{Pb}t_m}\right]\left[N'_{Pb}(0) - \frac{\lambda_{Po}}{\lambda_{Pb}-\lambda_{Po}}\,N'_{Po}(0)\right] + \frac{\lambda_{Po}}{\lambda_{Pb}-\lambda_{Po}}\,N'_{Po}(0)e^{-\lambda_{Po}t_t}\left[1-e^{-\lambda_{Po}t_m}\right] \tag{4}$$

The Bi-214 detected decay is given by:

$$N_r(Bi-214) = \left[N'_{Bi}(0) - \frac{\lambda_{Pb}N'_{Pb}(0)}{\lambda_{Bi}-\lambda_{Pb}} + \frac{\lambda_{Po}\lambda_{Pb}}{\lambda_{Pb}-\lambda_{Po}}N'_{Po}(0)\right]e^{-\lambda_{Bi}t_t}\left[1-e^{-\lambda_{Bi}t_m}\right] + \left[\frac{\lambda_{Pb}N'_{Pb}(0)}{\lambda_{Bi}-\lambda_{Pb}} - \frac{\lambda_{Po}\lambda_{Pb}N'_{Po}(0)}{\lambda_{Pb}-\lambda_{Po}}\right]e^{-\lambda_{Pb}t_t}\left[1-e^{-\lambda_{Pb}t_m}\right] \tag{5}$$

If $N'_{Po}(0)$ and $N'_{Pb}(0)$ were known, it would be possible to obtain $N'_{Bi}(0)$, but, since N'_{Po} is small due to the period of Po-218 (3.05 minutes), the authors made this approximation.

$$C_{Po} = F \frac{C_A(Rn-222)}{\lambda_{Po}} \quad (6)$$

Where C_{po} is the concentration of Po-218 in the air at the beginning of the suction. Being F an initial equilibrium factor estimated and $C_A(Rn\text{-}222)$ the radon activity concentration in the air measured with the *SmartCam.*
Substituting the results into the previous equations and its results into the solution of the first differential equations system, the activity concentration of Bi-214 and Pb-214 was obtained. With those concentrations, the Eq. (1) offers a new equilibrium factor.

This value of F is introduced into Eq. (6) and the process is repeated, until the convergence.

A set of measurements have been taken with the procedure described before in the university facilities on different days. With this methodology the F averaged over the exposure period (about 22 minutes) is estimated. As exposures are short, the methodology allows easily estimating the F value in a short period time.

3.3 F calculation by Track-etch detector method

To study the radon concentration with track-etch detectors, the method published by (Elmagd, 2009) [9] has been performed. This study describes the can and bare method, that consists in exposing two equal State Nuclear Track Detectors (SSNTDs) to the radon source. Part of them are set with its diffusion chamber and the other part are exposed without the chamber.

The article describes the equations of the response of detectors with and without a camera. This response depends on the track density obtained and also considers some geometric camera parameters. The value of F is calculated as a function of the track density (D/D_0) measured, where D is the track density of bare detectors and D_0 is the track density of detectors with chamber.
F is also a function that depends on the geometry of the diffusion chamber by a geometric factor (V/A), where V is the volume of the chamber and A is the internal surface of the diffusion chamber.

To calculate the radon equilibrium factor, the following expression is used:

$$F = \left(0.15\left(\frac{V}{A}\right) + 0.26\right)\frac{D}{D_0} - 0.277 \quad (9)$$

In this work, six CR39 detectors were exposed at the university laboratory (three of them in bare conditions and the other three with its diffusion chamber) during two months.

4 RESULTS

Radon equilibrium factor measurements using the explained three methods were carried out in the Polytechnic University of Valencia, during the first trimester of 2020.
The average registered temperature and pressure in this period were 22.61±0.54°C and 103.02±1.56 KPa, respectively. Moreover, the equilibrium factor F was also measured in the underground bunker of this laboratory.

4.1 Continuous *SmartCam* method

During February 2020, different measures have been made for 24 hours period with the *SmartCam*. The equilibrium factor F obtained is shown in Table 1.
The table represents the mean value of the concentration of Rn-222, Po-218, total betas and Po-214 during several 24 hours' measures.

Table 1: Averaged results with the continuous *SmartCam* method

24 H MEASUREMENTS IN LABORATORY					
Date	**Radón (Bq/m^3)**	**Po-218 (Bq/m^3)**	**Beta (Bq/m^3)**	**Po-214 (Bq/m^3)**	**F**
11/02/2020	11.84±0.50	1.82±0.06	0.00	14.75±0.12	0.50±0.05
12/02/2020	11.17±1.17	3.54±0.13	0.00	23.73±0.26	0.84±0.11
13/02/2020	10.43±1.06	3.91±0.14	0.00	20.53±0.26	0.78±0.12
14/02/2020	26.28±1.03	4.87±0.18	0.00	46.34±0.40	0.69±0.05
				Mean value	**0.70±0.08**
24 H MEASUREMENTS IN BUNKER					
13/03/2020	114±4	14.04±0.64	4.9±1.4	18.77±0.56	**0.10±0.11**

As seen in Table 1, the value of the averaged equilibrium factor in the laboratory is 0.7 with a standard deviation of 0.15. On the other hand, *F* value obtained in the bunker was 0.1.

The *F* values obtained in the laboratory for the radon concentration in the air are much higher than the one obtained in the underground bunker. The average radon concentration value obtained in the laboratory is 14.93 Bq/m^3 and in the underground bunker it is 114 Bq/m^3. The concentration of radon in the bunker is higher because it is an enclosed underground space without ventilation. Radon tends to concentrate in underground sites that are not ventilated.

Due to the low air radon concentration in the laboratory, the *SmartCam* does not detect beta decays. Nevertheless, beta decays are detected in the bunker, due to the higher concentration of radon.

4.2 Gamma radon descendants method

The results obtained with this method are shown in the following table (Table 2):

Table 2: Measurement results obtained with the gamma radon descendants method.

MEASUREMENTS IN LABORATORY				
Date	**Pb-214 (net counts)**	**Bi-214 (net counts)**	**Radon (Bq/m^3)**	**F**
11/02/2020	69±30	99±17	11.18±0.50	0.53±0.08
12/02/2020	126±19	189±9	11.17±1.17	0.70±0.15
13/02/2020	165±15	181±10	10.43±1.06	0.84±0.17
14/02/2020	202±10	196±8	26.28±1.03	0.55±0.08
			Mean value	**0.66±0.12**
MEASUREMENTS IN BUNKER				
13/03/2020	312±6	189±8	112±4	**0.10±0.09**

Table 2 shows the measurement dates (coinciding with the continuous method measures), the net counts of Pb-214 and Bi-214, the radon concentration measured with the *SmartCam* and the equilibrium factor obtained using Eq. (2-6).

The mean value of F in this case is 0.66 and the standard deviation obtained with this method is 0.14.

Table 2 shows that the radon equilibrium factor is much higher in the laboratory than in the underground bunker. This is because there are more suspended aerosols in the air at the laboratory than in the bunker, since the underground bunker is a closed enclosure without ventilation and the presence of aerosols is lower.

4.3 Track-etch detector method

As explained, to carry out the can and bare methodology, 6 track-etch detectors were placed in the labora'tory, three of them with its diffusion chamber and the other three without its diffusion chamber. The detectors were placed at the same physics laboratory from January 3 to March 3, 2020.
The averaged track density (tracks/mm^2) results with chamber detectors and without detectors are shown in Table 3:

Table 3. Mean values of track density (can and bare method) and resulted equilibrium factor.

Filtered detectors (tracks density) D_0 (tracks/mm^2)	**Bare detectors (tracks density) D (tracks/mm^2)**	**Mean Value obtained of F**
Mean value	Mean value	**0.7±0.2**
2.4±0.3	5.4±0.8	

Knowing the diffusion chamber dimensions, (Fig.3), and the mean track density values (D_0 and D) showed in Table 3, the radon equilibrium factor was obtained using Eq. (10):

Being $\frac{V}{A} = 0.7 \pm 0.1\ cm$ and $\frac{D}{D_0} = 2.6 \pm 0.2$ (10)

As can be seen in table 3, the obtained value for the equilibrium factor with this methodology is 0.7±0.2.

4.4 Equilibrium factor comparison

As it is compared in Table 4, the three methodologies offer similar *F* values. The values are within the uncertainty margins, both in the laboratory and in the bunker measures. The track-etch detector method presents a greater uncertainty. This uncertainty could be reduced if more detectors were used in measurements.

Table 4. Comparison between *F* obtained with different methods.

MEASUREMENT IN LABORATORY			MEASUREMENT IN BUNKER	
Continuous *SmartCam* method	**Gamma radon descendants method**	**Track-etch detector method**	**Continuous *SmartCam* method**	**Gamma radon descendants method**
0.70±0.06	0.66±0.12	0.7±0.2	0.10±0.11	0.10±0.09

Since obtained results are stable in both locations, the three studied methodologies can accurately calculate the *F*. The continuous method offer F estimation instantly, the gamma method in a short period of time and the track-etch method in a long term average.

The main advantages for each method are:

- **Continuous *SmarCam* method:** It is a fast methodology since it gives an immediate reading of F, and allows its evolution study. Its versatility in the short and long term and an easy portable detector
- **Gamma radon descendants method:** It is a fast and accurate methodology.
- **Track-etch detector method:** Integrates long-term measures and keeps a physical record.

Each of these methodologies allows to calculate *F* under specific conditions. To obtain *F* at a specific moment, the *SmartCam* continuous and gamma radon descendants methods must be used, although to obtain the average over a long period of time, the more convenient method to use is the track-etch detector.

5 CONCLUSIONS

In this work, three different methods to estimate the equilibrium factor have been compared. The *SmartCam* continuous method is based on a continuous air monitoring to consider the direct measurement of the concentrations of alpha and beta radon descendants. The gamma radon descendants method is a point method that estimates the value of *F* at a precise moment through gamma spectrometry. Finally, the track-etch detector method is a long-term measurement method that integrates the equilibrium factor, considering the alpha decays of radon and its descendants. The three methodologies offer similar *F* values, being within the uncertainty margins, both in the laboratory and in the bunker measures.

The Spanish Regulatory Council (Consejo de Seguridad Nuclear) establishes that long-term measures (3 months or more) must be carried out in workplaces to control the concentration of radon to which workers are exposed. According to this, the estimation of *F* for inhalation dose calculation could be performed with these three methods, although the more convenient method should be the track-etch method since it performs an average of *F* during the whole exposed period.

Despite being different methods, we have obtained similar values for the equilibrium factor. The obtained *F* in the university laboratory is 0.7, higher than the one recommended by ICRP65 (3) and UNSCEAR (4) for indoors calculations 0.4. This highlights the importance of considering the correct F in the dose calculation, since if the value of 0.4 were chosen instead of the obtained 0.7, the dose per inhalation would be underestimated by 30%.

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