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Deliverable 2.7

Workplace-type specific methods to assess the exposure of workers to radon

Focus on underground workplaces and itinerant workers

Work Package 2

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Disclaimer

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Executive Summary

Within the work package 2 dealing with “Exposure”, the task “Exposure to radon in buildings” aims at studying building materials (subtask 2.3.1), radon exposure in workplaces (subtask 2.3.2) and the contribution of other sources than local geology on radon exposure in buildings (subtask 2.3.3). This report concerns the subtask 2.3.2 and presents the technical recommendations that might be taken into consideration to develop radon and radon progenies measurement protocols of some of member states and some non-European countries. The technical measurement recommendations are focused on underground workplaces and issues regarding itinerant workers. Some examples are given to illustrate the recommendations and to provide an overview of some country’s practices. Measurements and tests in underground workplaces are still ongoing at the publication date of this report, thus the resulting information will be analysed and published at the end of the project.

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Glossary

Itinerant worker:

Workers who work at various locations and who are not employees of the facility where they are working.

The following definitions are given in ISO 11665-1 standard [1]:

Active sampling:

Sampling using active devices like pumps for sampling the atmosphere

Passive sampling:

Sampling using no active devices such as pumps for sampling the atmosphere, whereby in most instruments sampling is performed mainly by diffusion.

Grab sampling:

Collection of a sample (i.e. of air containing radon or aerosol particles) during a period considered short compared with the fluctuations of the quantity under study (i.e. volume activity of air).

Continuous measurement:

Measurement obtained by taking a sample continuously (or at integration intervals typically in range of 1 min to 120 min) with simultaneous or slightly delayed analysis.

Integrated measurement:

Measurement performed by continuous sampling of a volume of air which, over time, is accumulating physical quantities (number of nuclear tracks, number of electronic charges, etc.) linked to the disintegration of radon and/or its decay products, followed by analysis at the end of the accumulation period.

Spot measurement:

Measurement based on a grab sample taken within a period of less than one hour, at a given point in space, together with an analysis (e.g. count) carried out simultaneously or after a set period of time.

Radon exposure:

Integral with respect to time of radon activity concentration accumulated during the exposure time.

1. Introduction

This work is carried out in the framework of RadoNorm project subtask 2.3.2 “Radon exposure in workplaces” and aims at proposing technical recommendations to be considered in the development of national measurement protocols for radon-222 in underground workplaces and for itinerant workers in all workplaces and national measurement protocols for radon-222 progenies in specific workplaces. The recommendations are illustrated by examples of current practices in different countries.

This methodology complies with the Euratom Directive requirements [2].

Underground workplaces can be sport facilities arenas, cave restaurants, catacombs, castles or museums, touristic caves, agricultural cellars, dams, sewers, waste storage facilities, quarries, tunnels, mines, mining museums, shafts, car parks, urban transport facilities, technical galleries, underground warehouses, etc. However, working areas situated in the basement of a building should not be considered as underground workplaces.

As pointed out in the beginning of the project in this subtask, underground workplaces and itinerant workers represent a type of workplace and occupational situation, respectively, in which measurement protocols for radon and radon progenies are missing in many countries.

The recommendations and examples exposed in the present report can be helpful for the stakeholders involved in radon risk management in different countries and can be used and adapted regarding their own regulation.

Figure 1 presents the scheme of the graded approach of radon risk management at workplaces in the Directive 2013/59/Euratom as reported in the EC report “RP-193 Radon in workplaces” [3], visualising the various steps in the decision-making process.

It is worth noting that this scheme, as well as the chapter of the RP-193 report where the scheme is reported, is focused on the optimisation of exposures above reference levels. However, optimisation has to be considered also for levels below reference level, although with a lower priority. This follows clearly from the definition of reference level reported on Article 4(84) of the Directive: “*a reference level means, in an emergency exposure situation or in an existing exposure situation, the level of effective dose or equivalent dose or activity concentration above which it is judged inappropriate to allow exposures to occur as a result of that exposure situation, even though it is not a limit that may not be exceeded.”* and from the Article 7(1) on reference levels that requires *“Optimization of protection shall give priority to exposures above the reference level and shall continue to be implemented below the reference level*.”.

The graded approach of radon risk management at workplaces requires either radon measurement or radon progenies measurement. The methodology relies mainly on a reference level implying the radon activity concentration measurement in Bq/m^3. However, for certain working situations, effective dose assessment may be necessary and can be performed by using either the radon activity concentration measurement or the radon progenies measurement.

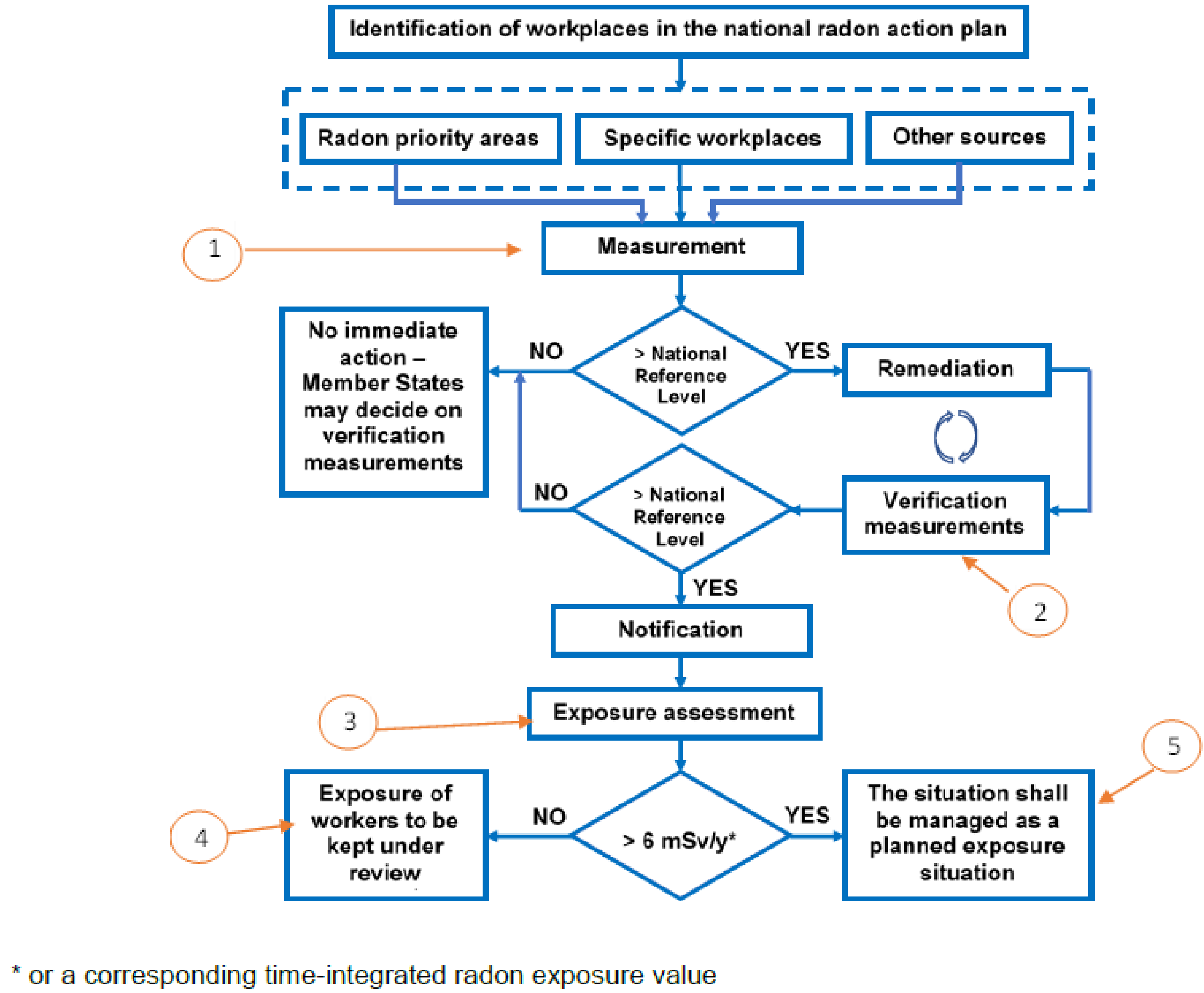

Figure 1 – Scheme of the graded approach of radon risk management at workplaces in most European countries [3]

The objective of the different steps of the graded approach are:

Step 1: initial investigation. Any correction factor for daily time-controlled ventilation or seasonal variation may be also applied at this step.

Step 2: verification measurements performed to assess the effectiveness of remedial actions undertaken regarding the national reference level.

Step 3: exposure assessment by calculating the effective dose received by workers from the radon activity concentration or from the radon progenies concentration (= potential alpha energy, developed in chapter 4 of the present report) and the annual occupancy at the workplace. The annual occupancy may depend on the national regulation (in the EC report "Radon in workplaces" [3], 2000 hours/year is given as an example for a full-time annual working time). This step 3 consists of a calculation of the annual effective dose based on the measurements made in step 1 or 2, or from radon progenies measurement (see chapter 4 for details). But in the case of itinerant workers, some additional or specific radon measurement may be carried out at this step.

Step 4: exposure of workers to be kept under review. If the exposure assessment confirms that the effective dose to workers is less than or equal to 6 mSv per year or less than the corresponding time-integrated radon exposure value [3], the competent authority shall require that exposures are kept under review. In order to confirm the exposure assessment, the competent authority may require, among other things, a periodic re-measurement of the radon concentrations in the workplace or a re-assessment of effective doses as appropriate, in particular in cases where workplace conditions have changed. Thus, this step 4 may also require some additional measurements of radon or radon progenies.

Step 5: planned exposure situation.

The aim of the report is to present the recommendations to be considered to carry out radon measurement in underground workplaces (chapter 2), radon measurement for itinerant workers in all types of workplaces (chapter 3) and radon progenies measurement in specific workplaces (chapter 4). Those measurements may be necessary at the steps 1, 2, 3, 4 or 5 of the graded approach of radon risk management.

At the steps 1 and 2, the annual average radon concentration in each working place shall be measured to be compared to the reference level.

At the steps 3, 4 and 5, the annual exposure in each working place shall be assessed, from measurement results, with the greatest possible accuracy, or if not, by being conservative.

The provided recommendations include the type of the measurement device, the placement and number of devices, the measurement duration, the possible application of seasonal and ventilation correction factors, the acceptable uncertainties of the results and the frequency of measurement for the follow-up of the radon level in workplaces. The document also gives some recommendations on how to compare measurements to the reference level (RL) for the purposes of demonstrating compliance or assessing the need for remedial actions. Accompanying the general recommendations, some examples are given to illustrate the variety of practices that are applied in different countries.

Some field tests were performed, to test and improve the recommendations. A part of them is integrated in the present report (see Annex A) but many of them were not finished at the publication date of the report. In this regard, this work will be continued in order to collect a maximum of results and relevant feedback from those tests and produce more complete technical recommendations at the end of the RadoNorm project (2025).

2. Recommendations for the measurement of the radon activity concentration in underground workplaces

The underground workplaces have been selected for this report because of the missing measurement protocols in some countries in these places with peculiar conditions, such as extreme environmental parameters (humidity, temperature, etc.), high radon concentration, non-uniform radon distribution or the presence of forced-ventilation systems.

The recommendations described in the present chapter are applicable to the following steps of the graded approach (Figure 1): initial measurement (1), verification measurement post mitigation (2) or workplace surveillance (4). The exposure assessment (3) and planned exposure situation (5) are not directly addressed in this chapter as it is a dose calculation and may be more related to the radon progenies measurement (see chapter 4).

Underground workplaces can be sport facilities arenas, cave restaurants, catacombs, castles or museums, touristic caves, agricultural cellars, dams, sewers, waste storage facilities, quarries, tunnels, mines, mining museums, shafts, car parks, urban transport facilities, technical galleries, underground warehouses, etc. However, working areas situated in the basement of a building should, in this context, not be considered as underground workplaces.

Note that the above-mentioned areas which are “physically” connected to underground areas (like changing rooms, shops, office, etc.) are also considered in these recommendations.

2.1 Materials

2.1.1 Type of measurement devices

In general, in underground workplaces where the environmental conditions show extreme temperatures, high humidity or dust, the measurements should be carried out with instruments whose response is not affected by such conditions.

In the framework of the RadoNorm project, three other subtasks are related to measurement instrument tests, being task 2.1.4 with an intercomparison of low-cost electronic radon monitors (led by BfS), task 5.4.2 with an intercomparison of radon monitors in different ambiances including mix of radon/thoron (led by SURO) and task 5.4.3 with an intercomparison of active and passive dosimeters (led by SUJCHBO). Results from these intercomparisons will be available at the end of the RadoNorm project (2025), so some adjustments may be expected regarding the proposed recommendations in this report.

2.1.1.1 Integrated measurement

An integrated measurement method is recommended in underground workplaces for step 1 and 2 of the graded approach and even for step 4.

For integrated measurement, inexpensive detectors (e.g. Solid State Nuclear Track Detectors, SSNTD, “closed-type”, electrets) can be used. They should be provided and analysed by accredited laboratories. It has to be evaluated whether radon detectors are capable to perform measurement during the whole sampling period without being overexposed.

From the task 5.4.3 study, it was pointed out that outside the working hours the integrated passive dosimeters must be stored in a storage room with low background. This storage room with low background can also be used to perform the measurement of the background (which will be subtracted to the measuring results) by a control passive dosimeter.

Such integrated measurements provide the average radon activity concentration for the exposure period. However, if the ventilation system is causing diurnal variation the integrated measurements may have to be followed up with additional continuous measurement (see § 2.1 and 2.2, Norway and Finland examples).

2.1.1.2 Continuous measurement

Continuous radon monitors (CRMs) are normally used to evaluate the temporal variation of the radon concentration (daily, seasonal, or during specific occupancy periods for example). Many instruments are available in a large price range, from low-cost electronic detectors to more sophisticated and expensive monitors. Those devices can be used as CRM, providing they respond to the following points:

- the response time of the instrument is short enough to allow reliable detection of changes in radon concentration,
- the instrument must be suitable for the environmental conditions in which the measurement is made (e.g. radon concentration, temperature, humidity),
- battery life should be sufficient if no power is available,
- the memory capacity must be sufficient for the intended measurement.

Depending on the national regulation, the mean radon concentration of the continuous measurement may be allowed to be compared to the RL, like in Austria and Norway, but only if the same measurement time as for integrated measurements has been used (two months for underground workplaces). In some other countries, like in France, the results of electronic devices or other continuous measurement cannot be compared with the RL in step 1 or 2, but only the results of integrating devices.

Similarly, if continuous measurements are authorised by national regulation in step 4, they can be useful for the ambient surveillance of a workplace (see § 2.2.1 for details). They can help to refine the exposure assessment of workers if records of working times in different workplaces are kept. For example, in waterworks, radon levels in the air follow the cycles of water treatment, which means that radon levels can vary widely during the working day. This allows water plant roving maintenance crews (itinerants) to plan their routes so that maintenance work is carried out when radon concentrations are at their lowest.

Some northern countries (Canada, Sweden, Norway and Finland) use continuous measurement as an additional measurement, in step 1, 2 and 4, for workplaces where a ventilation system is causing diurnal variation. In workplaces with time-controlled forced ventilation, which is switched off outside working hours, the radon concentration at working hours is normally lower than the measured integrated radon concentration. It is also possible that the type of work requires local exhaust ventilation that is only operated during working hours (e.g. removal of fumes and dust). In these cases, significant negative pressure may only occur during working hours, and the radon concentration during this time may therefore be higher than the long-term mean concentration. If the measured integrated radon concentration is above the national RL, a ventilation correction factor should be introduced by doing a phase-two measurement (see details in § 2.2, Norway and Finland examples).

Sometimes continuous measurements will reveal that it takes some time for the ventilation system to reduce the radon concentrations after it is turned on which can probably be fixed by turning on the ventilation earlier. Continuous measurement is also useful in the context of building maintenance work services on radon remediation, e.g. when adjusting the efficiency of a radon sump. The sensitivity characteristics of a CRM should be regarded to choose the suitable instrument to follow-up the dynamic of indoor radon.

2.1.1.3 Spot measurement

In some cases, the measurement conditions are so difficult that an integrated or continuous measurement cannot be made. For example, high humidity, dust, machinery movement, vibration, exhaust fumes and splashing water can damage instruments. In these cases, one viable option is often to perform instantaneous radon measurements and grab sampling.

In Finland, for example, radon exposure in underground mines and tunnel workings is determined by sampling in sealable Lucas cells and measuring radon by spot measurements [4].

However, there are unknown uncertainties in this assessment method. Although the measurement of radon concentration itself can be carried out with a high degree of confidence, there is a high degree of uncertainty in the sampling. The temporal variation of radon concentration in underground passages follows the seasons. In summer, mines typically have the highest radon concentrations when the air outside is much warmer than the air inside the mine. In winter, the situation is reversed, and the mine is ventilated by gravity. The active ventilation used in the mine, e.g. with rag pipes, follows the progress of the work. When the tunnel is no longer being mined, ventilation may no longer be provided, which could lead to increased radon levels. On the other hand, the tunnel can still be used to move between actively used work areas.

In addition to temporal variation, there is also spatial variation. The local radon concentration in the tunnel network depends on factors such as the porosity of the rock, local ventilation, the type of rock in the walls and, in particular, the discharge of groundwater into the facilities. It is clear that radon levels cannot be measured at all points in the tunnel network, so the choice of measurement points by the person carrying out the measurements can have a major influence on the outcome of the exposure assessment.

2.1.2 Calibration and quality assurance of the measurements

As a general recommendation, for both integrated or continuous measurement methods, the quality of provided results should be guaranteed ideally through accreditation, or through calibrations and participation of the calibration facilities to interlaboratory comparison exercises. Calibration facilities or interlaboratory comparisons are proposed by various institutes such as BfS, SUJCHBO, SURO, PHE, SSM, STUK, ENEA, IRSN and others. In the EURAMET project "MetroRadon – Metrology for radon monitoring" (www.metroradon.eu) one work package was dedicated to the validation of traceability of European radon calibration facilities. Information about existing calibration facilities in Europe was collected (Status 2018) and comparison exercises were performed. Results are summarised in the Deliverable D7 of the MetroRadon project (http://metroradon.eu/wp-content/uploads/2017/06/16ENV10-MetroRADON-D7-final_accepted.pdf).

In addition, the uncertainty of the results shall be regarded to consider the results as valid or not. The uncertainty may depend on the radon level. Generally, an uncertainty value not higher than 30 % (at k=2) is recommended.

2.2 Method

2.2.1 Location and number of measurement points

The radon measurements need to be performed at each underground working place, being at one static place or various locations. The above-ground areas which are connected to underground areas (like changing rooms, shops, offices, etc.) are also to be measured. Thus, as a preliminary step, all the working places must be identified by the employer. In some specific cases, an itinerant pathway may need to be characterised, like in touristic caves, where measurements should be performed along the way of the touristic tours used by the guide, specially where the guides usually stop and stay longer.

The radon measurements are carried out for steps 1 and 2 (initial and verification measurement, respectively) at all the working places and in poorly ventilated areas. Depending on the national regulation, working places with very low occupancy time can be excluded from radon measurements (example below 50 to 100 hours per year).

For the different working places determined, according to their size, the number of measuring points may depend on the national procedure. The table 1 provides some examples for steps 1 and 2.

Table 1 – Specifications related to the location and number of measuring points at underground workplaces in different countries

Country	Specifications related to the location and number of measuring points
Austria	1 integrative detector at each workplace or working area
Belgium	1 integrative detector per homogeneous zone[1]
Czech Republic	- 1 integrative detector per 50 m^2 - integrative detectors in all rooms - in underground corridors: 50-100 m intervals for small-scale sites, and 200-400 m intervals for large-scale sites where the total length of corridors used for workers is longer than 1 km, or at nodal points of the wind network.
Finland (Regulation STUK S/6/2022)	A conventional underground workplace is a workplace with ventilation, temperature, humidity and other physical characteristics similar to those of the interior of a conventional building. In such workplaces, radon measurements shall be carried out in each separate building and, as a minimum, in each work area served by a separate ventilation machine: 1. one measurement if the surface area does not exceed 100 m^2; 2. two measurements if the surface area is greater than 100 m^2. In addition, where the surface area exceeds 200 m^2, at least one measurement per 200 m^2 or, in the case of a continuous open space, at least one measurement per 3000 m^2 or more shall be taken. In underground mines and quarries and in tunnels, the location and number of measurement points shall be such that the results provide a reliable estimate of the radon concentration in the workplace. When using grab sampling and spot measurement, depending on the size of the site to be measured, there are between 4 and 20 sampling points, on average ten. The points are usually located where workers work or spend most of their time, and where radon concentrations are suspected to be unusually high, such as at the ends of tunnels and where groundwater discharges into the mine.
France	- if the area is less than 200 m^2, at least two integrative detectors nearby the working place - if the area is above 200 m^2, then identify a homogeneous zone and place: - At least one integrative detector every 200 m^2 per homogenous zone if the shape of the place is more room-like - Or at least one integrative detector every 500 m if the shape of the place is more tunnel-like
Ireland	One integrative detector in each separate room, section or area irrespective of size

[1] Homogeneous zone: zone where the potential radon source, interface with the surrounding rock, temperature or aeration are quite similar.

Country	Specifications related to the location and number of measuring points
Italy	Measurements should be performed, referring to technique specific for existing climatic conditions, at positions occupied by employees in tunnels, underpasses, catacombs, caves, subways. - Measurements should be performed in all rooms physically separated. - In case of several rooms analogous for structure, occupancy patterns and ventilation, it is possible to perform measurements on a reduce sample, i.e. not less than 50% of total. If the room surface is less than 100 m^2, at least one measuring point per 50 m^2 should be chosen. - If the surfaces are greater than 100 m^2, at least one measuring point per 100 m^2 should be chosen.
Norway (recommendations, not requirements)	Furnished underground workplaces: An initial measurement should be carried out as a long-term measurement in all frequently occupied rooms and premises. The measurements should be evenly distributed. Include locations where there is a greatest risk of exposure, for example places where workers stay and poorly ventilated areas. If the results are above the action level (AL, which is 100 Bq/m^3, and lower than the RL (200 Bq/m^3)): additional measurement in rooms or selection of rooms with values above AL. Tunnels, mines and other non-furnished underground workplaces: stationary or person/individual measurements. Stationary: The measuring equipment is placed in representative locations in premises where the employees stay. The number of measurements and placement of measurement equipment must be evaluated for each case. Personal/individual measurements: If the employees work in several locations, measurements must be carried out in all relevant areas and working hours in each area must be recorded.
Portugal	At least one integrative detector in each main working area
Sweden	For completed and furnished rock rooms, rock facilities, basements and similar environments, the following method description used in workplaces in general can be applied, but a special assessment may then need to be made to determine applicability: - Measurement of radon levels should be carried out in each separate building and on each floor. - At least two measurement points shall be used per building. - When measuring radon levels on floors with ground contact, measurements shall be made in at least every fifth room used as a workplace. - At the same time, at least one measurement point per 200 m^2 must be used (even on floors with no ground contact). - If there are several ventilation units in a building, measurement points should be selected so that all areas that covered by each ventilation unit are included in the measurements. - In cases where radon measurements are to be carried out in very large premises such as warehouses or sports halls, it may be sufficient to have one measurement point per 1000 m^2.
United Kingdom	at least one integrative detector in each main working area

Concerning continuous monitors, the location and number should be determined as for integrated detectors. However, the cost of such instruments compared to integrated detectors could limit their use for big workplaces. For example, in Finland, additional measurements are not required at each sampling location where integrated measurements are done if the measured concentrations are similar. In these cases, continuous measurements are carried out in each ventilation zone (corresponds to homogenous zone), in a central spot of the zone.

Whatever the type of measurements (continuous or integrated or spot), the instruments shall be placed at a height that is coherent with the working place, for example at a height of about 1 – 2 m above the ground, at a distance of at least 20 cm from the wall (if possible), in a stable and secure location, representative of the ambiance of the working place. Those recommendations can be found in ISO 11665-1 [1] and NF M60-772 [5] standards.

Regarding step 4, exposure monitoring, the measurements can be made differently according to national regulation. The measurement devices, either integrated or continuous, can be placed:

- at all workspaces so as to regularly update exposure calculation and thus re-assess the worker's annual exposure.

- only at locations with radon concentrations exceeding the RL for a survey of the radon ambiance (e.g. in France, permanent continuous measurements or annually repeated integrated measurement can be performed).

2.2.2 Sampling duration and period

Since for steps 1 and 2 of the graded approach the aim is to evaluate the annual average concentration of radon at a working place, the sampling duration needs to be representative of the annual average radon concentration. The most reliable way to fulfil this condition is to perform the measurements for one year. However, for practical reasons, shorter durations can be used if they are considered as representative of the annual exposure of the workers or at least, representative of an exposure that is considered as conservative.

The period should be adapted to the workplaces depending on the operational time and the seasonal radon concentration variability (either winter/summer, or only summer, or other).

Some examples of measurement duration for steps 1 and 2 are given in Table 2.

For step 4, the sampling duration and period are to be adapted to the occupation of the locations concerned by an exceeding of the radon RL. If the location is regularly occupied, the duration and period can be similar to the above-mentioned ones for steps 1 and 2. On the contrary, if the location is poorly occupied, the duration can be shorter (at least two months if integrative measurements are done and at least one week if continuous measurements are done) and the period can be chosen during the occupational activity period. Such measurements can be repeated as specified in the following subsection 2.2.3 (frequency of the measurement) to follow-up the radon concentration evolution of these locations.

Table 2 – Specifications regarding the measurement duration at underground workplace in different countries

Country	Specifications regarding the measurement duration
Austria	At least two months, between 15th April and 15th October (for underground workplaces in mines, shafts, galleries, tunnels, caves and touristic caves and mines)
Czech Republic and France	If the workplace is operated during the whole year then one measurement during at least two months in winter and one measurement during at least two months in summer. If the workplace is occupied only a part of the year, the measurement is done during at least two months only in the operational period.
Finland	The initial measurement shall be carried out by means of an integrated radon measurement lasting at least two months between the beginning of September and the end of May (the measurement season). Measurements may be carried out at other times if there is a justified reason for doing so. For workplaces where a ventilation system is causing diurnal variation, if the at least two months integrated measurement results are above the RL then additional continuous measurement are carried out during the measurement season and shall last for at least seven days. The determination period shall be equal to or a multiple of seven days and shall be representative of a typical working week.
Ireland	The measurement period should be at least three months and less than 12 months (to avoid ageing and fading).
Italy	Indoor radon concentration should be measured over a period of one year, eventually by more than one subsequent sampling period.
Norway	Furnished underground workplace: the measurements should last for a period of at least two months. If the radon concentration exceeds the action level and the facilities has time-controlled ventilation, it has to be followed up by continuous measurement for a week to find the ventilation correction factor (see § 2.2.4). In workplaces where there are stable conditions, radon can be measured in the same way as for furnished underground workplaces. But if the conditions are more unstable, the employer should assess the need for continuous monitoring either through stationary measurements or by using person-borne measurements.
Portugal	At least three months and no longer than 12 months
Spain	For each homogeneous zone, a representative value of the mean annual concentration of radon-222 must be given together with the upper limit of one tail of that parameter, for a level of 90% confidence.
Sweden	The initial measurement shall be carried out by means of an integrated radon measurement lasting at least 60 days between the 1st October and the 30th April. Measurements may be carried out at other times if there is a justified reason for doing so. An additional measurement applying continuous measurement should be made for at least seven days of which five days should be during working days and analysis of results is performed for a 7-day period. Measurement should be carried out during days when activities are taking place on workplace premises.

2.2.3 Frequency of the measurements

As the situations can change, being the occupational activity or the structure of the underground workplace, radon concentration can change in working places leading to the necessity to repeat the evaluation of the radon concentration at the workplace. Basically, it corresponds to step 4 of the graded approach. The countries shall decide how to define the frequency. Some examples are given in table 3.

Table 3 – Specifications regarding the frequency of the measurement at underground workplace in different countries

Country	Specifications regarding the frequency of the measurements
Austria	Measurements and effective dose assessment shall be repeated in underground workplaces where the reference level has been exceeded and the worker's effective dose is below 6 mSv/y every five years. If the worker's effective dose is above 6 mSv/y, a permanent dose monitoring is required. Measurements and/or effective dose assessment needs to be also repeated in case of changes (technical, constructional or administrative), which could lead to an increase of the radon exposure of the workers
Finland (Regulation STUK S/6/2022, [6])	At an underground (tunnel, parking lot, etc.) excavation site, radon levels must be measured every six months. However, the interval between measurements shall be one year if the result of two consecutive measurements at each measurement point is less than 100 Bq/m^3. In an underground mine, the radon concentration must be measured every two years. However, the interval between measurements shall be five years if the result is less than 100 Bq/m^3 in three consecutive measurements at each measuring point. For *conventional* underground workplaces STUK *recommends* that measurements be repeated in: • every ten years if the previous radon concentration was 100–300 Bq/m^3 • every ten years if the reduction of radon concentrations below the reference value has been achieved by radon remediation • every five years if the radon concentration below the reference value has been achieved by radon remediation and the radon concentration before remediation was higher than 1000 Bq/m^3. • as soon as possible after any substantial structural or ventilation-related construction or alteration work (e.g. replacement of concrete slab, drainage or ventilation).
France	Measurements shall be repeated in workplaces where the RL has been exceeded and the worker's effective dose is below 6 mSv/y (typically step 4). Such repeated measurements are aimed at surveying the radiological ambiance of the radon zone of the workplace. The measurements are carried out periodically or, if necessary, continuously. Measurements shall be repeated in workplaces where a radon zone has been identified (worker's effective dose above 6 mSv/y). In this case, the maximum interval between two measurements cannot exceed five years. But this interval is one year if radon concentration is above 1000 Bq/m^3.

<table>
<tr><th>Country</th><th colspan="2">Specifications regarding the frequency of the measurements</th></tr>
<tr><td>Italy</td><td colspan="2">The measurements must be repeated after eight years in all workplaces if results are below the RL.
If the results are above the RL, remedial action must be taken within two years and their efficacy must be demonstrated with new measurements. Then the measurements have to be repeated every four years.
The measurements must be repeated if the workplace undergoes substantial structural renovation.</td></tr>
<tr><td rowspan="6">Norway (recommendations and not requirements)</td><td>Where</td><td>Frequency of the measurements</td></tr>
<tr><td>Tunnels, mines and other non-furnished underground workplaces</td><td>After start-up and when breaking into new areas. Minimum annual measurements.</td></tr>
<tr><td>Furnished underground workplace</td><td>After start-up and in case of major changes in use and rebuilding (including ventilation)</td></tr>
<tr><td>Furnished workplaces and premises where previous measurements show stably low radon levels below action level (AL in Norway: 100 Bq/m^3)</td><td>Around every ten years, if there have been no changes in ground conditions, facilities or ventilation during the period.</td></tr>
<tr><td>Furnished workplaces and premises where measures have previously been taken against radon or where the location is in a radon-prone area</td><td>Around every five years, or more often if the radon problems have been serious.</td></tr>
<tr><td>Person/individual measurements</td><td>When needed or every three months</td></tr>
<tr><td>Portugal</td><td colspan="2">Every 12 months. If the results of the initial measurements (step 1) or the measurements after the implementation of mitigation actions (step 2) are below 250 Bq/m^3, the frequency is every five years.</td></tr>
</table>

2.2.4 Data analysis

In case of continuous measurements performed for one year, an annual mean can be calculated only for working hours and by correcting the value (subtract the background level and consider the calibration factor, as mentioned in the ISO 11665-5 standard [7]).

For other measurement durations, the value representative of the annual mean radon concentration shall be assessed.

Some seasonal or ventilation correction factors can also be applied. These factors are described in national regulation or guidelines if necessary (see examples hereunder).

Then the obtained value of annual radon concentration shall be compared to the national RL by either considering or not considering the uncertainties of the measurement. Some specific analyses can be done depending on the national regulation and some different methods applied for various situations in some countries are described as examples.

Austria: Radon measurements in underground workplaces (underground WPs in mines, shafts, galleries, tunnels, caves and touristic caves and mines) needs to be done at least for two months during summer (between 15th April and 15th October). This value is considered to be representative/conservative for the annual mean and is directly used for comparison with the RL. To verify compliance with the RL, the radon concentration at each workplace shall be compared with the RL, leaving measurement uncertainties aside.

Czech Republic: the annual average radon concentration is not calculated. If the underground workplaces are operated only during summer period, the effective dose is calculated from summer radon concentration and time spent at the workplace. In case the underground workplace is operated during the whole year, the effective dose is the sum of "summer" and "winter" effective dose. The uncertainties of measurement are basically not taken into account due to high variability of radon concentration, which is higher than the uncertainty.

Finland: For conventional underground workplaces, where the air exchange in the workplace is regulated according to working hours, additional continuous measurement is carried out for at least one week. The results are reported as the average radon concentration during the working hours of the determination period (168 hours or its multiple) and the average radon concentration during the determination period [6, 8]. The annual average (C_a) in Bq/m^3 is estimated as follows:

$$C_a = C_T \times C_{wo}/C_{wh} \times k_s = C_T \times k_v \times k_s$$

where

C_T is the mean radon concentration in Bq/m^3 measured with an integrated method (typically SSNTD),
C_{wo} is the mean radon concentration in Bq/m^3 during working hours (typically 40 h) within the evaluation period,
C_{wh} is the mean radon concentration in Bq/m^3 of the whole evaluation period (168 h or its multiple), and
k_s is a seasonal correction factor, without unit, used to assess the annual radon concentration from the integrated measurement during the measurement season (its generic value in Finland is 0.9).The ratio C_{wo}/C_{wh} is called ventilation correction factor k_v in Finland.

For underground mines and tunnels, the data analysis is as follows: the arithmetic mean of the spot measurement results is calculated (without correction factors) and the mean is compared to the RL. Then, the measurement results for an individual point are compared with the RL (without correction factors) and, if the RL is exceeded and a significant number of hours are worked at that point, an exposure reduction order is issued.

A new test protocol in underground mines is being tested under this work package. The first results are presented in Appendix A.

France: The data analysis practice is described in the guide published by the Ministry of Labour, which is mainly based on the French standard NF M60-772 [5]. For each working place or each homogeneous zone, and for each season or operational period, the results are examined regarding their uncertainties. For each working place or each homogeneous zone, the mean value is calculated if the dispersion is lower than the uncertainties, otherwise the maximum value is selected. These mean values or maximum values are expressed without uncertainties. In case the underground workplaces are operated during one period, for example in the summer period, the radon concentration measured during summer is compared to the RL. In case the underground workplaces are operated the whole year, the measurements are performed at two seasons, for each working place or each homogeneous zone, and the mean value is calculated on the base of the values selected in summer and in winter. The resulting annual average of radon concentration for each place or homogeneous zone, expressed without uncertainty, is then compared to the RL (see example in table 4).

Note that if a technical problem can explain the large dispersion of the results regarding to the uncertainties, then the measurements must be done again.

Table 4 – Example of a touristic cave, with data analysis practiced in France

Measured zones	Radon concentration (Bq/m^3)	Radon concentration per zone (Bq/m^3)	Radon annual average to be compared to the RL (Bq/m^3)
Zone 1: main cavity	Winter season 145 + /- 25 320 +/- 40 920 +/- 80 600 +/- 55 890 +/- 80 960 +/- 85 630 +/- 50 710 +/- 65 Summer season 190 +/- 33 380 +/- 40 1050 +/- 90 1080 +/- 85 1100 +/- 115 1450 +/- 120 960 +/- 75 790 +/- 60	Winter: 960 Summer: 1450	**1205**
Zone 2: nearby the abyss	Winter season 420 +/- 40 530 +/- 50 Summer season 660 +/- 60 760 +/- 75	Winter: 530 Summer: 710	**620**

Ireland: The results of each workplace measurement are seasonally corrected by dividing the measured radon concentration with the seasonal correction devisors (Table 5). This gives the seasonally adjusted radon concentration for each workplace measured.

Table 5 – One-month seasonal correction devisors for radon measurements in Irish workplaces

Month	Seasonal correction
January	1.16
February	1.16
March	1.12
April	1.05
May	0.96
June	0.89
July	0.85
August	0.84
September	0.88
October	0.96
November	1.04
December	1.11

Seasonal correction is carried out for all measurements that are carried out over less than 12 months.

This is carried out by:

- (a) Averaging the monthly correction devisors given above for the measurement period. For example, where the measurement period covers the months of December, January and February, the seasonal correction devisor is calculated as follows:

  (1.11 + 1.16 + 1.16) / 3 = 1.14

- (b) Applying the seasonal correction devisor of 1.14 to the individual room measurements. For example, measurements with the following results:
  - Office A: 280 Bq/m^3
  - Office B: 350 Bq/m^3
  - Office C: 220 Bq/m^3

  Resulting in seasonally corrected results of

  - Office A: 280/ 1.14 = 246 Bq/m^3
  - Office B: 330/ 1.14 = 290 Bq/m^3
  - Office C: 220/ 1.14 = 193 Bq/m^3

The seasonally corrected radon concentration is then compared to the national RL for workplaces of 300 Bq/m^3.

Norway: No default seasonal correction factors have been prepared for the use for radon measurements at underground workplaces.

In a workplace with time-controlled ventilation system, the radon measurements are performed by following two steps. The purpose of the initial measurements is to determine the possible presence of high radon levels, while additional continuous measurements are used to find the quotient between radon concentrations at working hours and the average of the whole continuous measurements [9].

The annual average radon concentration during working hours is then calculated (C_a, in Bq/m^3):

$$C_a = \frac{c_1}{c_2} \bullet C_{LT} ,$$

where C_1 is average radon concentration during working hours based on a continuous radon measurement of a week, C_2 is average radon concentration of the whole continuous radon measurement and C_{LT} is the result of the long term (> two months) radon measurement.

2.2.5 Recording

The measurement results shall be recorded in an appropriate document (test report or similar), so as to be consulted by stakeholders. Such documents can be defined in national regulation. ISO standards also specify what information should be included in the test report.

3. Recommendations for radon measurement for itinerant workers

This chapter deals with the specific case of the radon exposure assessment of itinerant workers who can be exposed to variable radon levels in all types of workplaces with generally low occupancy.

The definition of itinerant workers may be based on the one given in IAEA Safety Standards [10], "*itinerant workers are occupationally exposed persons who work in supervised areas or controlled areas at various locations and who are not employees of the management of the facility where they are working*". To this definition, it might also include the "not occupationally exposed workers" who have to enter in radon areas. And finally, it also concerns the workers of a company who intervene in the different sites of the company. In underground and poorly ventilated facilities, itinerant workers are susceptible to be exposed to high radon concentrations.

Itinerant worker activities are for example, professional cleaners, technical maintenance workers, inspectors, scientific researchers, etc. They intervene either regularly in the same locations or punctually in various locations for a limited period.

The working places in this chapter are not only underground but all types of workplaces.

In some situations, long-term radon measurement is not applicable and/or the radon concentration in the workplaces cannot be known before intervention.

Depending on the different types of situations that are described in this chapter, corresponding specific recommendations for radon measurement are provided.

3.1 The workplaces where the radon concentration can be measured before intervention

For a technical agent who intervenes in different sites of his own company or, a cleaner or technical agent who intervenes for one or several companies, in the same site(s) all over the year, the radon measurement can be performed before intervention.

Technical recommendations:

If time is not a constraint, the radon concentration in this case can be measured in each workplace, by following the recommendations described in chapter 2, for the different steps of the graded approach.

As previously mentioned in § 2.1.1, continuous measurements made for the workplace surveillance (step 4) may help itinerant workers to plan their routes so as to work when radon concentrations are at their lowest (for example in waterworks).

If the time is constraint, some short-term measurements can be performed. For example, in Switzerland, a short-term radon measurement method in building has been approved, by using radon continuous monitors (one per floor) in occupied areas during at least five days, whatever the season.

Also grab sampling and spot measurement can be used before the work starts. In this measurement method, an air sample is taken and measured immediately. This is to check whether it is safe to start working in the room at that moment. The efficiency of many measuring instruments allows for very short measurements to determine whether the concentration is, for example, above the RL. For example, in RAD 7 sniff mode, an 8-minute measurement is sufficient (@200 Bq/m^3 the uncertainty is in the order of ± 30 %). Many Lucas chambers, e.g. Pylon 300A + counter AB7, are even more efficient and the result can be obtained in even shorter time.

According to the radon measurements results obtained and the resulting effective dose assessment (step 3), a personal dosimetry may be decided for the itinerant workers.

3.2 The workplaces where the radon concentration cannot be measured before intervention

Workplaces where the radon concentration has not been measured might be encountered for various reasons:

- because the employers are at the beginning of the application of the legislation;

- because the working areas are very large, and/or very rarely occupied.

In such locations, itinerant workers can occasionally intervene during short time durations. For instance, it may concern a technical agent who operates/provides maintenance in galleries of different companies, a worker who operates in water facilities or a researcher who studies different caves, etc.

In workplaces where the annual average radon concentration has already been measured, the radon value at the moment of the intervention might be different from the annual average one, especially in underground workplaces, then a new radon measurement might be necessary.

For those situations the radon measurement method has to be adapted.

Technical recommendations:

Depending on the time available to perform the measurement, it may be useful to start with a first measurement just before the start of the work. This first measurement can help to evaluate if ventilation is needed during intervention in order to lower the radon concentration. Just before intervention, either grab sampling (by like Lucas cell or radon sniffing instrument) or continuous radon monitors (CRM) can be used. The CRM shall be used with a pump, to increase the air volume analysed in the instruments and reduce the response time.

If time is a constraint and the measurement can only be performed during the intervention/presence, then CRM shall be used, with pump if possible, so as to record the variations of radon concentrations during the time of intervention/presence. CRM with an alarm function may be useful to help the workers to be alerted in case of any sudden increases in radon concentration. For example, the French national regulation defines for short time intervention a precautious value to be set up in the instrument at 1000 Bq/m^3 in underground workplaces where radon concentration has not been measured but is expected to be high.

In both cases, just before and during intervention, instruments shall be placed at workplaces, between 1 and 2 m above ground, or held by the worker, and as far away as possible from a ventilation system if ventilation is on. In workplaces where the environmental conditions show extreme temperatures, high humidity or dust, the measurements should be carried out with detectors whose response is not affected by such conditions.

The measurement duration of CRM is a critical criterion since a minimal duration is necessary to obtain valuable results. This criterion depends on the response time and sensitivity of the instrument thus the manufacturer specifications shall be carefully regarded to choose the most appropriate instrument. Some information is published for instance in the study of Dimitrova et al, 2023 [11]. In this study, the performances of four CRM instruments (RAD7, RadonEye, Alphaguard and AlphaE) were compared at different radon concentrations in a lab radon chamber. The quantified response times ranged between 2 min and 90 min for reaching 90 % of the equilibrium activity after a spike of radon. STUK has also studied the response times of RadonEye [6], AlphaE and Doseman, and the results of the latter two are presented in Appendix A. In the framework of the RadoNorm project, three other subtasks are related to the testing of measuring instruments, task 2.1.4 with an intercomparison of low-cost electronic Radon monitors (BfS), task 5.4.2 with an intercomparison of Radon monitors in different ambiances including mix of Radon/Thoron (SURO) and task 5.4.3 with an intercomparison of active and passive dosimeters (SUJCHBO). The results from these intercomparisons will be available at the end of the RadoNorm project (2025), so some adjustments may be expected regarding the proposed recommendations in this report.

If the radon level is significant (value to be defined by each national regulation) and cannot be lowered during the intervention, it may be recommended to estimate the individual provisional worker's effective dose for the time of work in the place (step 3). The annual effective dose received by each itinerant worker has to take into account the effective doses received in all previous interventions during the year. If the annual effective dose exceeds 6 mSv/year (for most EU members), then this may implicate an individual monitoring of the workers. Such monitoring is based on radon progenies measurements (see § 4.2.2).

4. Recommendations for radon progenies measurement in workplaces

This chapter provides technical recommendations to be taken into consideration for the measurement of radon progenies in some specific workplaces or in situations of exception (studies, research, etc.). It consists of measuring the potential alpha energy of short-lived radon decay products.

The measurement of Potential Alpha Energy (PAE) can be used from step 3 of the graded approach of radon risk management in European workplaces (Figure 1), to assess the annual effective dose of the workers that is compared to the annual effective dose reference level of 6 mSv/year. If the resulting value of the effective dose exceeds this reference level, the situation shall be managed as a planned exposure situation.

At step 3, the calculation of the annual effective dose can be realised either from radon activity concentration or from radon progenies PAE:

- **From radon activity concentration:**

$$\mathbf{E = C \times T \times DCF}$$

Where

E: annual effective dose (mSv/year)

C: radon annual average activity concentration (Bq/m^3)

T: annual occupancy (hours/year)

DCF: dose conversion factor [mSv/(Bq.h.m^{-3})], for an equilibrium factor value of 0.4. The DCF should be defined in national regulation (e.g. from ICRP [12]).

- **From radon progenies PAE:**

$$\mathbf{E = PAE \times T \times DC}$$

Where

E: annual effective dose (mSv/year)

PAE: radon progenies potential alpha energy (nJ/m^3)

T: annual occupancy (hours/year)

DC: dose coefficient [mSv/(nJ.h.m^{-3})]

The choice between radon activity concentration or PAE measurement to assess the effective dose shall be examined regarding different critical parameters: uncertainty of the equilibrium factor when using radon measurement and lack of primary standard calibration of measurement devices when using PAE measurement. Moreover, the radon measurements are usually preferred because of its relative simplicity and cost effectiveness. The PAE measurement is theoretically the best solution to evaluate the effective dose of workers. This calculation is more direct and can be more precise than the one using the radon activity concentration and a mean value for the equilibrium factor.

4.1 General consideration about radon progenies

Radon progenies behaviour in air:

^{222}Rn disintegrates into ^{218}Po which interacts with the atmosphere and forms aggregates by attaching to aerosols. This atom will then disintegrate into ^{214}Pb, then ^{214}Bi and ^{214}Pb and so on. The source of aerosols and their behaviour may depend on the working activity in the workplace, but also on the number of present people (a human being is a source of aerosols). Besides, the air is renewed, either by a ventilation, or through fissures. A part of the aerosols and radon progenies will deposit on the ground by sedimentation or will attach to the walls, ceiling, furniture and other components.

Variability factors impacting the effective dose:

- Equilibrium factor (Feq) reflects the relative importance of short-lived radon decay products in relation to the radon. In a ventilated room where radon is present, if the ventilation rate is one volume of room air per hour for example, then all the radon decay products will not have the time to appear. A part of them will also deposit on the surfaces of the room, consequently PAE will remain inferior to the radon activity and Feq will be < 1
- Variation of the radon activity concentration, impacting then the Feq calculation
- Variation of PAE, also impacting the Feq calculation
- Fluctuation of the particle's concentration, mainly related to source of aerosols and presence of people
- Size distribution of ambient aerosols
- In air, two populations of short-lived radon decay products co-exist, being the unattached fraction of several nanometres in diameter, and the fraction attached to the aerosols. The unattached fraction varies inversely with the aerosol concentration.

Principle of radon progenies PAE:

All available methods are based on the collection of the radon decay products on filters and a subsequent activity measurement on the filter. The measurement devices include gross alpha counters, integrating alpha-track decay product detectors, alpha-spectrometric devices with surface barrier detectors, and attached-unattached samplers. In workplaces with dusty conditions, it will be necessary to frequently replace the filter because of their limited dust capacity.

In the frame of RadoNorm project, subtasks 5.4.2 and 5.4.3 are organising an intercomparison of PAE monitors in different ambiances including mixes of radon/thoron progenies (SURO and SUJCHBO respectively), which are especially relevant to improve these recommendations. Results from those intercomparisons will be available at the end of the RadoNorm project (2025), so some adjustments may be expected regarding the proposed recommendations in this chapter.

Some additional measurement of size-particles and attached/unattached fractions may also be realised but generally for scientific purposes on the factors influencing the effective dose and research on dosimetry. Therefore, such measurements will not be detailed in this report.

4.2 Radon progenies measurement in the graded approach

Radon progenies PAE measurement can be made if necessary to evaluate the annual effective dose, at the last steps of the graded approach. Such measurements can be performed to assess the provisional annual effective dose in a workplace or the individual dose of a worker. Different measurement methods can be used.

4.2.1 PAE measurement at a working place

4.2.1.1 Materials

- Type of measurement devices

Different spot PAE measurement instruments exist, such as MEAP from Algade, MAAF (Czech Republic), and for continuous PAE measurement, many instruments are available such as RPM 2200 from SARAD, EQF3220 from SARAD, BWLM-Plus-2S from Tracerlab, alphaPM from Bertin, Fritra 4 from SMM-CZ, etc.

The integrative PAE devices are detailed in § 4.2.2.

The choice between spot, integrative or continuous measurement instruments may rely on the time and the season variability of the radon activity.

For example, in an underground workplace where radon activity concentration is stable between seasons, then continuous PAE measurements are recommended as a first approach to verify if the variability of PAE during the year is the same, during at least one month at each season, or repeated spot measurements at different hours within a day and at different days for one month.

- Calibration and quality assurance of the measurements

As a general recommendation, the quality of provided results should be guaranteed ideally through accreditation, or through calibrations and participation of the calibration facilities to interlaboratory comparison exercises. Secondary calibrations are proposed at least by SUJCHBO, BfS, and interlaboratory comparisons are organized by SURO in the frame of RadoNorm project WP5.4.

Nevertheless, note that a primary standard does not exist yet for PAE measurement. Few laboratories propose that PAE calibration and metrological biases may be observed between results from different instruments. Such discrepancies lead to difficulties to interpret the data.

4.2.1.2 Method

- Location and number of measurement points

Like for radon measurements, the PAE measurements need to be performed at each working place, being at one static place or various locations. In some specific cases, an itinerant pathway may need to be characterized, like in touristic caves, where measurements should be performed along the way of the touristic tours used by the guide, specially where the guides usually stop and stay longer.

- Sampling duration and period

The aim is to evaluate the annual average PAE at a working place, the sampling duration needs to be representative of the annual average exposure.

Like for radon measurements, the most reliable way to fulfil this condition is to perform the PAE measurements for one year. However, for practical reasons, shorter durations can be used if they are considered as representative of the annual exposure of the workers or at least, representative of an exposure that is considered as conservative.

The period should be adapted to the workplaces depending on the operational time and the seasonal radon concentration variability (either winter/summer, or only summer, or other).

Moreover, the measurement duration can be adapted to the response time of instruments. The duration has to be sufficient to get a reliable PAE measurement. The measurement cycle shall be optimised by considering the variation of the PAE and the data capacity of the instrument. Again, the instrument manufacturer specifications shall be carefully regarded to choose the most appropriate instrument that fit for the purpose.

- Frequency of the measurements

If the situation changes regarding the occupational activity or the structure of the underground workplace or the ventilation or the variation of aerosols, then the PAE measurement shall be repeated to update the effective dose assessment of the workers.

- Examples

  - In a cheese cellar where the radon activity concentration is higher in summer than in winter and the temperature and humidity are controlled, the time of a worker’s activity can be taken as a reference period to perform the measurements (e.g. few hours per day) by using either continuous instrument or repetitive grab sampling measurements. In such cellar, the PAE measurement shall be performed in summer and in winter. The average PAE between all the measurements is used in the effective dose calculation.
  - In case of a technical gallery where workers intervene during few hours per day, in a first approach continuous or spot PAE measurements can be performed during the presence of workers. The results will be used to assess the annual individual effective dose.
  - Touristic cave can be a complex workplace due to the various working spaces, the humidity and the presence of natural ventilation which is specific to each cave. Moreover, the presence of workers and visitors can influence the aerosols concentration. In such cases, the PAE measurement shall be performed along the way of touristic tour used by the guide. Continuous PAE measurement during all the period of a workers’ activity should be necessary to take into account the possible spatial and temporal variations. Note that, especially in workplaces with active ventilation, the points where radon activity concentration is high might not be the same as the ones where PAE is high. Depending on the source of aerosols and the ventilation of the workplace, the spatial PAE variation may be different from what is observed for radon variation.

4.2.2 Individual dosimetry

This method is carried out in a workplace mostly in step 5, but could also be used in step 3, to obtain the individual effective dose with accuracy. Note that it implies some wearing constraints for the workers.

Individual dosimetry consists of measuring the PAE by a dosimeter, which is an integrative device or continuous monitor held by the worker. Different individual dosimeters exist, such as Algade dosimeter, Sarad DosemanPro, OD-88 (CZ), Radonis (CZ), etc. Some dosimeters for example are equipped with a sampling head containing filter and the foil LR115, and with an internal pump, which actively samples the ambient air inhaled by the worker. The manufacturer's recommendations should be respected to use it properly.

The worker shall wear the individual dosimeter during each exposure period, at the belt and not under clothes. Some manufacturers may propose an evaluation of the dosimeter at monthly intervals. They analyse the foils and transmit the PAE results to the customer (employer). The PAE results are then used to calculate the individual effective dose of the concerned worker.

A "blank" dosimeter which is stored out of the radon area should be used. Similarly, the dosimeters that are held by workers shall be also stored out of the radon area when they are not used.

From the study in task 5.4.3, it was pointed out that the response time of a PAE continuous monitor like DosemanPro is rather long. After the start of the measurement, a difference of 30% compared to the reference value in the testing chamber was observed. Thus, for short periods of time, this instrument may not be adapted.

Complementary recommendations could be provided from the studies of other sub-tasks at the end of RadoNorm Project.

4.2.3 Perspectives

Currently, only few experts are working on radon progenies measurements. These initial recommendations are based on feedback from the field, which need to be further expanded to take into account the many existing work situations, and the use of various commercially available instruments. In addition, current feedback highlights the need for primary calibration of radon progeny measurement equipment.

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Appendix A. Protocol for measuring radon exposure in underground, alternating workspaces – tests carried out by STUK (Finland)

Introduction

This report describes the protocol previously used in Finland to assess the radon exposure of mine workers and compares the results with the first results obtained with a new type of measurement protocol. Testing of the new measurement protocol has so far only been carried out at one mine. The study will continue in August 2023 at another mine.

Regulatory control and radon measurements in underground mines

According to Regulation STUK S/6/2022, radon levels in underground mines must be measured every two years. However, the interval between measurements is five years if the result is less than 100 Bq/m^3 in three consecutive measurements at each measuring point. The method used is grab sampling in sealable Lucas cells and spot measurement using scintillation counter. There are about ten measurement points, typically in the places where employees work or spend most time and in places where radon levels are suspected to be abnormally high, such as tunnel ends and places where groundwater discharges into the site (Kojo et. al, 2021, [4]).

The arithmetic mean and median of the results have been calculated. In almost all cases the median has been well below the arithmetic mean, i.e. the results have not been normally distributed, but there are 'hot spots' of radon in the mines.

In workspaces where an individual worker works more than 600 hours per year, the reference value for radon concentration is 300 Bq/m^3. In these workspaces, the competent authority requires a reduction in radon exposure. This can be done, for example, by increasing ventilation or reducing working hours in the workplace concerned.

In addition to the reference value for radon concentration, there is always a reference value for individual radon exposure of 500 kBqh/m^3 per year. This reference value is often used in workplaces where workers are spread over several alternating workspaces and only some of the spaces have radon concentrations above 300 Bq/m3 (similarly to nomadic workers).

The assessment is carried out using the exposure calculator provided by the competent authority. The calculator is input with estimates of the hours worked by each worker in the different spaces annually and the radon concentrations measured in these spaces. The concentration is always estimated at 0 Bq/m^3 in the outdoor air or in vehicles, and a generic value of 40 Bq/m^3 is used for the second or upper floors of indoor spaces. The calculator also ensures that the annual working hours are realistic (1650 hours on average).

In mines, it is often difficult for an employer to estimate the annual working hours in different parts of the mine because the working areas are constantly changing as the extraction work progresses. As a result, the reference value for annual occupational exposure to radon is rarely used in mines. In Finland, the practice is that if the average concentration at the measuring points exceeds 300 Bq/m^3, an order is issued to reduce the radon exposure of workers. Orders to reduce radon concentrations can also be issued on a point-by-point basis for points where working hours are regular. This is probably a safe way to ensure that radon exposure does not exceed the reference value. However, it is possible that with the procedure described above, there will still be some locations in the mine where radon levels are too high and where workers will be exposed, as measuring points cannot be located everywhere in the mine. Therefore, the suitability of portable, battery- powered personal radon detectors for radon control in mines was investigated.

It is important that the instrument used to measure personal radon exposure has a sufficiently short response time. The response time is the time it takes for the instrument to reach 90% of the final value of the signal when the meter is moved abruptly from a low to a high radon concentration or vice versa (standard IEC 61577-4). Other criteria include that the instrument is easy to carry, i.e. it is small and lightweight. The instrument should also be resistant to the environmental conditions of the mine and should be as easy to use as possible to facilitate employee engagement with the instrument.

Experimental work

In order to evaluate their suitability, the response times and sensitivity to humidity of two battery-powered radon detectors measuring personal radon exposure were first measured at STUK's Radon Standard Laboratory. The laboratory is equipped with a reference atmosphere, where radon concentration, temperature and humidity can be adjusted. The values of the variables are monitored with reference instruments traceable to the primary standard. The tested instruments were Doseman (Sarad GmbH) and AlphaE (Bertin instruments).

In the response time test, the instruments were set to integrate radon concentration at half-hour intervals. The instruments were enclosed with reference instruments in a radon-tight 101-litre container, from which the radon was completely removed by flushing with activated carbon-filtered air. At time t=0, radon-containing air was injected into the tank for one minute, resulting in a high radon concentration in the tank. The measurement was continued for a few hours and the response time was calculated from the results. The effect of humidity was studied by determining the calibration factor of the instrument at four different humidity levels by keeping the chamber temperature constant.

After testing, one of the instruments was selected for field testing. In the field test, the mine company was asked to take measurements with two radon meters as follows:

1. the first meter is placed in a room where efforts have been made to reduce the radon concentration, e.g. by moving a portable fan. If necessary, the meter can be attached to a lockable wall bracket if there is a risk that it could be moved by mistake. However, the meter must not be fixed to bedrock.

2. the second meter is carried by an employee. It is attached to the overalls/belt by means of the belt buckle provided. A worker, who works in the areas where instantaneous radon measurements indicate the highest radon concentration, is selected.

No precise measurement protocol was given, but the company was asked to do the measurements in a way they considered practical. The mining company was also asked to carry out an exposure assessment of the workers using the exposure calculator provided by the competent authority. This would allow a comparison between the estimates obtained with the personal meter and the exposure calculator. The company was also asked to comment on the usability of the meter.

Results

Laboratory tests

Figure A1 shows the results of the response time test. The raw data were fitted to the exponential function. After radon injection, an exponential term was fitted based on the first three hours of measurements (six measurement points). The rest of the measurements were used to fit the calibration coefficient.

The fastest response time, around 30 minutes, was obtained in Doseman's FAST mode. In this mode, the instrument only counts the alpha decays of polonium-218, the immediate decay product of radon. Since the alpha decay of polonium-214 is not taken into account, the sensitivity of the instrument is rather poor. This is evident from the scattering of the data. In the NORMAL mode, less scattering occurs but the response time in this mode is in the order of 130 minutes. The AlphaE instrument does not have separate modes and was determined to have a response time of about 70 minutes.

The values of the conditions used in the humidity sensitivity test are shown in Table A1. The temperature was kept constant at around 21°C. The radon content was set at about 9750 Bq/m^3. Prevailing conditions were monitored every 10 minutes.

Table A1. Exposure conditions during the humidity sensitive test. The uncertainty relating to the mean radon concentration is expressed with coverage factor of k = 1. The environmental conditions are reported as an arithmetic mean value ± standard deviation.

Exp.	Duration [h]	Rn-222 [Bq/m^3]	Temp [°C]	RH [%-rh]	Pressure [hPa]
1	14	9796 ±308	20.8 ± 0.3	6.67 ± 0.14	999 ± 0
2	18	9604 ± 301	20.8 ± 0.3	34.9 ± 1.4	996 ±1
3	18	9714 ± 305	20.8 ± 0.3	58.0 ± 4.5	1000 ± 1
4	14	9764 ± 308	20.9 ± 0.4	74.4 ± 7.1	998 ± 2

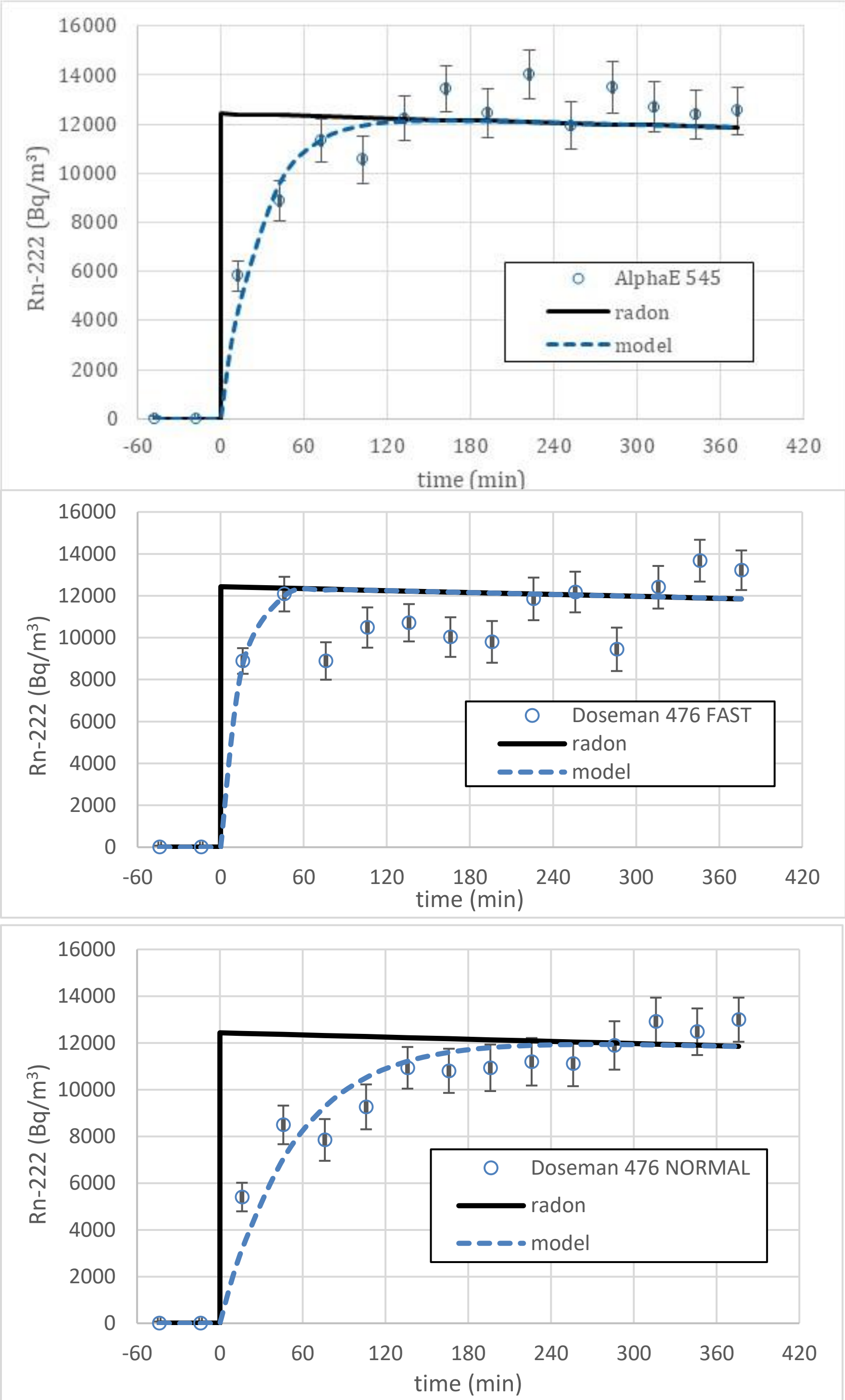

Figure A1. Response time tests performed on AlphaE and Doseman instruments. Response time in both FAST and NORMAL modes were estimated.

Figure A2 shows that the measuring instruments were not significantly sensitive to humidity. Humidity can reduce the efficiency of instruments that collect short-lived radon decay products on the detector by means of an electric field (Hopke, 1989). When water molecules are abundant in the air, the strongly positively charged progeny from radon decay are neutralised when polar water molecules react with them. At the same time, the amount of decay products collected on the detector is reduced and the calibration factor of the instrument is increased.

The Doseman calibration factor did not show any correlation with air humidity, so it was correctly designed. In contrast, a small negative correlation between humidity and calibration factor was observed for the AlphaE meter. Surprisingly, the calibration coefficient for very humid air is about 10% lower than for dry air. Since this instrument also registers the humidity, it is possible that the instrument overcompensates for the loss of collection efficiency in high humidity and thus the calibration factor is lower.

Although Doseman performed better than AlphaE in the response time test, a major deficiency was found during the test. When DoseMan is switched off, the data stored on it is lost. Therefore, data from Doseman has to be downloaded to a computer after each working shift. It is also not possible to read the instrument directly using Bluetooth or a cable, but a separate optical dock is required, which increases the purchase price of the device. The battery life of the device is reasonable, about 12 days, but it is clumsy to use because of the daily data reading.

The AlphaE, on the other hand, can be switched off and on without losing the recorded data. In addition, the device has a long battery life of up to six months. This means that the AlphaE can be used for up to months of radon measurements during shifts before the results need to be read. Therefore, the AlphaE was chosen for the field tests testing even though its response time is a bit too long for detecting rapidly changing radon concentrations.

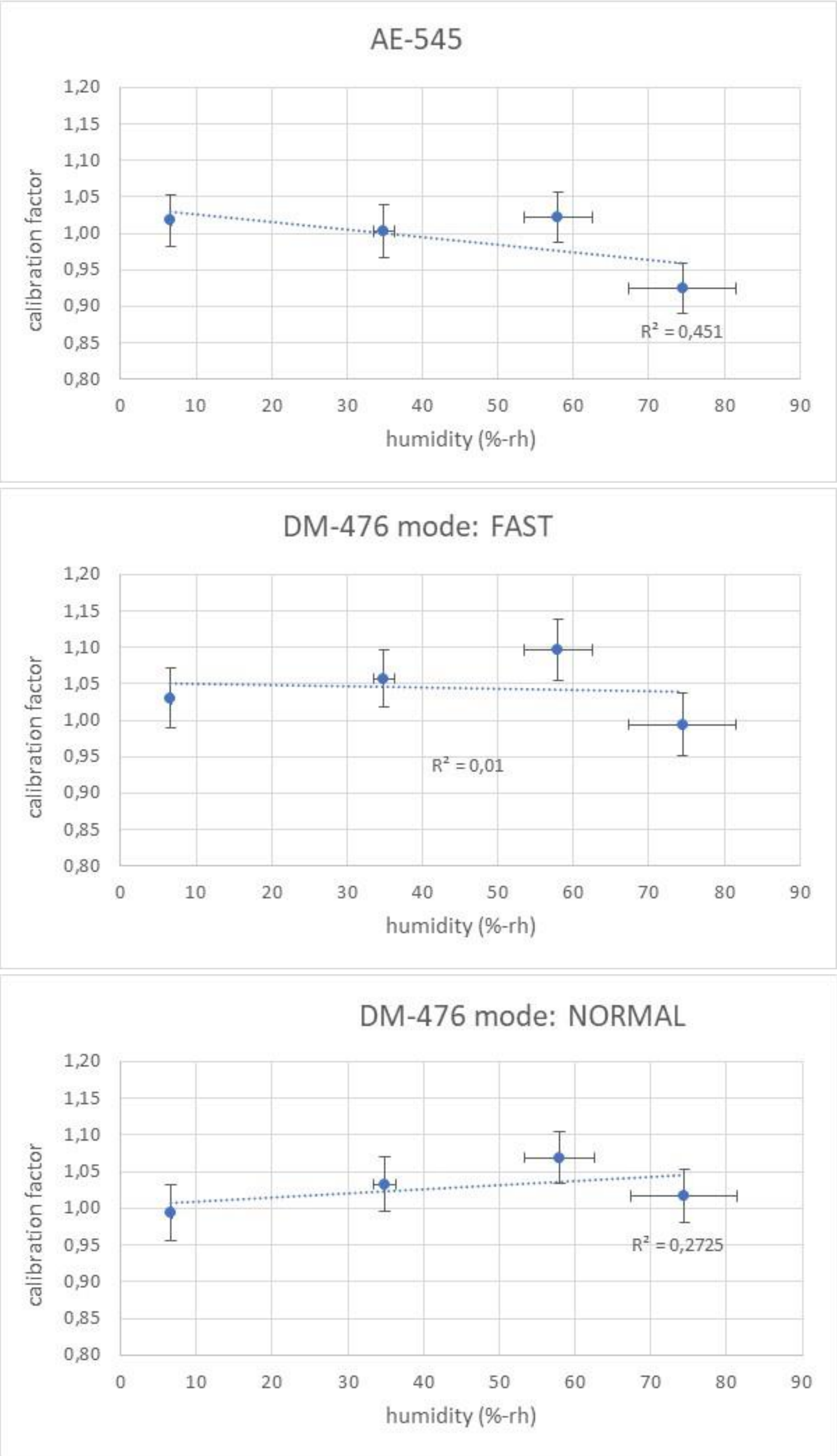

Figure A2. The results of the humidity sensitivity test. AE refers to AlphaE, DM to Doseman.

Field tests

The measurements were carried out at the Pyhäsalmi mine, where the safety manager coordinated the measurements. Over the years, many radon measurements have been taken at the mine, and based on the results and the working hours of the workers, the safety manager filled in the data in the exposure calculator.

The most exposed person was given a portable radon meter AlphaE, which was kept in the mine, underground, when the employee was not present during work. This way, the response time was not so meaningful, as the meter started to measure the real radon concentration as soon as it was switched on.

The working shift lasts from 6:00 to 14:00, the last hour of which is spent in the lift and in the aboveground washing facilities. The exposure time of the worker in the mine is hence between 7 and 7.5 hours per day. The integration of the instrument time was set to half an hour, so a maximum of 14 measurements were recorded during the day.

Personal radon measurements were carried out between 8 May and 7 June 2023. The total number of measured days was 12, with the duration of a daily measurement ranging from one hour to seven hours. The median duration of a daily measurement was 6.5 hours. The daily results are presented in Table A2. The measurement results indicate that there are working days when workers are only in the mine for a short time in the morning, after which they return to the surface.

Table A2. Daily radon measurement results with the portable AlphaE radon instrument.

Day	Measurement duration (h)	Radon-222 (Bq/m^3)	
		Mean	Median
8 May	3	298 ±60	217
9 May	6,5	237 ±36	145
10 May	6,5	243 ±37	214
15 May	7	306 ±40	321
16 May	6,5	276 ± 39	285
17 May	7	190 ± 31	214
23 May	4,5	286 ±48	285
24 May	7	102 ±23	72
25 May	1	145 ±72	145
5 June	7	262 ±37	219
6 June	6,5	154 ±29	143
7 June	3,5	367 ± 61	357
All data	66	236 ± 11	214

The daily minimum mean concentration is 102 Bq/m^3 and the maximum mean concentration is 367 Bq/m^3. The unweighted mean of daily radon concentrations was 239 Bq/m^3 and the associated standard deviation 77 Bq/m^3. The day-to-day variation would possibly be even greater if there were ongoing mining/excavation activities in the mine. Even under such stable mining conditions, radon levels vary by a factor of three. Obviously, a single day's measurement is not sufficient.

The measurements were carried out during the time of year when radon concentrations in the mine are average or slightly above average. It can therefore be concluded that the mean radon concentration to which a worker is exposed during the year is below 300 Bq/m^3. In the extreme case, the worker's entire annual working time (1650 hours) is spent in the mine. Even in this scenario, the radon exposure is around 390 kBqh/m^3 per year, so the worker's radon exposure is very likely to be below the reference value of 500 kBq/m^3 per year.

Let us now look at the exposure calculator completed by the Safety Manager for the period 1 January to 31 May (Table A3, Table A4).

Table A3. Summary of the results of the exposure calculator.

Worker	Number of assessment points	working durat. (h)	Exposure ($kBqh/m^3$)	Mean exp. concentration (Bq/m^3)
1	11	610	156	255
2	11	537	150	280
3	11	577	107	186
4	13	611	175	286
5	3	366	29	78
6	22	625	62	100
7	6	590	20	35

Worker 4 is the most exposed worker. His calculated radon exposure over five months was 175 $kBqh/m^3$. Dividing the radon exposure by the number of hours worked gives 286 Bq/m^3. For the other workers, the estimated mean exposure concentrations are between 35 and 280 Bq/m^3.

These results are based on spot radon measurements and grab sampling over the years and the safety manager's estimates of working hours in different parts of the mine. Worker 4 carried a radon meter during the 12 working days and the average exposure measured with it was somewhat lower, 236 Bq/m^3. According to the safety manager, the worker in question worked more in areas with lower radon levels in May. This may explain why the measured concentration was slightly lower than the estimated concentration.

The mine foreman used another AlphaE meter to map radon levels in different parts of the mine and to test the effect of ventilation on radon levels. According to him, "It was easy to take readings from it on the computer. So not difficult to use at all."

According to the Safety Manager, the use of an exposure calculator is the most convenient way to conduct an exposure assessment at this stage of the mine's life cycle. The mine is being run down and all internal structures are being dismantled. The mine is divided into an old site and a new site.

“Radon concentrations are consistently higher at the old mine site. There is a lot of leakage water that runs through the old extraction areas, which certainly increases the radon levels. On the old mine side, the old ventilation routes are also no longer fully used as they once were during the extraction period. Therefore, increasing ventilation in all locations is not feasible.”

Conclusion

A personal radon meter is likely to provide as reliable an estimate of radon exposure in mines as spot measurements and the use of an exposure calculator. If the exposure calculator is not used in conjunction with spot radon measurements, all sites with radon concentrations above 300 Bq/m^3 can be mitigated to ensure that the annual exposure of workers is below the reference value.

The success of radon remediation may be a specific feature of Finnish mines. In all operating mines, radon exposure is below the reference value and no mine has had to organise dose monitoring or apply for a radiation safety license.

Testing will continue at one other mine and the impact of the length of the measurement period on the results will be investigated.

References

Hopke PK. Use of electrostatic collection of 218Po for measuring Rn, 1989. Health Physics 57(1): 39–42.

Kojo, K., Laine, J-P., Turtiainen, T., Kurttio, P., 2021. Radon in Finnish underground mines 2011-2019. Journal of Radiological Protection; 41: 619–627. https://doi.org/10.1088/1361-6498/ac08f0

Table A4. A screen shot of the exposure calculator used in this study.

Työpaikka	Pyhäsalmi Mine Oy
Työpaikan osoite	Mainarintie 2, 86900 Pyhäkumpu
Työnantajan yhteyshenkilö	Safety Manager

		TYÖNTEKIJÄ 1		**TYÖNTEKIJÄ 2**		**TYÖNTEKIJÄ 3**		**Työntekijä 4**		**Työntekijä 5**		**Työntekijä 6**		**Työntekijä 7**		**Työntekijä 8**	
Työpiste/mittauspisteen nimi	**Radonpitoisuus, mittaustulos (Bq/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**	**Työaika (tuntia/ vuosi)**	**Radonaltistus (Bq h/m3)**
Taso 85	495	80	35 640	75	33 413	90	40 095	60	26 730	35	15 593		-		-		-
Taso 45	495	51	22 721	34	15 147	16	7 128	45	20 048	25	11 138		-		-		-
Taso 210	448	8	3 226		-		-	10	4 032		-		-		-		-
Taso 500	303	76	20 725	58	15 817		-	83	22 634		-		-		-		-
Taso 530	335	70	21 105	45	13 568	88	26 532	75	22 613		-		-		-		-
Taso 600	364	6	1 966	66	21 622	50	16 380	52	17 035		-		-		-		-
Taso 630	414		-		-		-		-		-		-		-		-
Taso 660 murtaja	484		-		-		-		-		-		-		-		-
Taso 970	556	95	47 538	94	47 038		-	98	49 039		-	2	1 001		-		-
Taso 990	400		-		-	25	9 000	25	9 000		-		-		-		-
300 VT	430		-		-		-		-		-	21	8 127		-		-
365 VT	430		-		-		-		-		-	6	2 322		-		-
Taso 400 luokkatila	863		-		-		-		-		-		-		-		-
Taso 400 murtaja	418		-	2	752	2	752	2	752		-	15	5 643		-		-
1095 VT	230		-		-		-		-		-	3	621		-		-
Taso 1125	40		-		-		-		-		-	1	36		-		
Taso 1150	150		-		-		-		-		-	3	405		-		-
Taso 1200	122		-		-		-		-		-	1	110		-		
Taso 1225	87		-		-		-		-		-	65	5 090		-		-
Taso 1250	80		-		-		-		-		-	4	288		-		
Taso 1275	79		-		-		-		-		-	4	284		-		-
Taso 1300	80		-		-		-		-		-	94	6 768		-		-
1370 räjähdevarasto	33		-		-		-		-		-		-	4	119		
1400 murska	52		-		-		-		-		-	1	47		-		
1430 TP	287		-		-		-		-		-	48	12 398		-		-
1430 pumppaamo	60		-		-		-		-		-	2	108		-		
VT (vinotunneli)	294		-		-		-		-		-	2	529	20	5 292		
Pinta/Uusi Kaivostupa	38	26	889	20	684	27	923	26	889		-	36	1 231	34	1 163		-
Pinta/Tepa	7	144	907	80	504	66	416	50	315	306	1 928	12	76	71	447		-
Pinta/Ruokala	6		-		-	16	86		-		-	16	86		-		-
Pinta/ulkona tai autossa	0	16	-	5	-	4	-	23	-		-	4	-	8	-		-
1410 Päätaso	33	38	1 129	58	1 723	193	5 732	62	1 841		-	99	2 940	453	13 454		-
Maanalaiset pumppaamot	85		-		-		-		-		-	186	14 229		-		-
	Yhteensä	610	**155 846**	537	**150 268**	577	**107 044**	611	**174 928**	366	**28 659**	625	**62 339**	590	**20 475**	0	**-**