

## 10.3 Radiological protection measurements: internal exposure

### 10.3.1 Measurement of radon and its progeny

Radon ( $^{222}\text{Rn}$ ) and thoron ( $^{220}\text{Rn}$ ) are gaseous radionuclides in the U- and Th-decay chain, respectively, occurring naturally in the ground and escaping from there into air and water (see Chapter 11). Their decay products are metallic radionuclides (see Tables 10.8 and 10.9). In air usually a mixture of radon/thoron and short-lived radon/thoron progenies exist. The progenies are mostly attached to aerosols with sizes of about 0.01 - 10  $\mu\text{m}$  in diameter. Some (few percent only), however, are “non-attached” (cluster <0.005  $\mu\text{m}$  in diameter). Due to the short half-life of 55 s of thoron this nuclide and its decay products are less important for dose from inhalation than radon ( $T_{1/2} = 3.825$  d) and its short-lived progeny. In special situations, however, they may contribute to the total potential alpha energy concentration from radon and thoron progenies up to 50 %.

While the inhaled radon is mostly exhaled again, the progeny are deposited in the respiratory tract where their decay by alpha-particle emission is seen to be most relevant for the dose to the lung and hence for lung cancer induction. Their contribution to the dose is generally 2 to 3 orders of magnitude greater than that of  $^{222}\text{Rn}$ . In measurements, however, the radon is given the highest interest, because action levels and reference values are nearly always specified in terms of radon concentration (in  $\text{Bq m}^{-3}$ ) or radon exposure (in  $\text{Bq m}^{-3} \text{ h}$ ) and not in terms of dose quantities (see Sect. 4.8). If doses wanted to be specified, the radon progeny concentrations in air or the equilibrium factor  $F$  need to be determined. For radon in homes often an equilibrium factor  $F = 0.4$  is applied, if no measurements are available.

**Table 10.8.**  $^{226}\text{Ra}$  decay chain with radon and its progeny (data from [98NN]).

Radionuclide	Half-life $T_{1/2}$	Radiation energy and relative emission probabilities					
		$\alpha$ -particles		$\beta$ -particles <sup>(1)</sup>		$\gamma$ -rays	
		MeV	(%)	MeV	(%)	MeV	(%)
$^{226}\text{Ra}$	1 600 a	4.59	(4.16)			0.186	(3.51)
		4.78	(94.5)				
$^{222}\text{Rn}$	3.825 d	5.49	(100)				
$^{218}\text{Po}$	3.10 min	6.00	(100)				
$^{214}\text{Pb}$	26.8 min			0.67	(48)	0.242	(7.4)
				0.73	(42)	0.295	(19.3)
				1.02	(6)	0.359	(37.6)
				other	(4)		
$^{214}\text{Bi}$	19.9 min			1.00	(23)	0.609	(46.1)
				1.51	(40)	1.120	(15.1)
				3.26	(19)	1.764	(15.4)
				other	(18)		
$^{214}\text{Po}$	164 $\mu\text{s}$	7.69	(100)				
$^{210}\text{Pb}$	22.3 a			0.015	(81)	0.047	(4.05)
				0.061	(19)		
$^{210}\text{Bi}$	5.013 d			1.161	(100)		
$^{210}\text{Po}$	138.4 d	5.30	(100)				
$^{206}\text{Pb}$	stable						

(1) The energy given is the maximum energy of  $\beta$ -particles emitted in the specific decay channel.

Specific quantities have been defined taking care of the complex decay chain of radionuclides (see Sect. 3.4.1) and the importance of the progeny for internal dosimetry. While in measurements of radon/thoron the actual *activity concentration* or its mean value over a longer period is usually determined, for the progeny the *potential alpha energy concentration* (PAEC), the *equilibrium equivalent concentration* (EEC), the *equilibrium factor* and the *potential alpha energy exposure* are measured (see Sect. 4.6).

For radon the concentration in air above ground, in the air, in the ground, and in water from the ground are of interest, while the progeny are important only when produced in air above ground. In buildings often the exhalation rate of radon from the ground or wall materials is looked at. This can be determined by measuring the increase of the radon concentration in a closed volume after it has been well ventilated.

The diffusion of radon in air is very fast and its concentration in a closed room is, therefore, usually homogeneous. Mostly there is no equilibrium with its progeny because of a continuous deposition of aerosols on the walls and other surfaces. Often an equilibrium factor between 0.3 and 0.7 is achieved. Local radon concentrations in air, however, may strongly vary with time depending on environmental parameters like weather conditions, pressure, wind, temperature as well as ventilation in rooms. Care must, therefore, be taken when using data from short time measurements. Also the positioning of instruments for measurement of radon needs attention in order to avoid erroneous results. In rooms detectors should usually not be positioned near windows or doors or directly on a wall.

For thoron, the situation is generally different. Free in air, there is mostly a strong decrease of the thoron concentration with height above ground due to the short half-life of 55 s, and equilibrium with thoron progeny is never achieved.

**Table 10.9.**  $^{228}\text{Th}$  decay chain with thoron and its progeny (data from [98NN]).

Radionuclide	Half-life $T_{1/2}$	Radiation energy and relative emission probabilities					
		$\alpha$ -radiation		$\beta$ -radiation <sup>(1)</sup>		$\gamma$ -radiation	
		MeV	(%)	MeV	(%)	MeV	(%)
$^{228}\text{Th}$	1.913 a	5.34	(27.0)			0.0837	(1.2)
		5.43	(73.0)			0.216	(0.25)
$^{224}\text{Ra}$	3.66 d	5.45	(4.9)			0.241	(4.1)
		5.68	(95.1)				
$^{220}\text{Rn}$	55.6 s	6.29	(100)			0.55	(0.1)
$^{216}\text{Po}$	0.15 s	6.78	(100)				
$^{212}\text{Pb}$	10.64 h			0.331	(83)	0.239	(43.3)
				0.569	(12)	0.300	(3.3)
				other	(5)		
$^{212}\text{Bi}$	60.6 min	6.05	(25)	1.55	(5)	0.040	(1.1)
		6.09	(10)	2.26	(55)	0.727	(6.6)
				other	(40)	1.620	(1.5)
$^{212}\text{Po}$	304 ns	8.78	(100)				
$^{208}\text{Tl}$	3.04 min			1.28	(23)	0.511	(22.6)
				1.52	(22)	0.583	(84.5)
				1.80	(51)	0.860	(12.4)
				other	(4)	2.614	(99.1)
$^{208}\text{Pb}$	stable						

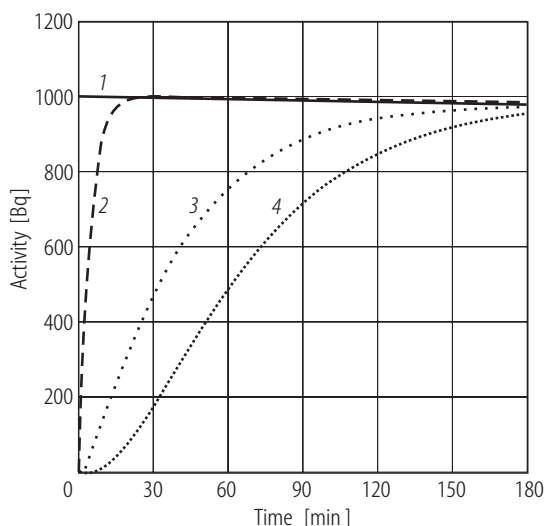
(1) The energy given is the maximum energy of  $\beta$ -particles emitted in the specific decay channel.

Radon/thoron and its short-lived progeny form a decay chain and the relation of their activity concentrations is generally described by a set of differential equations (see Sect. 3.4.1.4). If, for example, a closed chamber is filled only with radon with an activity  $A$  at a time  $t = 0$ , the activity of the progeny will increase from 0 Bq until after about 3 h it reaches an equilibrium ( $F = 1$ ), where the activities of the progeny equal that of radon (see Fig. 10.28).

Another example may be the build up and decrease of the activity of radon progeny absorbed in a filter flowed by air during a fixed period. In this case, the activities of the decay products on the filter are described by a set of differential equations:

$$dA_i/dt = c_i \dot{V} + \lambda_i (A_{i-1} - A_i) \quad i = 1 - 4 \quad (10.3.1.1)$$

with  $A_i$  activity of radionuclide  $i$  on the filter in Bq,  $c_i$  activity concentration of radionuclide  $i$  in air in  $\text{Bq m}^{-3}$ ,  $\dot{V}$  air flow through the filter in  $\text{m}^3 \text{h}^{-1}$  and  $\lambda_i$  decay constant of radionuclide  $i$  in  $\text{h}^{-1}$ . Fig. 10.31 shows a typical example. The same equations can be used when the activity  $A$  is exchanged by the number of the corresponding particles  $N$ .



**Fig. 10.28.** Example for the decay of radon and built up and decay of radon progeny in a closed chamber.

Activity at  $t = 0$ :  $A_{\text{Rn-222}} = 1000 \text{ Bq}$ ,  $A_{\text{Po-218}} = A_{\text{Pb-214}} = A_{\text{Bi-214}} = A_{\text{Po-214}} = 0 \text{ Bq}$ .  
(1)  $^{222}\text{Rn}$ , (2)  $^{218}\text{Po}$ , (3)  $^{214}\text{Pb}$ , (4)  $^{214}\text{Bi}$  and  $^{214}\text{Po}$ .

Different types of measurements are performed in the assessment of radon and radon progeny concentrations. Measurements within a period of up to 2 days are called *short-time measurements*. They are performed by either a sequence of single short measurements, by a continuous measurement or by a measurement with an integrating device. Such measurements provide the actual radon concentration at a place of interest but are usually not sufficient for the estimation of a representative mean annual or monthly value because of the possible environmental variations.

*Long-term measurements* ranging for some months or a year are usually performed with integrating passive detectors which at the end deliver a value integrated over the selected period and hence a mean radon concentration which can be related to reference values, action levels or annual limits.

*Continuous measurement* means that an instrument is continuously measuring and periodically delivering data where the smallest time period depends on the instrument and the accuracy needed. Those measurements are performed with active electronic devices and are used if short-time or daily variations are investigated.

While radon and thoron are mainly emitting  $\alpha$ -particles, their various progenies decay by emission of  $\alpha$ - or  $\beta$ -particles accompanied by  $\gamma$ -rays (see Tables 10.8 and 10.9). Therefore, depending on the aim and type of measurement very different detector systems are applied, ranging from simple and cheap passive ones e.g. for screening measurements in houses up to detectors with complex electronic devices used as reference instruments.

In the following an overview is given on the measurement techniques and devices in use for detection of radon and its progeny (see also [88NC, 88Naz, 02SSK]). For thoron similar instrumentation may be applied if care is taken of the short half-life of thoron which limits its diffusion time and, for example, has the effect that a strong decrease of the thoron concentration exists with increasing height above ground.

In any way, care must be taken that devices may be sensitive to both radon and thoron and their progenies, and then the influence of thoron on measurements of radon should be estimated. Often a sufficiently long diffusion time through a filter can avoid such problems.

### 10.3.1.1 Measurement of radon in air

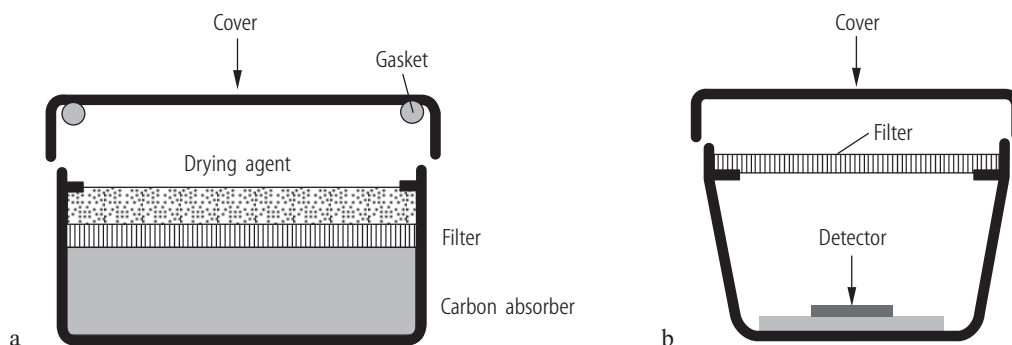
#### General

Radon measurements in air are performed in homes or dwellings or at work places as well as outside in areas where the exhalation from the ground may be high. Most methods for the measurement of the radon concentration in air are based on the principle that radon is entering a closed chamber or is adsorbed in carbon material, while the radon/thoron decay products in air which would strongly influence the measurement are absorbed before entering the system by a filter. This is realized either by pumping air through the filter to the chamber or by diffusion of radon through the filter. The radiation from radon and its progeny from the decay of radon in the chamber or in the carbon absorber are then contributing to a detector signal. If the diffusion time is longer than some minutes, the contribution from thoron to the detector response is small due to its short lifetime ( $T_{1/2} = 55$  s). Depending on the detector device either the charge produced in the chamber by ionisation is measured or  $\alpha$ -particles from both radon and its progeny or  $\beta$ -particles and  $\gamma$ -rays from its progeny are detected individually.

#### Passive integrating systems

Passive integrating systems are those which do not allow a continuous or quasi continuous read out but deliver a value of the radon concentration integrated over a longer time period (in  $\text{Bq m}^{-3} \text{ h}$ ). These are either systems with a passive detector, e.g. a detector chamber with an etched track detector (see Sect. 10.1.7) which detects the  $\alpha$ -particles emitted by the radionuclides in the chamber gas, or an electret detector, where the discharge of a charged electret by ionisations in the chamber gas is determined by a voltage measurement [88Kot], or systems with a radon adsorbing material (an activated carbon absorber) where radon is trapped on the active sites of the carbon beds, and afterwards the  $\gamma$ -radiation which is emitted from the radon decay products  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  produced in the absorber is measured by a gamma spectrometer (see Sect. 10.1.4) [84Geo, 90Geo]. All systems are equipped with a filter in front of the chamber for retaining radon progeny from entering the chamber (see e.g. Fig. 10.29). Because water vapor and also temperature influences the radon collection efficiency the activated carbon collector systems should be used indoors only. Table 10.10 gives an overview on different systems with passive detectors in use and provides some further information. More details about special systems available on the market are given in a review by George [96Geo] and a report on a European intercomparison of passive radon detectors [00How]. Depending on the diffusion time of radon through the entrance filter or plastic foil the system may also be sensitive to thoron or not.

Integrating detectors are usually mailable and relatively cheap. They are often used for medium and long time measurements in dwellings where knowledge about radon concentration values averaged over 3 to 12 months are most important. The analysis of the detector response is mostly performed at a central laboratory and needs more expensive additional equipment.



**Fig. 10.29.** Schematic diagram of passive devices for radon measurement in air; (a) chamber with activated carbon absorber; (b) diffusion chamber with either an etched track detector or an electret detector.

In principle, also active systems which allow to nearly continuously providing data may be used as an integrating device. For long term measurements, however, they become much more expensive.

**Table 10.10.** Integrating systems with passive detectors for the measurement of radon in air

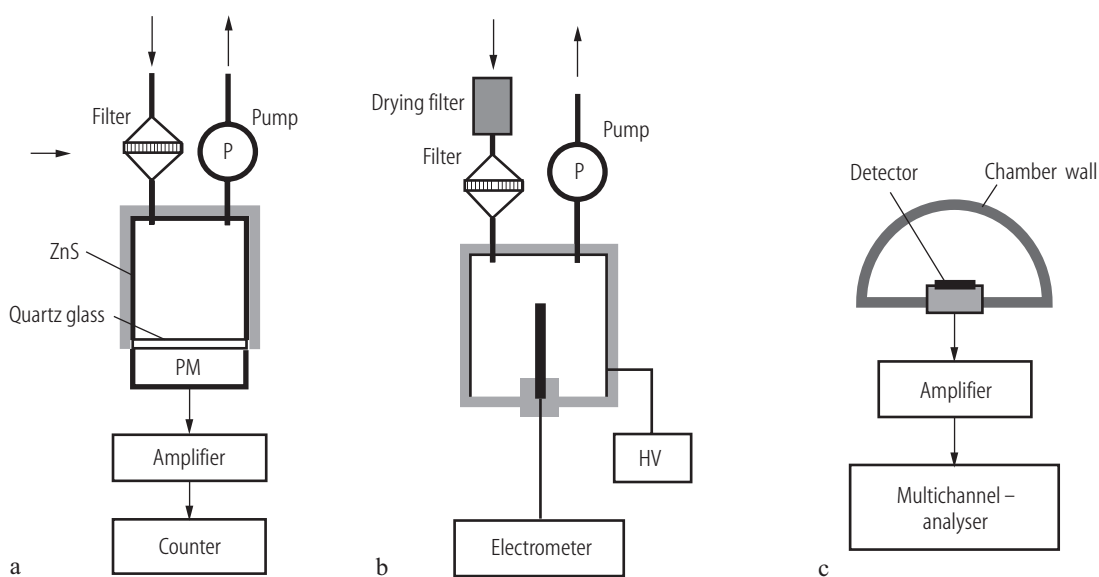
Method	Measured radiation	Detector	Lower detection limit	Influenced by	Main application
Absorption of radon in a carbon filter	$\gamma$ -rays	$\gamma$ -spectrometer	$\sim 5 \text{ Bq m}^{-3}$ in $0.5 \text{ m}^3$ air	air humidity, temperature	short time measurement
Absorption of radon in a carbon collector with entrance filter	$\gamma$ -rays or $\alpha$ -particles	$\gamma$ -spectrometer or liquid scintillation counter	$\sim 10 \text{ Bq m}^{-3}$ (3 h measurem.)	air humidity, temperature	short time measurement up to 3 d
Diffusion chamber with entrance filter	$\alpha$ -particles	etched track detector (CR-39, LR-115 etc.)	$\sim 10^5 \text{ Bq h m}^{-3}$	air pressure, temperature,	long time measurement 1-12 months
Diffusion chamber with entrance filter	charge from ionisations	electret detector	$\sim 10^3 \text{ Bq h m}^{-3}$	air pressure, dose rate, $\gamma$ -radiation	long time measurement 1 w - 1 a

### Active detector systems

These systems allow a single measurement within a short time period or quasi continuous measurements to register temporal variations of the radon concentration. All systems are supplied with an entrance filter for absorption of the progeny from outer air. Usually, the  $\alpha$ -particles emitted in the chamber (mostly from progeny produced in the chamber and deposited on the inner chamber wall) are directly measured (see Fig. 10.30). The use of a scintillation cell, where the walls are coated with a scintillating material (mostly silver activated ZnS(Ag) powder), is one of the eldest methods (Lucas chamber [57Luc]). Others are using silicon surface barrier detectors or diffused junction detectors for the detection of  $\alpha$ -particles. In other systems the charge or charge pulses from ionisations in the chamber gas are measured [92Bal]. Table 10.11 gives an overview on different systems with active detectors in use and some additional information. More specific details on devices already used in practice are given by George [96Geo].

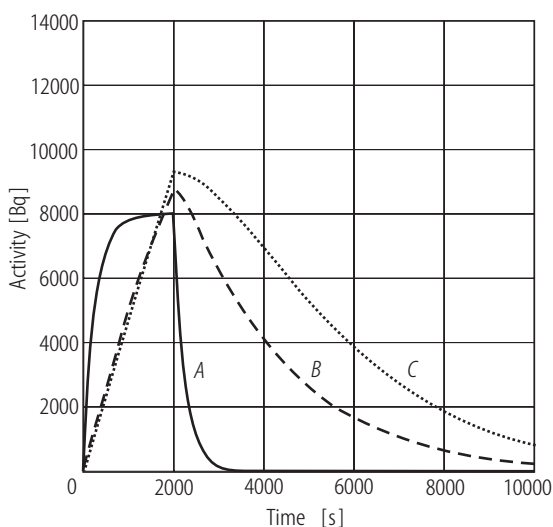
**Table 10.11.** Active detector systems for the measurement of radon in air

Method	Measured radiation	Detector	Lower detection limit	Influenced by	Main application
Ionisation chamber with entrance filter	$\alpha$ - and $\beta$ -particles	charge or charge pulse measurement	$\sim 5 \text{ Bq m}^{-3}$ ( $10^3 \text{ cm}^3$ volume, 3 h measurem.)	air humidity	single or continuous measurement
Multi-wire ionisation chamber with entrance filter	$\alpha$ -particles	charge pulse measurement, $\alpha$ -spectrometry	$\sim 5 \text{ Bq m}^{-3}$ ( $10^3 \text{ cm}^3$ volume, 3 h measurem.)	air humidity vibration	single or continuous measurement
Scintillation chamber with entrance filter	$\alpha$ -particles	ZnS(Ag) scintillator	$\sim 20 \text{ Bq m}^{-3}$ ( $250 \text{ cm}^3$ volume, 3 h measurem.)		single or continuous measurement
Chamber with entrance filter, electrostatic deposition	$\alpha$ -particles	silicon surface barrier detector	$\sim 5 \text{ Bq m}^{-3}$ ( $10^3 \text{ cm}^3$ volume, 3 h measurem.)	air humidity	single or continuous measurement
Diffusion chamber with $\alpha$ -spectrometry	$\alpha$ -particles	silicon surface barrier detector	$\sim 100 \text{ Bq m}^{-3}$ ( $10^2 \text{ cm}^3$ volume, 3 h measurem.)	air humidity	single or continuous measurement
Two filter method (also for thoron)	activity of 2 <sup>nd</sup> filter	activity determination of filter, various detectors	$\sim 10 \text{ Bq m}^{-3}$ ( $10^5 \text{ cm}^3$ volume, 10 h measurem.)		single measurement

**Fig. 10.30.** Schematic diagram of active devices for radon measurement in air; (a) Lucas chamber [57Luc] (PM: photomultiplier); (b) ionisation chamber with charge measurement (HV: high voltage); (c) diffusion chamber with semiconductor detector.

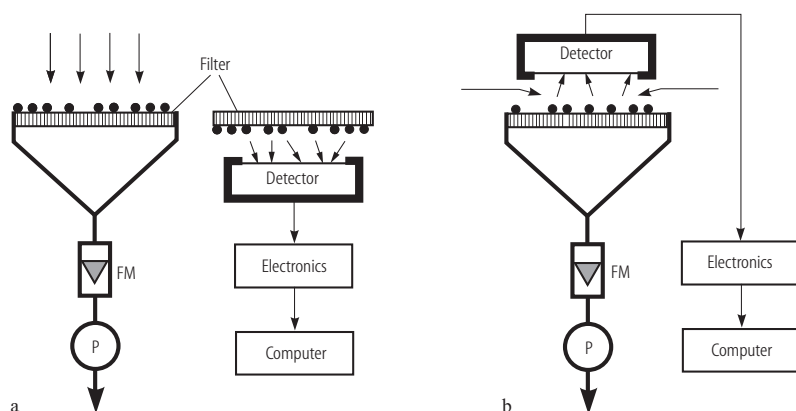
### 10.3.1.2 Measurement of radon progeny in air

Nearly all devices for the measurement of radon progeny are using the filter method which can in general be described by the following. A pump is sucking air through a filter where the aerosols with the radon progeny are absorbed. A flow meter is measuring the air volume flowing through the filter and the activity of the filter is determined by measuring the  $\alpha$ -,  $\beta$ - or  $\gamma$ -radiation emitted from the progeny either quasi-continuously or after the collection period at different time intervals. As shown in Fig. 10.31 the activity of  $^{218}\text{Po}$ ,  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  on the filter vary differently with time, while the activity of  $^{214}\text{Po}$  equals that of  $^{214}\text{Bi}$  because of the short lifetime ( $T_{1/2} = 164 \mu\text{s}$ ). From these data the potential alpha energy concentration (PAEC in  $\text{J m}^{-3}$  or WL) or the activity concentration of the different decay products can be calculated using the set of differential equations (see equ. (10.3.1.1)).



**Fig. 10.31.** Build up and decrease of the activity of radon progeny deposited on a filter with 100 % collection efficiency which for 2000 s is flowed by  $10^3 \text{ cm}^3 \text{ min}^{-1}$  of air with a radon activity concentration of  $1 \text{ kBq m}^{-3}$  and an equilibrium factor  $F = 1$ . (A)  $^{218}\text{Po}$  ( $\alpha$ -emission), (B)  $^{214}\text{Pb}$  ( $\beta$ ,  $\gamma$ -emission), (C)  $^{214}\text{Bi}$  ( $\beta$ ,  $\gamma$ -emission) and  $^{214}\text{Po}$  ( $\alpha$ -emission).

The sampling unit and the activity measurement unit are either separated or combined in one system (see Fig. 10.32). The absorbing filter should have a high efficiency. For  $\beta$ - or  $\gamma$ -radiation measurements a total absorption efficiency of  $>98 \%$  is sufficient. For  $\alpha$ -particle detection, however, it is additionally important that the progeny are adsorbed at the filter surface. This affords membrane filters with pore sizes of less than  $3 \mu\text{m}$ .



**Fig. 10.32.** Schematic diagram of devices for radon progeny measurements [96Por] (FM: flow meter, P: pump); (a) with separated sampling and detector systems; (b) with a combined sampling and detector system.

The sensitivity of a system depends strongly on the power of the pump. Mostly pumps with flow rates from  $0.1 \text{ m}^3 \text{ h}^{-1}$  to  $1 \text{ m}^3 \text{ h}^{-1}$  are used, but for special short time measurements also pumps with flow rates up to  $100 \text{ m}^3 \text{ h}^{-1}$  are applied. Care must be taken that the aerosols are not already be deposited in the entrance region of the device in front of the filter.

If a flow meter is included in the system, its position is important. On the one hand it should not be influenced by the pump (e.g. by vibrations), but on the other hand it should not influence the flow in front of the filter and the deposition of aerosols. Immediately behind the filter might be the best position.

### Determination of the activity concentration of the radon progeny

Three independently measured total count numbers for decay by  $\alpha$ -particles during different counting intervals after the sampling period can be used to calculate the progeny concentrations using equ. (10.3.1.1) [96Por]. This method has been developed by Tsivoglou [53Tsi] and was further improved by various groups [72Tho, 80Bug, 81Sco, 84Naz] in order to improve its application also for low count rates. Mostly ZnS(Ag) scintillation detectors or proportional counters are applied (see Sect. 10.1.3 and 10.1.2) but also other active detectors are in use.

Raabe and Wrenn have developed a method measuring the total alpha particle count number in many successive intervals and fitting the obtained decay curve with a theoretically calculated decay function using the maximum likelihood method [69Raa]. As a result the three activity concentrations of the radon progeny are obtained.

A further development is the use of  $\alpha$ -spectrometry [69Mar, 80Por] or even  $\alpha$ - and  $\beta$ -spectrometry [97Ruz] for the identification of the different radon progeny. Silicon surface barrier or diffused junction detectors are usually used with multichannel analysis. These methods are generally more complex, however, with  $\alpha$ -spectrometry measurements in two intervals and with  $\alpha$ - and  $\beta$ -spectrometry a single measurement is sufficient. It allows also a correction for the contribution of thoron progeny. In general, the detection limit is lower than in methods with gross alpha counting.

The spectrometry allows also a continuous measurement, if the filter and the detector are combined in one unit. The continuous detection of  $\alpha$ -particles from  $^{218}\text{Po}$  and  $^{214}\text{Po}$  are not sufficient to determine the concentrations of the 4 radon progeny, if no further information is available. Very often, however, an equal ratio of the activity concentrations  $c_{\text{Po-218}}/c_{\text{Pb-214}} = c_{\text{Pb-214}}/c_{\text{Bi-214}}$  is fulfilled.

Most algorithms for the calculation of concentrations from measured data assume constant progeny concentrations during the sampling period. If this is not the case, more complex calculations are necessary and the uncertainty will be higher.

### Determination of the potential alpha energy concentration $c_p$ (PAEC)

In principle, PAEC can be calculated from measured activity concentration data of the progeny (see Section 4.6.2). Often, however, methods are used which are simpler in instrumentation and optimised with respect to direct PAEC determination.

A simple method is based on gross  $\alpha$ -counting during a single period [56Kus]. After a short sampling time, a measurement of the number of  $\alpha$ -particles from  $^{218}\text{Po}$  and  $^{214}\text{Po}$  during some hours, where most of these radionuclides decay, multiplied with the mean  $\alpha$ -energy provides a PAEC value with an uncertainty of at least 10 % due to the difference in the  $\alpha$ -energies from  $^{218}\text{Po}$  and  $^{214}\text{Po}$ . For these measurements mainly active detector devices (e.g. solid state detectors, electret ionisation chambers or scintillation detectors) are used.

If shorter counting periods are used, this needs a correction of the calibration factor and an assumption on the equilibrium status because of the different decay times of the progeny (see Fig. 10.3.1). For quasi-continuous measurements the filter and the detector must be combined in one unit. A short sampling time may then be followed by a counting time of about 1 hour. After about 3 measurement cycles a correct PAEC value is achieved. This may, however, not be the case, if the progeny concentrations vary strongly in time.



Due to the short lifetime of  $^{218}\text{Po}$  ( $T_{1/2} = 3.1$  min) the  $\alpha$ -particle measurement needs a precise timing. This is not the case, if instead  $\beta$ - or  $\gamma$ -radiation from  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  is measured. Then, however, corrections need to be applied for the influence of environmental background radiation.

While the foregoing methods provide an actual PAEC value, often a value averaged over a long time period or the exposure  $E_p$  is wanted. In this case, in addition to the above mentioned active devices also passive detectors, e.g. etched track and TL detectors, are used. While etched track detectors are sensitive to  $\alpha$ -particles only, TL detectors are also sensitive to beta and  $\gamma$ -radiation, e.g. from environmental background. In this case, two TL-detectors are applied, where one measures the background only.

The thoron progenies are also deposited on the filter. Especially the long-living progeny  $^{212}\text{Pb}$  ( $T_{1/2} = 10.64$  h) may therefore be enriched on the filter during long sampling times and will together with its progeny  $^{212}\text{Bi}$  influence the PAEC measurement. This can be checked when an additional measurement of the filter is performed at about 10 h after the end of the sampling period, where the radon progeny are already decayed.

### Determination of the unattached fraction of the progeny $f_p$

A separate measurement of the unattached fraction of the progeny is based on the different diffusion properties. Due to the small size of the unattached progeny ( $<5$  nm) compared to the aerosols they have a much higher diffusibility and are deposited on surfaces much faster than those.

For measurements instead of a filter a diffusion battery – a system of small diffusion tubes or a wire screen – is used where mainly the unattached fraction is deposited [96Por]. The further measurement of its concentration or PAEC is similarly performed as described for the attached progeny. If a filter is deposited after the diffusion battery, the PAEC of the attached fraction can additionally be measured.

The unattached fraction  $f_p$  is then given by

$$f_p = \frac{c_p^f}{c_p^a + c_p^f} \quad (10.3.1.2)$$

where  $c_p^a$  is the PAEC of the progeny attached to aerosols and  $c_p^f$  is that of the unattached fraction.

### Determination of the equilibrium equivalent concentration $c_e$ (EEC) and the equilibrium factor $F$ .

The *equilibrium equivalent concentration* (EEC)  $c_e$  of radon for a non-equilibrium mixture with its progeny in air is the fictitious activity concentration of radon which is in radioactive equilibrium with its short-lived progeny and has the same PAEC as the actual non-equilibrium mixture. The *equilibrium factor*  $F$  is then defined as the quotient of  $c_e$  and  $c_{\text{Rn}}$  (see Sect. 4.6.2). It is always  $c_e \leq c_{\text{Rn}}$  and hence  $F \leq 1$ .

$c_e$  and  $F$  are not directly measurable. A determination needs the measurement of the concentrations of radon and their progeny. While  $c_{\text{Po-214}}$  can be ignored (see Sect. 4.6.2),  $c_e$  of radon and  $F$  are given by the equations

$$c_e = 0.106 c_{\text{Po-218}} + 0.513 c_{\text{Pb-214}} + 0.381 c_{\text{Bi-214}}. \quad (10.3.1.3)$$

$$F = c_e / c_{\text{Rn}}$$

The unit of  $c_e$  equals that of  $c_{\text{Rn}}$ , but is often marked  $\text{Bq m}^{-3}$  (EEC).

### 10.3.1.3 Measurement of radon in the ground and in water

Radon and thoron are continuously produced in the ground by the decay of  $^{226}\text{Ra}$  and  $^{224}\text{Ra}$ , respectively. The radon/thoron is partially transferred from minerals to pores of air in the ground (emanation) and then it may diffuse to the surface and exhale to the atmosphere. The radon concentration in the ground air (*effective radon concentration* in the ground) is about 100 to 10 000 times higher than in the open air while for thoron the ratio is even higher. Near the surface (<1 m) the concentration decreases due to the exhalation at the surface. The actual exhalation rate is also influenced by the air pressure and the temperature in the atmosphere.

The radon concentration in the ground can be indirectly determined by measuring the specific activity of  $^{226}\text{Ra}$  in the soil together with the determination of the emanation probability (usually 0.2 - 0.5 depending on the soil type and on the humidity of the ground). The  $^{226}\text{Ra}$  content in a soil sample can be measured by  $\gamma$ -spectrometry. If the sample is deposited for about 25 days in a closed box, equilibrium of radon with  $^{226}\text{Ra}$  is achieved and the total content of radon in the soil sample can also be determined by  $\gamma$ -spectrometry ( $\gamma$ -rays from  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ ).

The effective radon content in the sample can be determined when equilibrium is achieved by flowing radon-free gas through the chamber and adsorbing the radon in an activated carbon absorber afterwards. The radon content in the absorber is then determined by  $\gamma$ -spectrometry ( $\gamma$ -rays from  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ ). The same can be achieved by measuring the radon content in the sample before and after the flow of gas through the chamber and taking the difference.

A direct measurement of the effective radon concentration in the ground is performed by inserting a probe into the ground, at minimum 1 m below the surface in order to avoid surface effects. The probe may be a special diffusion chamber for local radon measurement (see Tables 10.10 and 10.11) or a system connected with a pump to collect a known amount of ground air into an external radon measuring device. In this case the ground air is often returned to ground in a closed loop. In any way care is needed to avoid atmospheric air entering the probe.

Most of the methods can also be used for the measurement of the thoron activity concentration in the ground, if special care is taken considering the fast decay of thoron. It should also be looked at, if thoron is influencing the radon measurement. Larger diffusion times or waiting some time before measuring a probe may avoid these problems.

The specific activity concentration of radon dissolved in water can be directly measured in a water sample (after 3 h when equilibrium exist between radon and its progeny) by detecting  $\gamma$ -rays from  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  with a  $\gamma$ -spectrometer. Also a liquid scintillation detector may be used.

The radon of a water sample may also be exhaled with a radon-free gas, dried and either absorbed in a carbon filter or transferred to a detector chamber. The radon measurement is then performed by methods given in Table 10.11.

A fast and simple technique which avoids the sampling of water is the use of a diffusion chamber of a material (e.g. a membrane tube of polypropylene) which allows a fast diffusion of radon. The radon concentration can then be conventionally measured.

Glass fibre filters of a certain brand were found to be very efficient for the adsorption of short-lived radon decay products during filtration of water [97Phi] where they are in equilibrium with radon. The  $\beta$ -radiation from  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  on the dried filter can then simply be measured using a proportional counter with a thin window.

**10.3.1.4 References for 10.3.1**

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