Lessons Learned from Surveillance: Measuring methods and monitoring strategies

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1. Abstract

According to the international recommendations of radiological protection work activities associated with increased exposure of workers to radon should be included in the system of radiation protection control if, in spite of mitigation, the action level is exceeded. In these cases workers and workplaces should be subject to an appropriate regime of radiation protection control that is oriented towards the requirements for the radiation protection control for artificial sources. The exposure of workers has to be monitored systematically in order to verify that the exposure limits given by the international recommendations or the national regulations are not exceeded. Strategies and measurement methods that can be applied in monitoring of the exposures of workers to radon are discussed.

Because of the direct relation of the time-integrated concentration of the potential alpha-energy of the short-lived radon decay products (potential alpha energy exposure, P_P) to the risk, the measurement of this value should be obvious. Several types of instruments, also portable instruments, are available and suitable for practical applications or can be adapted to the conditions at the workplaces. Portable instruments to measure P_P can be used for individual monitoring and have been applied successfully at closure and remediation of uranium mines and mills. However, purchasing and running costs of devices for individual monitoring are high.

In most cases, however, instruments measuring the time-integrated radon concentration (exposure to radon) are preferred for monitoring. These instruments use passive radon detectors. The main advantages of these instruments are their availability in large quantities to low costs. But it must be considered that uncertainties in dose assessment are caused by the equilibrium factor, which is to be assumed. Investigations have shown that at numerous workplaces the equilibrium factor is in the range from 0.2 to 0.7. Within this range the overall uncertainties of the measurements are comparable to uncertainties that are acceptable in other fields of individual monitoring of exposures, too. Taking into account the costs of monitoring programmes the individual monitoring of the exposure to radon applying passive radon instruments is the method of choice.

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2. Introduction

Radon is ubiquitous in the air outdoors and in buildings as well as in all workplaces. In some geographical locations but also at particular workplaces such as underground mines, caves, spas and water supply stations the radon concentrations can cause elevated exposures, which cannot be disregarded from the radiation protection point of view.

Title VII of the Directive 96/29 EURATOM has set out a framework for controlling exposures to natural radiation sources arising from work activities. The Directive has been transferred into national laws. To ensure the radiation protection at work the national authority shall define work activities within which the exposures caused by radon have to be regarded as occupational exposure. For these work activities the authorities shall require the setting-up of appropriate means for monitoring exposures and as necessary:

- the implementation of corrective measures to reduce exposures, and
- the application of radiation protection measures pursuant to that for artificial radiation sources or parts of them.

The intention of this paper is to discuss the methods of monitoring the occupational exposure to radon. The particular issues of exposures to radon and its decay products, the manifold circumstances at the workplaces of concern, the suitability to satisfy the monitoring objective and not least the costs are addressed. These issues have to be taken into account if an optimised approach to monitor workers occupationally exposed to radon is developed.

3. Basics

3.1 Characteristics of radiation exposures from radon

Radon is a natural noble gas, and all isotopes of it are radioactive. The isotopes radon-222 and radon-220 may cause elevated exposures leading to health hazards and therefore they are of concern from the radiation protection point of view. The noble gas isotope radon-222 is formed by the decay of radium-226. Radium-226 is one of the nuclides formed in the decay series of uranium-238. The isotope radon 220 is formed by the decay of radium-224 of the decay series of Thorium-232. Commonly, the isotope radon-220 is called by the term “Thoron”.

Health hazards of radon and thoron are not due to those isotopes directly but rather due to the short-lived decay products that are inhaled. These short-lived decay products (radioactive isotopes of solid elements) can be attached to aerosols, dust etc. In comparison to the gases, which are exhaled rather than they decay in the respiratory tract, the decay products deposit there. The biological processes linking the inhalation of the radon decay products to the risk of lung cancer are very complex. Therefore special quantities were developed that give a simple relationship between the exposure and the risk.

3.2 Special quantities for assessment of risk due exposures to radon

The special quantities and their definitions given below are in accordance with IEC 61577 [1,2,3].

3.2.1 Activity concentration (C)

Activity per volume. The SI unit is $Bq \cdot m^{-3}$.

3.2.2 Exposure to radon (P_{Rn}), exposure to thoron (P_{Th})

The time-integral over the activity concentration of radon or thoron, for a defined period of time. The quantity is expressed in the SI unit $Bq \cdot h \cdot m^{-3}$.

3.2.3 Potential alpha energy (e_P)

The total alpha energy emitted during the decay of an short-lived radon or thoron decay product along the decay chain up to ^{210}Pb or ^{208}Pb respectively for the decay chains of radon and thoron. If N is the number of isotops the potential alpha energy can be expressed in the SI unit J.

3.2.4 Potential alpha energy concentration (C_P)

The concentration of any mixture of short-lived radon or thoron decay products in air in terms of the alpha energy released during complete decay through 210Pb respectively 208Pb. The quantity is expressed in the SI unit $J \cdot m^{-3}$.

3.2.5 Potential alpha energy exposure (P_P)

The time-integral of the potential alpha energy concentration in air, CP, over a given time period. The quantity is expressed in the SI unit $J \cdot h \cdot m^{-3}$.

Table 1. Special units for exposures to radon and the conversion to the annual effective dose.

	Units of potential alpha energy exposure of short-lived radon decay products			**Effective dose [4]**
	$MeV \cdot h \cdot m^{-3}$	**$J \cdot h \cdot m^{-3}$**	**WLM [1]**	**MSv**
1 $MeV \cdot h \cdot m^{-3}$	1	$1{,}60 \cdot 10^{-13}$	$4{,}52 \cdot 10^{-11}$	$2{,}24 \cdot 10^{-10}$
1 $J \cdot h \cdot m^{-3}$	$6{,}24 \cdot 10^{12}$	1	$2{,}82 \cdot 10^{2}$	$1{,}4 \cdot 10^{3}$ [3]
1 WLM [1]	$2{,}21 \cdot 10^{10}$	$3{,}54 \cdot 10^{-3}$	1	5 [4]
1 $Bq \cdot h \cdot m^{-3}$ [2]	[5]	$2{,}22 \cdot 10^{-9}$	[5]	$3{,}11 \cdot 10^{-6}$

1) 1 WL represents the potential alpha energy concentration of 100 $pCi \cdot l^{-1}$ (3700 $Bq \cdot m^{-3}$) –radon in equilibrium of its short-lived decay products. (1 WL = $1{,}3 \cdot 10^{8}$ $MeV \cdot m^{-3}$; 1 WLM = 1 WL · 170 h)
2) Assuming an equilibrium factor F = 0.4
3) Dose conversion convention according to ICRP 65 und Directive 96/29/EURATOM
4) Effective dose of occupational radiation exposures
5) This transformation is not recommended.

Table 1 shows the transformation of units used in surveillance of radon measurements.

3.3 Equilibrium factor

The short lived decay products of radon and thoron can not only be attached to aerosols or dust but also be deposited at surfaces (e.g. walls) in the volume. Therefore in a real atmosphere the short-lived decay products are not in the radioactive equilibrium to radon or thoron. The equilibrium factor, F, expresses the level of the disturbance of the radioactive equilibrium. To illustrate this issue the equilibrium factor indicates the relation between the activity concentration of radon or thoron, which would be found if radioactive equilibrium exists in the volume of concern, to that, which is really existing in the volume. The equilibrium factor, F, can be expressed by the measured concentration of the potential alpha energy C_P and the measured radon concentration, C_{Rn}, by

$$F = \frac{C_P}{5.56 \cdot 10^{-9} \cdot C_{Rn}} .$$

with C_{Rn} in $Bq{\cdot}m^{-3}$ and C_P in $J{\cdot}m^{-3}$. The same equations can be found for the units exposure to radon, P_{Rn}, and potential alpha energy exposure, PP, of the short-lived radon decay products. The relations of the equilibrium factor for thoron and its decay products can be derived in an similar manner.

3.4 Conversion to the effective dose

Estimates of health risks due to radon exposures result from epidemiological studies. The studies carried out for miners show a direct relation of the health risks to the potential alpha energy exposure. However, in the general concept of radiation protection, in particular for regulatory purposes, the effective dose is the quantity being an adequate indicator of the health effects and dose limits are given in that quantity. In order to compare the exposures from natural radiation with other exposures (e.g. from external sources) and to apply dose limits committed, the quantity potential alpha energy exposure must be converted into to the quantity effective dose.

ICRP has recommended, that a potential alpha energy exposure of $1 J{\cdot}h{\cdot}m^{-3}$ is equivalent to an effective dose of 1.43 mSv. Based on ICRP publications the Annex III of the Directive 96/29 EURATOM laid down a conventional conversion factor effective dose per unit potential alpha energy exposure of

$$1.4 \frac{mSv}{mJ \cdot h \cdot m^{-3}}$$ for radon at work and

$$0.5 \frac{mSv}{mJ \cdot h \cdot m^{-3}}$$ for thoron at work

3.5 Exposure from radon

The radon concentration can be variable in time and it governs the level of decay product concentrations. If the equilibrium factor is known the assessment of the effective dose can be based on the radon concentration integrated over time (exposure to radon).

Following international studies the averaged value of the equilibrium factor is 0.4 [5,6]. Indoor measurements show a range from 0.1 to 0.9 [5]. As shown in Figure 1 this value is also typical for workplaces. However, at a workplace of concern the true equilibrium factor can differ from the value of 0.4.

For determination of an appropriate variation range of the equilibrium factor the knowledge of its local and temporal variability for many workplaces and, in particular, the knowledge of the individual average equilibrium factor of employers at their work should be known. Because of only a few data it is easy to understand that the specification of a reliable figure for the equilibrium factor is impossible. Many measurements in homes, few in mines and recently a few in water-supply stations have been published. All measurements, however, are only local measurements for a short time and not sufficient describing the factor for a period of time. They are also true for place of measurements and the conditions prevailing there. Nevertheless, we have constructed a lognormal distribution for the equilibrium factor (see Figure 1), which fast converge to zero in the vicinity of zero and one. A lognormal distribution obviously reflects the likelihood for the occurrence of the equilibrium factor. Most of all values being represented by the 95% confidence interval of the lognormal distribution are within a range from 0.2 to 0.7. As a first approximation the equilibrium factor of 0.4 can be applied for dose assessments.

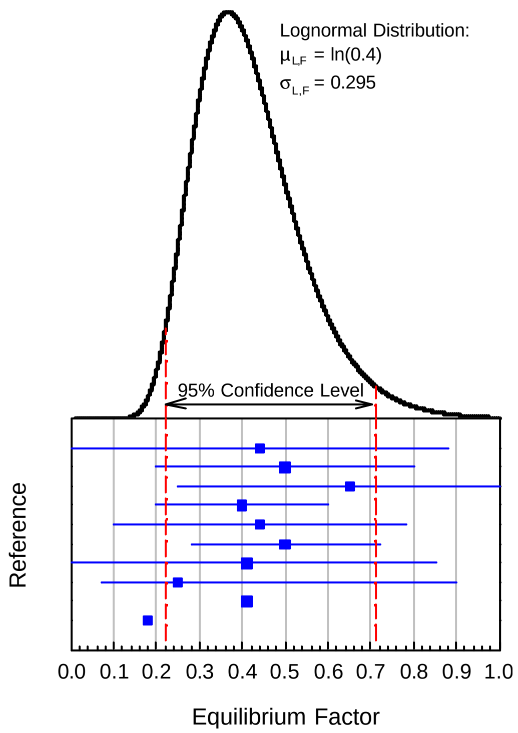

Figure 1. Distribution of the radon equilibrium factor using published values for homes and at workplaces [4].

3.6 Exposure from thoron

In principle the approaches for the measurement and dose assessment described for radon are similar to those for thoron but the application in practice is often limited because of the short half-live of thoron of approximately 1 min in comparison to the relative long half-live of one of its decay products, ^{212}Pb of approximately 10.6 hours. Thoron concentrations, therefore, are highly variable in both space and time and are not closely coupled with the decay product concentrations at a particular location. Since measurements of the activity concentration of thoron can not be applied for dose assessment the measurement of the potential alpha energy concentration (or exposure) of the thoron decay products must be carried out. For these types of measurements techniques are neither well established nor standardised, particularly with regard to routine monitoring of workers. Only a few electronic instruments are on the market for measurements of the potential alpha energy concentration of the thoron decay products. However, they are very expensive and a large expenditure is required for measurements.

Presently efforts are being made to ensure the traceability of the measurements to reference standards. The Physikalisch-technische Bundesanstalt of Germany maintains a primary standard for thoron measurements. Furthermore, a primary standard for the traceability of thoron decay product measurements is under development within the framework of a research project.

Nevertheless, it seems to be that the implementation of monitoring due to the presence of thoron at workplaces is usually not needed because of its generally low concentration connected with the lower health risks in comparison to radon. But attention is to be paid as thoron, even in low concentrations, can affect measurements of radon.

Although all concepts, strategies and most measurement approaches described in the following paragraphs can be applied in a similar way for cases in which exposures from thoron occur, this will not be mentioned explicitly. Instead of that the focus will be on the monitoring of the radon isotope ^{222}Rn (radon).

4. Aims and strategies of monitoring occupational exposures to radon

4.1 General requirements

In Article 40 of the Directive 96/29 EURATOM the European Commission gives a guideline for the national authorities, which work activities may be of concern. In article 41 of the Directive the general approach to protection against exposure from natural radiation sources is specified. As a rule, if exposures to radon and other natural radiation sources exist corrective measures to reduce the exposures have priority and should be implemented as part of the programme of health and safety at work in appropriate manner. If necessary, radiation protection measures pursuant to the requirements for artificial sources should be applied. Radiological surveillance including monitoring of the workers or workplaces is the central component of the radiation protection system for work activities, too.

Monitoring aims at both: verification of compliance with the limits specified for workers and providing information necessary for optimisation of radiation protection and safety. This means that the individual doses, the number of people exposed and the likelihood of incurring exposures should be kept as low as reasonable achievable [7].

General requirements concerning monitoring of workers specified in the Directive of EURATOM comprise:

- Monitoring of workers (individual monitoring) should be made systematically and based on individual measurements
- In cases of significant internal exposures an adequate system for monitoring should be set up
- In cases within which individual measurements are impossible or inadequate the individual monitoring should be based on an estimate arrived at either from individual measurements made on other exposed workers or from results of the surveillance of the workplace monitoring.

The individual monitoring programmes of workers (routine monitoring) should primarily focused on compliance the dose limits and secondarily to provide additional information for corrective measures to reduce exposures. The latter is related to operational radiation protection, which should be done before or parallel to the monitoring of workers. From the monitoring of workers only additional information can be obtained for that.

4.2 Dose limits and action levels

Exposure of individuals shall be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues exceeds relevant dose limits [7]. Since doses to organs (skin, eye, extremities) are not relevant in the context of exposures to radon at work only the limitation of effective dose has to be paid attention.

In [7] and other international recommendations the dose limits are specified as follows:

- an annual effective dose of 20 mSv averaged over five consecutive years and
- an annual effective dose of 50 mSv in a single year.

In most cases at wokplaces where the exposure to radon is dominating the exposure pathways other than inhalation of radon and its decay products, e.g. external exposures by gamma can be disregarded generally from the radiation protection point of view.

In the concepts of radiation protection action levels play an important role and serve for grading of measures to be implemented more restrictive towards higher doses. In [7] the action level for the radon concentration at workplaces is given as a yearly average concentration of 1000 $Bq \cdot m^{-3}$. For occupancy of 2000 hours per year, this result in an annual exposure to radon of 2 $MBq \cdot h \cdot m^{-3}$ or an annual effective dose of about 6 mSv.

4.3 Monitoring approaches

Two approaches – individual monitoring and workplace monitoring – may be used to asses the individual exposures. For individual monitoring each worker is provided with an individual instrument. During the works the instrument is worn on the trunk outside of the workers clothes.

For workplace monitoring one or more instruments are applied to determine the exposure of workers at the same workplaces and same work patterns who are unlikely to receive doses approaching the dose limit. Prerequisite for this strategy is that the conditions of exposure are nearly the same for all workers as well as the instruments being applied. In this way the measurements can be considered as representative for the exposures of workers. To determine individual exposures the occupational times at which the worker is attended at the workplaces must be recorded.

Experience has shown that workplace monitoring is indicated if the workplace is well ventilated, the radon concentration was verified as being approximately constant for longer time periods and the duration of stay at the workplace can be assessed reliably. In cases if workers do their jobs at several workplaces and both the duration of stay and the radon concentration can vary considerably. individual monitoring should be preferred.

4.4 Measuring period

The measuring period is the time between subsequently readings of measuring instruments to ascertain the radiation exposures of workers for that period. It should be determined by consideration the expected changes in the radiation environment. If the exposures are liable to vary considerably the measuring period shall be adjusted that operational actions can be introduced to avert elevated exposures of the person. For specification of the measuring period physical and technical properties of the instrument (e.g. battery power, specified working range of the instrument) and special conditions at the measurement location, which can affect on results (e.g. exposure levels, exposures by dust) must also be taken into account.

While reading the instrument the opportunity is given for controlling the operation and for carrying out measures needed to maintain and calibration. Depending on exposure rates for practical reasons the monitoring period should not shorter than one month but not longer than three months to give possibilities for intervention in elevated doses.

In many years of radon monitoring of workers in Germany it has been shown that measuring periods of two month are appropriate if passive radon monitors are used in underground mines. But in some cases it is essential to provide continuously measuring instruments with direct indication of the exposure value for operational radiation protection control and in special situations. These situations can occur when technical systems have been installed to diminish exposures, e.g. ventilation systems, and their operation and effectiveness are to be monitored.

5. Methods of radon monitoring and quality assurance

5.1 Investigation of the potential alpha-energy exposure by measurements

Already the first instruments applied for workplace monitoring in mines used simple alpha-counting techniques and algorithms for calculation of C_P values. This method of measurement consists of sampling aerosols on a filter followed by measurements of the alpha activity during several periods of time. The algorithm often used was the MARKOV algorithm [8]. The advantages of the instruments applying this are the simple and robust technique and the simple handling. Uncertainties of measurements using the MARKOV algorithm depend on the variation of the short-lived radon decay products in the air. In most cases, however, it is in the range up to 15 % [8]. The general disadvantage of this method is the short time interval of air sampling that results in concentrations that are valid only for the time period of air sampling. Therefore, these measurements can be used for the assessment of the annual exposure of workers only if the measurements are representative for the time period of interest and for the places occupied by the worker. Consequently measurements have to be made as often as possible at all workplaces of concern. Monitoring programmes applying this method can be costly if large working areas with many workers or many rooms have to be monitored.

The potential alpha energy exposure (PP) can be measured by electronic instruments, which continuously sample the aerosols on a filter and measure simultaneously the alpha activity. The exposure can calculated for given time periods. Modern instruments are battery powered, light, have a small size and can be worn by a worker. Although instruments measuring the PP seem to be the instruments of the choice they are only applied in special situations or workplaces. The relative high costs of the instruments are the reason for this.

According to the German recommendations for authorised monitoring programmes the direct measurement of the PP is recommended in situations, if dose estimations give rise to doses of 15 mSv or more,

- information on the equilibrium factor are not available or the equilibrium factor varies currently
- the mean equilibrium factor is lower than 0.2 or higher than 0.7.

From this enumeration it is obvious that in most cases the measurement of PP is not necessarily. Mostly the mean equilibrium factor during working hours is in the range between 0.2 and 0.7, even if the factor is occasionally out of this range. However, at several underground workplaces with high ventilation rates mean equilibrium factors lower than 0.2 can occur. Equilibrium factors above 0.7 are anticipated in large rooms with poor ventilation, e.g. during the cleaning of fresh water containers of water supply stations without any ventilation.

In Germany, the measurement of PP is only stipulated for monitoring workers employed with decommissioning underground uranium mines. The instrument applied measures not only the PP but also the external gamma dose and the exposure due to inhalation of long-lived alpha emitters since these exposure pathways have to be taken into account. Monitoring is carried out by these instruments for ‘reference workers’ because of the costs and expenditure to maintain. The exposure of workers with same or similar work patterns at the same place as the reference workers is equated with this of the reference workers taken the stay at the workplace of each into account.

5.2 Investigations of the radon exposure by measurements of radon

Instruments for measuring exposure to radon are frequently applied for monitoring tasks. Because of their availability in large quantities for low costs passive radon monitors are used for individual monitoring. They are portable and worn by the workers during the work activities. For evaluation of the detector and determination of exposure values radon services must be engaged. Besides passive monitors electronic radon instruments are on the market, also as portable instruments available in recent years. Electronic radon monitors are interesting for users if it is indented both at the same time: to monitor workers and to get information for operational radiation protection purposes.

For the dose assessment from exposures to radon, however, the equilibrium factor at the workplace must be known for time period within which the measurement was carried out. Because of the high technical expenditure needed to determine the equilibrium factor assumptions about it must often be made. For a workplace of concern the equilibrium factor can be estimated if measurements at similar workplaces are available. As shown in paragraph 2.5 most of all values of the equilibrium factors (represented by the 95% confidence interval of the lognormal distribution) lie within a range from 0.2 to 0.7 with an averaged value of 0.4. Within this range the uncertainty of dose assessment caused by the equilibrium factor is assumed as acceptable. Outside this range of the equilibrium factor the dose should calculated based on measurement of P_P to avert unacceptable errors. As mentioned in paragraph 4.1 it is assumed that workplaces at which equilibrium factors lower than 0.2 or higher than 0.7 occur are the exception. Surveys have localised the patterns of such workplaces, which gives the possibility for special requirements on monitoring. For all other workplaces a averaged equilibrium factor of 0.4 is assumed.

The knowledge of the variation range of equilibrium factor poses the question how accurate the dose can be determinate. Accuracy criteria for occupational radiation monitoring were published by ICRP and IAEA [9,10]. These criteria have been adopted into the evaluation of radon measurements [4]. As a result intervals are given, which indicate the highest and lowest factor of the relation of measured to true value for which the deviation is considered acceptable. Under realistic assumptions of the uncertainties of radon measurements and taken into account the variation of the equilibrium factor the accuracy of dose assessment (potential alpha-energy exposure) is given in Figure 2 (solid lines) and can be summarised by:

- In the region near the relevant limit of P_P a factor of 1.8 in either direction is acceptable for the overall uncertainty.

- For lower P_P the determined value overestimate the true value not more than a factor of 2.

- In the region of the recording level, an acceptable uncertainty of ±100% is implied.

From all this it follows that an exposure to radon of approx. 6000 kBq·h·m^{-3}, which corresponds to a PP of 14 mJ·h·m^{-3} for an assumed equilibrium factor of 0.4, the highest and lowest factor of the relation of measured to true exposure to radon, $P_{Rn,measured}$ and $P_{Rn,true}$ respectively, for which the deviation is considered as acceptable is

$$0.80 \leq \frac{P_{Rn,measured}}{P_{Rn,true}} \leq 1.2$$

For lower radon exposures the span of the interval expands. The restriction of the upper overall limit on factor 2 causes a restriction of the upper exposure limit. For radon exposures of less than 630 kBq·h·m^{-3} the allowable uncertainty of the relative exposure does not exceed a value of 1.5.

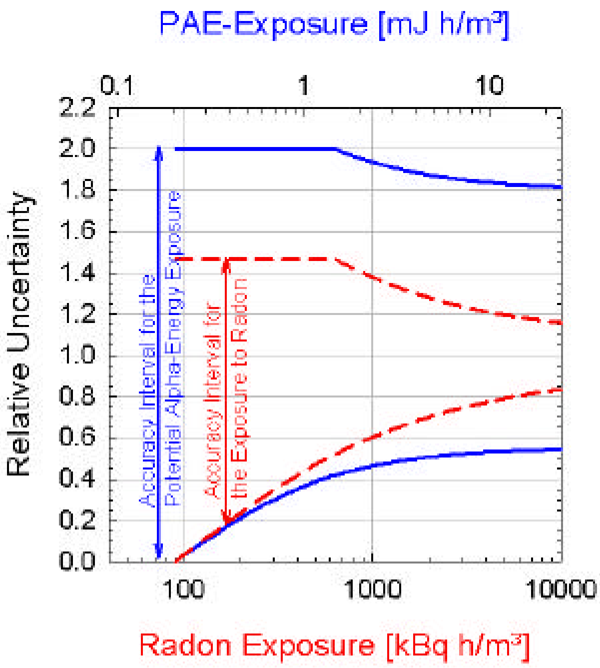

Figure 2. Derived accuracy interval for measurements of potential alpha-energy exposure (solid lines) and the restricted interval for radon exposure measurements (dashed lines).

5.3 *Quality assurance*

For compliance with dose limits it is essential to carry out correct and traceable measurements. Measuring instruments shall manufacture to a high level of quality in respect of the measurement technology and security of the measurement data. Criteria for the instruments offered on the marked have been specified in order to give manufacturers a guide for the development and the design and customer confidence in the performance of these instruments. Technical criteria are set out in internationally agreed normative documents. In the field of radon and radon decay product measurements normative documents with specific requirements for such instruments have been issued by the International Electrotechnical Commission [1,2,3]. The manufacturer has the responsibility for compliance with these requirements and should engage testing laboratories in order to undertake special testing. National authorities should take appropriate action to prevent non-complying measuring instruments from being applied in radiation protection monitoring.

In Germany, radon and radon decay product measuring instruments applied for the purpose of monitoring at workplaces must be approved by the competent authorities. A prerequisite is the compliance of these instruments with specific technical requirements. In the light of this regulation BfS intends to provide a scheme for type testing of electronic radon and radon decay product measuring instruments according to IEC 61577-2 and IEC 61577-3.

Beside type testing calibrations of electronic measuring instruments have been imposed every two years to prove the traceability of the measured quantity back to the national standard.

- Since radon services are involved for measurements using passive radon monitors the concept for approval differs slightly. German regulations demand that passive radon instruments are appropriate for purposes of occupational radiation monitoring if the devices are issued by approved radon services, and

- the service submits devices of the same type being issued for radon monitoring to regular intercomparisons conducted by BfS.

A radon service is approved if its organisational and technical competence is authorised, e.g. by accreditation. These regulations have been introduced for the quality assurance in the area of occupational radiation exposures.

Since 2003, BfS has conducted annual interlaboratory comparisons for passive radon instruments [11]. The interlaboratory comparisons comprise the organisation, exposure, and evaluation of measurements of radon activity concentration or exposure to radon. Radon services being interested can get further information from the European Information System on Proficiency Testing Schemes (eptis) available in the Internet.

6. Dose assessment for radon measurements

Based on the dose conversion convention discussed in paragraph 2.4 the quantity effective dose, E, in the unit mSv is calculated from the exposure to radon, P_{Rn}, in the unit $MBq \cdot h \cdot m^{-3}$ using an averaged equilibrium factor, F, of 0.4 by

$$E = 3.1 \cdot P_{Rn} \quad \text{for } 0.2 \leq F \leq 0.7$$

On incorrect or not happened measurements the competent authority should set up a surrogate dose. This can be necessary, if measuring instruments were not used in accordance to its instructions for application or the indication of measurement could not be read out. A surrogate dose can also be set up if the methods or the approaches of the measurement have been not suitable for assessment of individual exposures. In such cases the competent authority lays down the surrogate dose for a person in the following order:

- using exposures of persons doing the same work or working at the same or similar workplaces,
- effective doses having been determined during recent monitoring periods of that person at the same workplace, or
- using other values being available for estimating the dose.

7. Implementation of radon monitoring

As a summary of the aforementioned discussions Figure 3 gives a course for implementing radon monitoring at workplaces applied in Germany. According to the guideline 96/29/EURATOM national authorities shall ensure the identification of work activities, which lead to a significant increase in the exposure of workers. Employers that let workers carry out such work activities have to estimate the effective dose the worker received per year. The estimation shall include all work activities in relation to the time contributed of each. If the estimation of exposures caused by radon results in exceeding of an action level the employer has to introduce corrective measures and to implement the radon monitoring. The further approach to select an appropriate monitoring strategy and appropriate measuring instruments is shown in Figure 3.

- From practical point of view it has been shown that in most of all monitoring programmes passive radon measuring instruments are being applied. The reasons for this are
- passive instruments are cost-effective, even though a radon service must be engaged,
- instruments are robust and can be applied in different exposure conditions,
- individual measurements can be carried out,
- quality assurance and maintenance of the instruments are undertaken by radon service,
- the dose assessments are undertaken by radon service and in most cases the service gives support concerning administration matters, and
- the employer has low expenditure in managing the monitoring.

8. References

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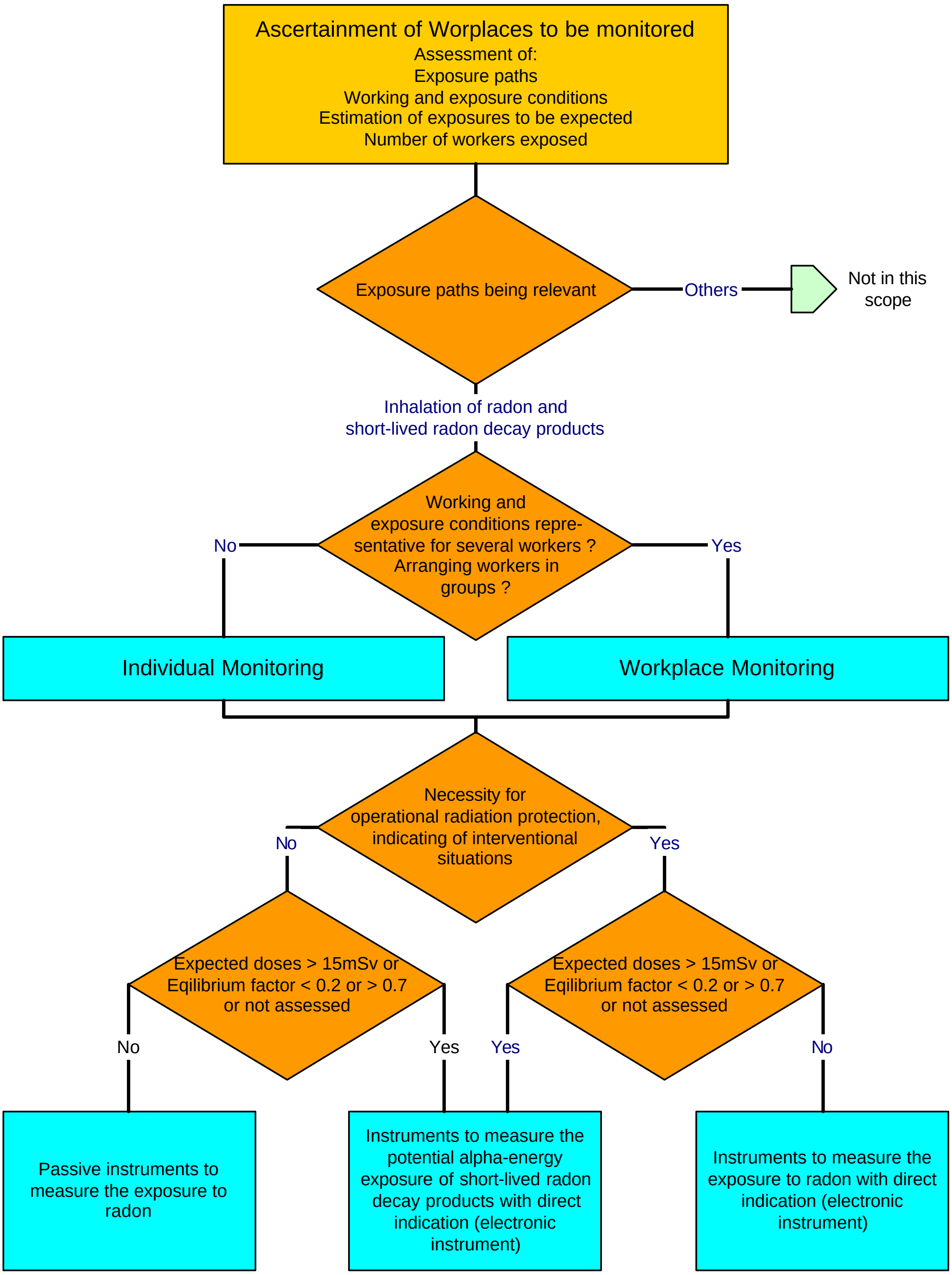

An approved radon service must be engaged to issue instruments and to assess exposures.

Instruments are suitable for the measurements if they have
- an approval for applying in workplace monitoring and
- a calibration which is valid.

Measures must be met to record the times at which the worker is attended at the workplace of concern.

Figure 3. Implementing and optimisation radon monitoring at workplaces.