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New S-chamber Mid-Term electrets: Experimental characterization and uncertainty evaluation

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ABSTRACT

Electret ion chambers are widely used passive detectors, employed for measurements of radon activity concentration in air. These devices are made of a Teflon electret coupled to an interchangeable ion chamber. A new type of electret produced by Rad Elec Inc., named Mid-Term, is used together with the S-type (200 cm^3) chamber. It is designed to be operated in an intermediate range with respect to the standard Short-Term and Long-Term electrets. This work describes the complete characterization of such device, performed according to the ISO guidelines. The characterization was carried out in the secondary standard calibration laboratory of Politecnico di Milano Italy, and with a traceable radon chamber. The coefficients and equations presented can be used by operators to assess both the radon activity concentration and the related uncertainty, with the only requirement of the knowledge of the background gamma air kerma rate of the specific measurement site and its related uncertainty.

1. Introduction

Electret ion chambers are widely used as passive radon activity concentration meters both for radon in water (Kotrappa and Jester, 1993) and in air (ISO 11665-4:2020, 2020; Kotrappa et al., 1990; Kotrappa and Stieff, 1994; Kotrappa, 2015). This work is focused on air measurements only. Rad Elec Inc. is a worldwide provider of such devices. Up to now, they are available with the combination of two types of Teflon electrets and four types of chambers. The electrets are Long-Term/low-sensitivity (LT) and Short-Term/high-sensitivity (ST). The chambers are characterized by different sensitive volumes, named D (10 cm^3), L (50 cm^3), S (200 cm^3) and H (1000 cm^3). The most used combinations are SST, LLT, SLT and LST (Collé et al., 1995; Budd et al., 1998; Cardellini et al., 2016; Berlier et al., 2019; Online, 2020). In particular, the SST configuration is used for the fast assessment of radon activity concentration (few days), while for long measurements the LLT is preferred (several weeks up to 6 months). For measurements lasting few weeks, the LST or SLT configurations are used.

The S chamber possesses an ON/OFF mechanism: in closed position the sensitive volume of the ion chamber is reduced almost to zero, while in open position the nominal sensitive volume is restored and ions can discharge the electret. This feature helps in lowering the background contribution and the related uncertainties during the experiment setup and the shipping procedures. Conversely, the L chamber, once mounted, starts integrating signal from radon activity concentration and gamma dose rate.[1]

In order to cover few weeks long measurements with the S chamber configuration, Rad Elec Inc. has produced a new type of electret called Mid-Term (MT). It is designed to be operated in the SMT configuration and to possess a response function analogous to the LST one. MT is designed also for measurements without an *a priori* information about the order of magnitude of the expected radon concentration. If radon concentration is considerably high, ST electret might be completely discharged. The intermediate range of the SMT can better cope with such situations.

In this study, the calibration factor F_c and its related uncertainties for radon exposure and gamma ray irradiation are derived. The complete characterization of these devices was performed in controlled conditions according to the ISO guidance (ISO 11665-4:2020, 2020), following procedure similar to the one described in Caresana et al. (2004). Irradiations in gamma fields were performed with a ^{137}Cs source available at the secondary standard calibration laboratory of Politecnico di Milano, Italy. Exposures to controlled radon concentration were carried out in traceable radon chamber also available at the Department of Energy of Politecnico di Milano. The obtained coefficients and related formulae for assessing the radon activity concentration can be directly used by operators once known the local background gamma air kerma rate and its related uncertainty.

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[1] Differently from the standard and widespread used L-chambers, a specific L-OO chamber produced by Rad Elec Inc. possesses an ON/OFF mechanism.

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2. Materials and methods

Electret ion chambers were supplied by Rad Elec Inc. The studied configuration comprised the new MT type Teflon electret with the 200 cm^3 chamber (S chamber). 30 electrets were provided. The initial voltages U_i of 29 electrets before the gamma irradiation were ≥ 750 V. One electret registered an initial voltage equal to 724 V.

2.1. Gamma irradiation

Electrets were irradiated using a ^{137}Cs source. The laboratory guarantees the metrological traceability by using graphite cavity ionization chambers as reference instruments. The ion chamber reading is done through a charge measuring system.

The standard uncertainty related to the conventionally true air kerma value delivered is equal to 0.8 %. The total air kerma delivered per irradiation was chosen considering an electret discharge equal to roughly 100 V ($D = 450 \pm 9$ μGy in roughly 6 min irradiation).

The 30 electrets were subdivided into 6 groups. The first group was irradiated one time, the second two times *etc.* in steps of 450 μGy per irradiation. The total number of measurements useful for the data analysis was equal to 105 minus 3 points which were found to be outliers. The statistical criteria for rejecting the three points is based on the median absolute deviations: points which were found to be more than three scaled median absolute deviations away from the median were rejected. The Grubbs test (Grubbs, 1969) revealed the same three outliers.

2.2. Radon exposure

Radon exposure was performed in a radon chamber at Politecnico di Milano. The chamber has been developed following the standard IEC 61577 (IEC 61577-2:2014, 2014). A double air lock system allows the insertion of devices, without perturbing significantly the radon concentration. Some fans are located in the chamber to ensure the radon concentration homogeneity in the whole volume. Radon is sucked from a ^{226}Ra source hosted in a vial containing a patented epoxy plastic foil with emanation power approaching 1. The chamber permits to perform exposures at different radon concentrations. An ion chamber AlphaGUARD DF2000 calibrated by a national metrological institute guarantees the metrological traceability.

The exposure reference value is given by the integration of *m*-samples of the radon concentration measured each hour by the reference instrument during the total *m*-hours exposure time. Thus, the total radon exposure $E_{Rn} = \bar{C} \cdot t$ results expressed in Bq h/m^3. The whole set of electrets (30) was exposed simultaneously for 48 h to obtain a voltage discharge equal to roughly 100 V ($E_{Rn} = 189 \pm 8$ kBq h/m^3). The same statistical tests of the gamma irradiation were performed on the radon exposure dataset, without revealing outliers; thus, the total number of useful points was equal to 30.

The radon exposure was performed with the same electrets used for the gamma irradiation, so the initial voltage was roughly equal to the final voltage after the gamma irradiation, *i.e.* five electrets ∼ 650 V, five electrets ∼ 550 V *etc.* down to 250 V. Since the radon exposure was performed several days after the gamma irradiation, the initial voltage of each electret was measured before the radon exposure to check the daily self-discharge of the devices. This means that there is no statistical correlation between the gamma irradiation and the radon exposure, *i.e.* the initial voltage of each electret was measured independently from the final voltage measured after the gamma irradiation.

The gamma background of the chamber was assessed equal to 134 ± 9 nGy/h. It was measured at different radon concentrations with an Automess 6150 AD/6 Geiger Müller counter coupled to the scintillator probe Automess 6150AD-b.

The measurement chronology is schematically listed in Table 1.

Table 1
Measurement chronology. The whole set of electrets was subdivided into 6 groups. The first group was irradiated one time with gamma rays, the second two times *etc.* After the gamma irradiation procedure, the electrets were exposed together in the radon chamber. The γ–1 irradiation took place on May 6, 2020. Irradiations from γ–2 to γ–6 took place on May 14, 2020. Radon exposure took place from 6 to 8 June, 2020 (two-days long exposure). The self discharge of the electrets was verified at the beginning of the γ–2 irradiation and before the radon exposure (SDV in the table).

Group	γ–1	γ–2	γ–3	γ–4	γ–5	γ–6	^{222}Rn
1	x	–	–	–	–	–	x, SDV
2	x	x, SDV	–	–	–	–	x, SDV
3	x	x, SDV	x	–	–	–	x, SDV
4	x	x, SDV	x	x	–	–	x, SDV
5	x	x, SDV	x	x	x	–	x, SDV
6	x	x, SDV	x	x	x	x	x, SDV

3. Data analysis

By definition, the Calibration Factor (F_c) is equal to

$$F_c = \frac{\Delta U}{D} \tag{1}$$

where ΔU is the voltage drop after exposure and D is the integral gamma dose or the radon exposure delivered. Since F_c is a function of the electric field, the following correlation is used (Usman et al., 1999)

$$F_c = b + d \cdot \ln\left(\frac{U_i + U_f}{2}\right) = b + d \cdot X \tag{2}$$

Eq. (2) states that F_c depends on the variable X, which is the natural logarithm of the mean voltage before and after irradiation (U_i and U_f are the initial and final voltage respectively). The uncertainty associated with Eq. (1) is derived following the uncertainty propagation law. The relative variance associated with F_c, $u^2_{rel}(F_c)$, is expressed as

$$u^2_{rel}(F_c) = u^2_{rel}(\Delta U) + u^2_{rel}(D) \tag{3}$$

The first term on the right represents the relative variance associated with the measurement of the voltage drop ΔU which is equal to

$$\Delta U = (U_i - U_0) - (U_f - U_0) \tag{4}$$

where U_0 is the reference potential, in this case equal to 0. The reference values for the uncertainties associated with the readout operations $u(U) = u(U_i) = u(U_f) = 1.5/\sqrt{3}$ and $u(U_0) = 0.5/\sqrt{3}$ are taken from Caresana et al. (2004). According to the uncertainty propagation law, the uncertainty related to ΔU is obtained:

$$u^2(\Delta U) = 2 \cdot (u^2(U) + u^2(U_0)) \tag{5}$$

The relative variance $u^2_{rel}(D)$ of Eq. (3) is related to the exposure procedure, which is different in the case of gamma and radon exposures, as discussed in Section 4. It depends on the metrological capability of the irradiation laboratory, and for the following discussion it is considered known and common to all measurements. The best fit for the F_c evaluation is performed basing on the generalized least squares method (Strang, 1986) . The vector $\vec{a}$ containing the b and d coefficients of Eq. (2) is calculated as:

$$\vec{a} = \begin{bmatrix} b \\ d \end{bmatrix} = \left[\mathbf{T}^{\mathrm{T}} \cdot \mathbf{V}^{-1} \cdot \mathbf{T}\right]^{-1} \cdot \mathbf{T}^{\mathrm{T}} \cdot \mathbf{V}^{-1} \cdot \vec{F}_c = \mathbf{M} \cdot \mathbf{T}^{\mathrm{T}} \cdot \mathbf{V}^{-1} \cdot \vec{F}_c \tag{6}$$

$\mathbf{T}$ is a matrix containing the experimental X_i values, while the vector $\vec{F}_c$ collects the experimental F_{ci} values:

$$\mathbf{T} = \begin{bmatrix} 1 & X_1 \\ 1 & X_2 \\ \vdots & \vdots \\ 1 & X_N \end{bmatrix} \qquad \vec{F}_c = \begin{bmatrix} F_{c1} \\ F_{c2} \\ \vdots \\ F_{cN} \end{bmatrix} \tag{7}$$

Two variance–covariance matrices, $\mathbf{V}$ and $\mathbf{M}$, appear in Eq. (6). $\mathbf{M}$ is the variance–covariance matrix associated with the fit coefficients, which

is expressed as:

$$\mathbf{M} = \left[\mathbf{T}^{\mathrm{T}} \cdot \mathbf{V}^{-1} \cdot \mathbf{T}\right]^{-1} = \begin{bmatrix} u^2(b) & u(b,d) \\ u(d,b) & u^2(d) \end{bmatrix} \tag{8}$$

The variance–covariance matrix **V** is related to the experimental uncertainties, and it is built in the following way:

$$\mathbf{V} = \begin{bmatrix} u^2(\mathrm{F}_{c1}) + c^2 & u^2(\mathrm{F}_{c1,2}) + u(D_{1,2}) & u(D_{1,3}) & \dots & u(D_{1,N}) \\ u^2(\mathrm{F}_{c2,1}) + u(D_{2,1}) & u^2(\mathrm{F}_{c2}) + c^2 & u^2(\mathrm{F}_{c2,3}) + u(D_{2,3}) & \dots & \\ u(D_{3,1}) & u^2(\mathrm{F}_{c3,2}) + u(D_{3,2}) & & & \\ \vdots & & \ddots & & \vdots \\ u(D_{N,1}) & & & & u^2(\mathrm{F}_{cN}) + c^2 \end{bmatrix} \tag{9}$$

The elements in the main diagonal are the experimental variances associated to F_c, corresponding to the sum of the experimental $u^2(\mathrm{F}_{ci})$ (Eq. (3) in absolute terms) plus a constant c^2. This constant includes the contributions of all the unknown experimental uncertainty sources and its value is tuned to obtain a χ^2 value statistically compatible with the expected value within a confidence interval of 90 %.

The elements outside the main diagonal correspond to the covariance contributions. The elements beside the main diagonal are composed by two contributions. The first term accounts for the common uncertainty of the ΔU value of two consecutive measurements, in case the final U_f value of the nth exposure is equal to the initial U_i value of the $(n+1)$th exposure. This common value is considered as a correlation element, whose variance is quantified as:

$$u^2(\mathrm{F}_{cn,n+1}) = \frac{u^2(U_{\mathrm{common}}) + u^2(U_0)}{D^2} \tag{10}$$

The structure of Eq. (10) implies that $u^2(\mathrm{F}_{cn,n+1}) = u^2(\mathrm{F}_{cn+1,n})$. The value of $u^2(\mathrm{F}_{cn+1,n})$ has no physical meaning and is introduced for obtaining an analytical solution for Eq. (6) (Strang, 1986). Note that D is not considered as a stochastic variable, because its uncertainty contribution is assessed in the second term $u(D_{i,j})$. For measurements which are not performed in sequence $u^2(\mathrm{F}_{cn,n+1}) = u^2(\mathrm{F}_{cn+1,n}) = 0$.

The covariance contributions related to the exposure uncertainties $u(D_{i,j})$ are introduced since the exposure uncertainty contributions are common uncertainties. They are evaluated as follows:

$$u(D_{i,j}) = u(D_{j,i}) = \frac{\Delta U_i}{D_i^2} \cdot u(D_i) \cdot \frac{\Delta U_j}{D_j^2} \cdot u(D_j) \tag{11}$$

For gamma irradiation the contribution of the common uncertainty is only the air kerma uncertainty. For radon exposure, its value depends on the uncertainties of both the radon exposure and gamma background. The common radon exposure uncertainty contribution derives from the statistical variability of the reference instrument only.

Once defined **V**, both the $\vec{a}$ fit coefficients and their variance are derived, and so **M**. Thus, the relative variance associated to the calibration factor is given as:

$$u_{rel}^2(\mathrm{F}_c) = \frac{u^2(b) + X^2 \cdot u^2(d) + 2X \cdot u(b,d) + d^2 \cdot u^2(X)}{\mathrm{F}_c{}^2} + u_{rel}^2(\mathrm{cal}) \tag{12}$$

For gamma irradiation $u_{rel}^2(\mathrm{cal})$ is null. For radon exposure $u_{rel}^2(\mathrm{cal})$ accounts for the uncertainties of the calibration factor of the reference instrument, without considering its response variability, which was already included in the terms $u(D_{i,j})$ of Eq. (11).

4. Results and discussion

The procedure described in Section 3 allows to calculate the fitting parameters b and d and their uncertainties from the **M** matrix for both gamma irradiation and radon exposure. The obtained curves are shown in Figs. 1 and 2 for gamma irradiation and radon exposure respectively. The fit results are listed in Tables 2 and 3 for gamma irradiation and radon exposure respectively.

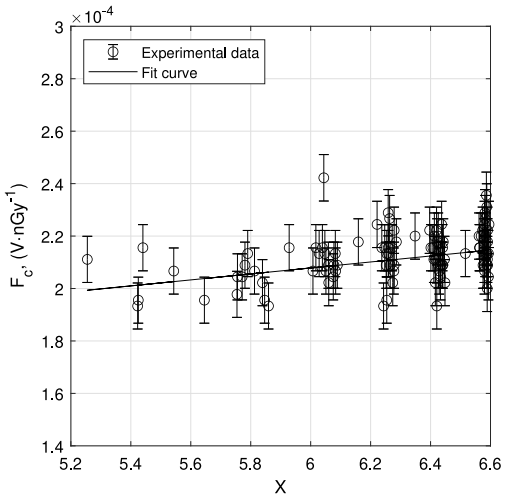

Fig. 1. Fit curve and experimental F_c values for the gamma irradiation.

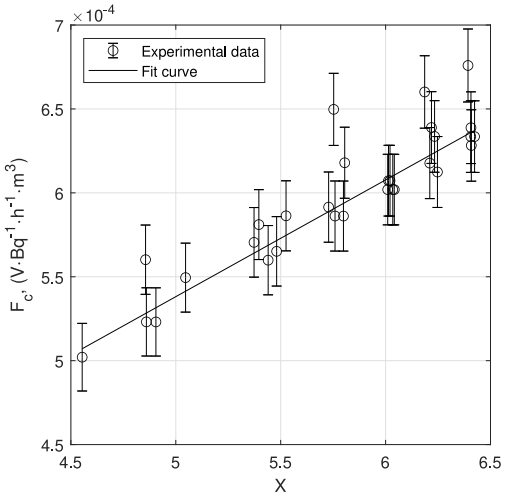

Fig. 2. Fit curve and experimental F_c values for the radon exposure.

Table 2
Generalized least squares fitting parameters for the gamma ray irradiation.

Parameter	Value
Degrees of freedom	100
b (V/nGy)	1.394×10^{-4}
d (1/nGy)	1.140×10^{-5}
$u^2(b)$ (V^2/nGy^2)	3.095×10^{-10}
$u^2(d)$ (1/nGy^2)	7.801×10^{-12}
$u(b,d)$ (V/nGy^2)	-4.884×10^{-11}
u_{rel}^2(cal)	0
c (V/nGy)	8.150×10^{-6}
χ^2	99.055

Concerning the gamma irradiation, the values of ΔU are directly related to the total air kerma, and no assumptions have to be done. Concerning the radon exposure, ΔU depends also on the gamma background and a correction factor is needed. The total electret discharge after radon exposure ΔU is caused by the superposition of the discharge due to the radon daughter nuclei ΔU_{Rn} plus the discharge due to the background gamma rays ΔU_γ. Thus, the following equation for the average radon activity concentration calculation is introduced:

$$\bar{C} = \frac{\Delta U_{\mathrm{Rn}}}{\mathrm{F}_{c\mathrm{Rn}} \cdot t} = \frac{\Delta U - \Delta U_\gamma}{\mathrm{F}_{c\mathrm{Rn}} \cdot t} \tag{13}$$

Table 3
Generalized least squares fitting parameters for the radon exposure.

Parameter	Value
Degrees of freedom	28
b (V m^3/(Bq h))	1.903×10^{-4}
d (m^3/(Bq h))	6.956×10^{-5}
$u^2(b)$ (V^2 m^6/(Bq^2 h^2))	1.320×10^{-9}
$u^2(d)$ (m^6/(Bq^2 h^2))	4.036×10^{-11}
$u(b,d)$ (V m^6/(Bq^2 h^2))	-2.198×10^{-10}
u^2_{rel}(cal)	1.444×10^{-3}
c (V m^3/(Bq h))	1.666×10^{-5}
χ^2	27.805

ΔU_γ is obtained considering Eq. (2) for the calculation of the corresponding $F_{c\gamma}$ multiplied by the background gamma air kerma rate, thus Eq. (13) becomes:

$$\bar{C} = \frac{U_i - U_f}{F_{cRn} \cdot t} - B_G \tag{14}$$

where $B_G = f_{cor} \cdot \dot{D}$ has the dimensions of Bq/m^3 and represents the radon equivalent concentration of the gamma contribution. The correction factor f_{cor} is equal to $F_{c\gamma}/F_{cRn}$, and has to be multiplied by the background gamma air kerma rate $\dot{D}$ to get the radon equivalent concentration due to the gamma background.

According to the ISO/IEC Guide 98-3 (ISO/IEC GUIDE 98-3:2008, 2008), the uncertainty of to the average radon activity concentration is obtained as:

$$u^2(\bar{C}) = \frac{u^2(\Delta U)}{(F_{cRn} \cdot t)^2} + \frac{(\bar{C} + B_G)^2 \cdot u^2(F_{cRn})}{F_{cRn}^2} + f_{cor}^2 \cdot u^2(\dot{D}) + \dot{D}^2 \cdot u^2(f_{cor}) \tag{15}$$

where the variance associated with f_{cor} is obtained as $u^2(f_{cor}) = f_{cor}^2 \cdot (u^2_{rel}(F_{c\gamma}) + u^2_{rel}(F_{cRn}))$.

As mentioned above, electret ion chambers are of various types, depending on the specific electret–chamber combination. Moreover, the electrets are supplied with an initial voltage U_i equal to roughly 750 V, but they can be reused several times, down to a voltage limit value provided by the manufacturer, usually around 200–300 V. Hence, for a specific environmental condition, *i.e.* expected radon concentration and mean gamma background, a specific electret–chamber–initial voltage combination might be preferred instead of another. ISO 11665-4:2020 addresses this task with a specific example in Section B.3 (ISO 11665-4:2020, 2020).

Following the ISO 11665-4:2020 example, the already available electret configurations are compared to the SMT. Fig. 3 compares the SMT configuration to the LST (corresponding to the ISO n1 combination), SLT (corresponding to the ISO m2 combination), LLT (corresponding to the ISO n2 combination) and SST electret configurations. The Figure refers to the ISO 11665-4:2020 example case environmental conditions: expected voltage drop of 30 V with 100 nGy/h ambient gamma radiation contribution at various radon activity concentrations.

A voltage drop of 30 V is usually considered the minimum for obtaining a reasonably precise result (*i.e.* relative uncertainty $\leq 10\,\%$). The F_c coefficients used for configurations other than SMT were taken from Caresana et al. (2004). The bands shown in the Figure enclose the extreme U_i range values (750–300 V). Exposures lower than one day are not considered in the graph because radon takes several hours to diffuse in the chamber. As expected, the SMT configuration covers the range between SLT and SST configurations. For example, for a voltage drop ΔU equal to 30 V, with an average radon concentration of 200 Bq/m^3 and an average background gamma contamination equal to 100 nGy/h, the sampling duration is about 30 days with the SLT configuration, about 2 days with the SST configuration and about 10 days with the SMT configuration.

The obtained result is in line with expectations also with respect to the LST configuration. In the LST case, under the same environmental conditions, the sampling duration is about 12 days. The sampling time covered with the SMT overlaps with the LST one, but the SMT configuration provides the previously addressed advantages of using the S-type chamber. Some examples are listed in Table 4.

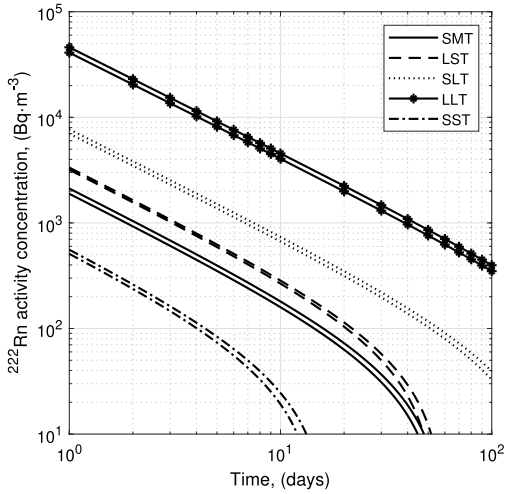

Fig. 3. Radon activity concentration measured over a given sampling duration for the SMT, LST, SLT, LLT and SST configurations. The voltage drop is fixed equal to 30 V, and the background gamma contribution is fixed equal to 100 nGy/h. Since the electrets can be reused several times, the initial voltage U_i usually varies between 750–300 V. The bands in the figure represent the extreme cases: per each configuration the top line corresponds to 300 V, bottom line 750 V. These curves let the operator select the best electret–chamber combination basing on the expected radon activity concentration, also taking into account the initial voltage of the electret.

Table 4
Examples of sampling duration, expressed in hours, for different electret–chamber combinations (SMT, LST, SLT, LLT and SST). Voltage drop ΔU = 30 V, U_i = 770 V, background gamma contribution $\dot{D}$ = 100 nGy/h.

Avg. ^{222}Rn conc.	Sampling duration for the combination, (h)				
(Bq/m^3)	LST (n1)	SLT (m2)	LLT (n2)	SST	SMT
200	300	750	>2400	50	200
400	170	380	2180	30	110
1000	75	160	926	12	45

The choice of ΔU equal to 30 V was assumed because it is the minimum electret discharge which generally guarantees a relative uncertainty on the radon activity concentration $\leq 10\,\%$. Fig. 4 shows a family of curves which correlate the SMT ΔU with the measured radon activity concentration relative uncertainty for the three different radon activity concentrations considered in the previous examples.

Following again the ISO example, the variation of the f_{cor} coefficient over the entire range of U_i variability lies in a pretty narrow range 0.333–0.346 Bq h/(m^3 nGy). Thus one can directly substitute a single value of $f_{cor} = 0.338 \pm 0.009$ Bq h/(m^3 nGy) in Eq. (15) without using the correlation $f_{cor} = F_{c\gamma}/F_{cRn}$. The procedure is in line with the ISO guidelines.

Elevation correction factors were not introduced in this study (measurements were performed at 120 m above sea level). However, these coefficients depend on the specific chamber used rather than the electret mounted. For the S-type chamber, the altitude influence becomes relevant above 1200 m and the reader is referred to Kotrappa and Stieff (1992) for getting the specific elevation correction factors.

4.1. Memory effects after high dose rate gamma irradiation

As mentioned in 2.2, the electret voltage was measured before the radon exposure, several days after the gamma irradiation. The time discharge of the electret between the end of the gamma irradiation and the beginning of the radon exposure (24 days) was measured to be of

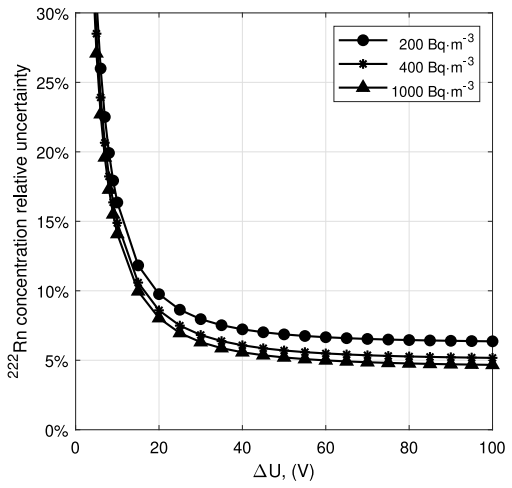

Fig. 4. Radon activity concentration relative uncertainties at different ΔU values for the SMT configuration. The initial voltage V_i is equal to 300 V (lower limit, *i.e.* uncertainty worst case scenario) and the background gamma contribution is fixed equal to 100 ± 20 nGy/h.

the order of 1.09 ± 0.65 V/d, that is a value surprisingly high. The same check of daily discharge was done also after the radon exposure, together with two non irradiated samples, and resulted to be 0.11 ± 0.23 V/d, that is a more acceptable value, in line with our experience.

It seems that after the relatively high voltage drop (~ 100 V) induced in short times (minutes) by a gamma dose rate in the range of mGy/h, the electret discharge continues also after the end of the irradiation. We called that "memory effect". The physical origin is still unknown and will be object of further investigations. Even if the memory effect has not been properly investigated, we considered important to report it, simply as an experimental evidence.

As far as radon measurements are concerned, the memory effect can be neglected, unless the exposure is performed in a radon chamber where the radium source emanating radon is placed inside the chamber itself. If so, the gamma dose rate could be not negligible and the presence of the memory effect cannot be excluded *a priori*.

5. Conclusions

The characterization of the new Rad Elec Inc. MT-type electret in the SMT configuration was performed both with gamma rays irradiation and radon exposure. The F_c calculation was performed according to the procedure presented in Caresana et al. (2004) and the ISO guidance (ISO 11665-4:2020, 2020), thus obtaining both the b and d coefficients for the F_c dependence on the average voltage and the related uncertainties.

The SMT response function is roughly superposable to the widespread LST one, although SMT provides the ON/OFF switching. This feature provides the advantage of neglecting the discharge contribution during the experiment setup and shipping, thus removing uncontrolled sources of uncertainty. MT is also suited for measurements if no radon concentration data of the site are available: if radon concentration is slightly high, the ST electret might completely discharge and information might be lost. The intermediate range of the SMT is well suited for such situations.

The operator could refer to Tables 2 and 3 and Eq. (14) for the assessment of the average radon activity concentration. Eq. (15) allows to calculate the related uncertainty in accordance with the ISO/IEC guidance (ISO/IEC GUIDE 98-3:2008, 2008). The equations require the *a priori* knowledge of the gamma background of the measurement site, together with its uncertainty, which can be assessed both with a direct measurement or from published data.

A memory effect was observed after the gamma irradiation at high dose rate, *i.e.* enhanced discharge per day. Further studies are required to characterize the behavior of the electret under these conditions. However, no memory effects were observed after the radon exposure. It is assumed that the presence of a high dose rate gamma source might bring to a non-linear behavior of the system. As a general rule, the operator should avoid using electrets in proximity of a high-activity gamma-emitting sources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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