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Radon dose coefficients for occupational exposures

Recommendation by the
German Commission on Radiological Protection

Adopted at the 341st meeting of the German Commission on Radiological Protection on 2/3 February 2026

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Empfehlung der Strahlenschutzkommission

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Preface

For occupational exposure new radon dose coefficients were published in ICRP Publication 137 in 2017 (ICRP 2017); these are based in particular on biokinetic and dosimetric models. In accordance with the recommendation 'Radon Dose Coefficients' by the German Commission on Radiological Protection (SSK) from December 2017 (SSK 2017), the new dose coefficients from ICRP Publication 137 have not yet been implemented in German radiation protection legislation for workplaces because there were concerns regarding the derivation of the values recommended by the ICRP and the regulatory implementation of these. Following the recommendation by the 'Group of Experts referred to in Article 31 of the Euratom Treaty' and the European Commission to adopt the dose coefficients, the German legislature is required to address this issue again.

Against this background, on 6 December 2023, the Federal Environment Ministry commissioned the SSK to prepare a statement on the applicability of the new radon dose coefficients in accordance with ICRP Publication 137 and to assess the implications for occupational radon protection, taking key aspects into account. The working group set up for this purpose consisted of the following members:

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We would like to thank the Federal Office for Radiation Protection (BfS) for providing us with comprehensive technical information and expert support.

Bonn, February 2026

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Chair of the working group on 'Radon dose coefficients for occupational exposure'	Chair of the German Commission on Radiological Protection

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1 Introduction

In general, the concept of radiation protection provides for the effects of ionising radiation resulting from different types of internal or external radiation exposure to be made comparable by specifying the dose, in particular the effective dose, caused by such exposure. If there are data on the distribution of specific radionuclides within the body for internal exposure, these must be converted into an (effective) dose using dose coefficients (ICRP 2010).

With regard to exposure to radon, the International Commission on Radiological Protection (ICRP) has, in various publications, addressed the conversion of radon exposure parameters (e.g. from a radon activity concentration (in units of $Bq\,m^{-3}$) or a cumulative radon activity concentration (in units of $Bq\,h\,m^{-3}$) into an effective dose (in units of mSv) and derives radon dose coefficients (RDC) from this. German radiation protection legislation (StrlSchV 2018) incorporates an RDC based on ICRP Publication 65 (ICRP 1993). Since then, the ICRP has published a number of further documents on the subject of RDC; these include ICRP Publication 115 from 2010 (ICRP 2010), ICRP Publication 126 from 2014 (ICRP 2014), and ICRP Publication 137 from 2017 (ICRP 2017). In particular, the dose coefficients from ICRP Publication 137 form part of a general method for calculating doses from occupational internal exposure to incorporated radionuclides. This has been presented in a series of five publications covering virtually all relevant radionuclides (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022). The calculations of these dose coefficients take into account numerous incurporation parameters, various biokinetic models, and many other assumptions regarding the relevant metabolic processes.

Compared with ICRP Publication 65, which has so far formed the basis of German law, ICRP Publication 137 results in an approximate doubling of the radon-222 dose coefficient. Internationally, there are different approaches to calculating the effective dose caused by radon[1]. While a number of countries have adopted the new ICRP values, in Germany, the RDC to be applied for workplace exposure assessment as set out in Annex 18, Part B, No. 3 of the Radiation Protection Ordinance (StrlSchV 2018) has remained unchanged. Given the general trend in radiation protection towards adhering to ICRP recommendations as a matter of principle, German legislators and regulatory authorities see a need for action. At present, the pressure to act is further increased by European Commission Recommendation 2024/440 (EC 2024) in which Member States are advised to use the dose coefficients from the Occupational Intakes of Radionuclides (OIR) series (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022) for estimating the effective dose and the equivalent dose from internal exposure within the meaning of Directive 2013/59/Euratom (Euratom 2014). However, adopting the ICRP values for radon would not only raise questions regarding practical implementation but also touch upon fundamental considerations and conceptual difficulties. In its 2017 recommendation (SSK 2017), the SSK had already highlighted several of these concerns, recommending that the limit value set out in the Radiation Protection Ordinance (StrlSchV) be retained. Against this background, the Federal Environment Ministry awarded the SSK the advisory mandate dated 6 December 2023; this reads as follows:

"For occupational exposure, new radon dose coefficients (RDC) were published for the first time in ICRP Publication 137 in 2018 and are based on biokinetic and dosimetric models. Based on the'radon dose coefficients' recommendation by the SSK of December 2017, the RDCs from ICRP Publication 137 for workplaces have not yet been incorporated into German radiation protection legislation. A call from the 'Group of Experts referred to in Article 31 of

[1] Unless otherwise stated, the term 'radon' is used throughout the text to refer to the radionuclide radon-222.

the Euratom Treaty' to adopt the dose coefficients set out in ICRP Publication 137 coupled with the fact that implementation has now progressed considerably at the international level is increasing the pressure on Germany to formally implement the RDC for workplaces. From a technical point of view, the application of the dose coefficients for workplaces proposed in ICRP Publication 137 raises considerable difficulties and, in particular, the following questions:

- *How should the methodologically different approach to dose conversion for radon, which takes into account differentiated workplace categories and new classes of workers with reduced breathing rates, be assessed in comparison with the established approach in radiation protection and general occupational safety, which uses a reference worker for other radionuclides? How could the combined assessment of inhalation doses from radon and other radionuclides at a workplace be effectively carried out and justified despite differences in breathing rates?*
- *In the biokinetic-dosimetric approach, assumptions are made regarding the particle distribution of radon decay products in the workplace. The calculations show that radon decay products in the size range of a few nanometres make a major contribution to the effective dose, thereby resulting in different dose coefficients for indoor workplaces and show caves compared with underground mines. From the perspective of the SSK, is the scientific evidence regarding the dosimetric effects of radon decay products of different particle sizes sufficiently robust to justify the use of different dose conversion factors at different workplaces?*
- *What conclusions can be drawn from new scientific findings, in particular the 'Pooled Uranium Miners Analysis' (PUMA) study, regarding the lifetime excess absolute risk (LEAR) assumed in ICRP Publication 137?*
- *One approach adopted in European countries is to apply the dose coefficient of 3 mSv/mJ h m^{-3}, which is recommended in ICRP Publication 137 and derived from calculations for people in predominantly sedentary occupations, to other – or even all – workplaces. Can a sufficiently conservative level of protection for all affected persons be achieved in Germany using a similar approach, taking into account all uncertainties in dose assessment for radon and the graded approach established in Germany?*
- *The aim of the graded approach set out in radiation protection legislation is to ensure adequate radon protection for workers, including compliance with the annual exposure limits for occupational exposure. From the perspective of the SSK, how can adequate radiation protection at workplaces be ensured in situations where a radon activity concentration of 300 Bq m^{-3} is not exceeded but the effective dose is not negligible from an occupational radiation protection perspective (e.g. because an effective dose of 6 mSv per year is exceeded)? The situation of persons under the age of 18 (trainees) and the limit of 1 mSv applicable to them (with a maximum of 6 mSv per calendar year subject to approval by the competent authority) should also be taken into account here.*

I request the SSK to issue a statement on the applicability of the dose coefficients proposed in ICRP Publication 137 for radon protection in the workplace and to assess the implications for protection against occupational exposure, taking into account the issues outlined above."

These questions are addressed in Chapter 3 of this recommendation and are substantiated scientifically in Chapter 4.

However, from the perspective of the SSK, unresolved issues remain in addressing the questions set out in the advisory mandate, and the answers provided are satisfactory only in a limited sense and not in a fundamental way.

The SSK therefore felt compelled to identify the fundamental and conceptual problems arising in connection with radon dose conversion and to discuss the associated principles of radiation protection. Given the complexity of the issue and the wide range of potential consequences, it was not possible to reach a consensus on all points during the controversialdiscussions. The recommendations set out here are therefore based on the views of the majority of the members. All those involved agreed that differing assessments are possible and can be scientifically justified. The dispute was of a more conceptual nature; in other words, there were differing views on whether and to what extent German radiation protection standards could and should deviate from international recommendations. The following section therefore outlines various options, and it is hoped that this approach will prove useful for further discussion, including at the international level.

According to the SSK, the scientific evidence for the introduction of new radon dose coefficients cannot be regarded as conclusive. In the context of radon exposure, an epidemiological approach could offer a viable alternative to radiation protection. For radiation protection in this context, assessment and documentation of radon activity concentrations are required. This can be accomplished with a high degree of certainty using measurement techniques. However, the documentation and use of activity concentration as a protective parameter does not correspond to the international approach proposed by the ICRP. In order to remain in line with the international consensus on radiation protection and to ensure international comparability, the determination of a risk estimate based on the epidemiological approach and analogue to dose could be introduced.

This risk estimator would therefore be equivalent to an effective dose for studies and comparative purposes as well as in cases of mixed exposures. Possible risk-modifying factors, e.g. physical activity (exercise) during radon exposure, would not be taken into account because of a lack of evidence.

Based on these considerations, the SSK goes beyond the scope of the advisory mandate and sets out further recommendations, outlining ways in which radon protection can be appropriately implemented as a logical extension of the procedures already established in existing German radiation protection legislation. These recommendations are set out in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** of this document.

The cut-off date for the data and literature considered in this paper is 31 December 2024.

2 Statement and recommendations

The aim of radiation protection is to limit the risk associated with radiation; this is generally expressed in terms of the effective dose. Here, an organ dose is linked to a specific lifetime excess absolute risk of cancer via the detriment. In the case of internal exposure (e.g. to radon and its decay products[2]), a radon dose coefficient is currently used to link a given cumulative radon activity concentration to the effective dose and thus indirectly to the risk.

For the estimation of the effective dose and the equivalent dose from internal exposure, in accordance with Euratom Recommendation 2024/440 (EC 2024), the European Commission supports the use of the ICRP publications on occupational intakes of radionuclides from the Occupational Intakes of Radionuclides (OIR) series (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022) and all dose coefficients contained therein when transposing into national law for the purpose of estimating the effective dose and the equivalent dose from internal exposure within the meaning of Directive 2013/59/Euratom (Euratom 2014). With regard to radon exposure, this refers in particular to ICRP Publication 137 (ICRP 2017). Using dosimetric and biokinetic models, along with reference assumptions regarding aerosol characteristics (e.g. $F = 0.2$), this calculation yields an RDC of 3.3 mSv/(mJ h m^{-3}) for reference workers in mines.

This RDC is supported by an epidemiological approach previously adopted by the ICRP; using a risk coefficient of $F \cdot 8 \cdot 10^{-4}$/(MBq h m^{-3}) and taking into account the detriment to an adult population as described in ICRP Publication 103 (ICRP 2007), it also estimates an RDC of 3.3 mSv/(mJ h m^{-3}). Using defined reference assumptions, various RDC values are estimated for reference workers in indoor environments and in show caves (i.e. 5.7 mSv/(mJ h m^{-3}) and 6.7 mSv/(mJ h m^{-3})). For these reference workers, a breathing rate of 1.2 m^3 h^{-1} is defined for both indoor environments and show caves; this corresponds to an exercise pattern comprising 2.5 h of sedentary occupations and 5.5 h of light exercise.

The baseline breathing rate is comparable to the breathing rates measured in miners, and it is thought to overestimate the breathing rates of office workers. Using a more realistic breathing rate based on measured values, an RDC of 4 mSv/(mJ h m^{-3}) was estimated for predominantly sedentary occupations.

Based on the estimated RDCs mentioned above, ICRP Publication 137 recommends using only two RDC values for the sake of simplicity:

- For mines and most indoor work: 3 mSv/(mJ h m^{-3}).
- For indoor physical work equivalent to that of reference workers and for work in show caves: 6 mSv/(mJ h m^{-3}).

Compared with the current RDC of 1.4 mSv/(mJ h m^{-3}) contained in the StrlSchV (2018), this represents roughly a doubling or a quadrupling. The risk predicted for a given exposure would therefore be two- to four-fold higher than previously assumed and as set out in radiation protection legislation.

Adopting the recommendation set out in ICRP Publication 137 would raise the following questions:

> **Do epidemiological data support the assumption that the risk is higher than previously thought?** The risk assumed in ICRP Publication 65 (ICRP 1993) is lower than that suggested by the current, expanded PUMA study (Kreuzer et al.

[2] Translator's note: The terms ‘radon decay products’ and ‘radon progeny’ are both used in the literature and in this text.

2024) (lifetime excess absolute risk of lung cancer mortality per cumulative radon activity concentration, LEAR/PA is $F \cdot 8.5 \cdot 10^{-4}/(\mathrm{MBq\,h\,m^{-3}})$) with the results suggesting that the risk is even higher, particularly at lower exposure levels.

– **Are the dosimetric and biokinetic models sufficiently robust?** These models incorporate a wide range of assumptions and parameters, each with associated uncertainties. Key factors influencing the lung dose resulting from exposure include particle size distribution, the unattached fraction of decay products, the equilibrium factor, and the breathing rate. The situation of miners can be assessed for plausibility using the epidemiological approach; however, for other workplace situations, there are insufficient epidemiological data. The reference assumptions only partially take account of the varying exposure conditions. Further customisation based on exposure conditions is neither practical nor feasible because of the considerable uncertainties involved. It is reasonable to assume that a lower breathing rate than that of the reference worker applies to predominantly sedentary occupations, particularly because mean breathing rates can be verified relatively easily.

– **Does it make sense to introduce different workplace categories here for the first time?** Given defined reference assumptions regarding aerosol characteristics, it is reasonable to apply the same RDC to both miners and office workers engaged in sedentary occupations. The latter probably account for most workers in basements and ground floors within radon precautionary areas. Problems could theoretically arise if they were also exposed to other radionuclides for which the reference worker assumption applies in the risk assessment. However, it is unlikely that such multiple exposure would realistically occur on a large scale among employees with sedentary occupations in radon precautionary areas.

  With regards to the introduction of a second workplace category with RDCs twice as high, this would entail a considerable increase in administrative burden as well as conceptual problems with the graded approach (see below). This therefore raises the question of whether its introduction is justified. It can be assumed that those affected are already listed in Annex 8 of the Radiation Protection Act (StrlSchG 2017) and are subject to dosimetric monitoring. The figure is likely to be several hundred people in Germany. This would include workers performing strenuous physical work indoors with activity concentrations above 300 $\mathrm{Bq\,m^{-3}}$ even after the introduction of reduction measures. It is expected that the number of people affected will remain manageable in this case as well.

  In addition to the high administrative burden involved for a relatively small number of people affected and the lack of reliable data on actual differences in risk, another argument against introducing such a second category is that, in radiation protection, individual differences such as sex are not taken into account in many other areas either. In the case of radon, smoking habits are not taken into account despite the fact that they result in a considerable change in the associated risk. It should also be borne in mind that compatibility with the regulations governing domestic exposure should be maintained.

Would an RDC of 3 $\mathrm{mSv/(mJ\,h\,m^{-3})}$ be sufficiently conservative? This RDC would be about twice as high as the one currently in use. For the 391 individuals who, according to the radiation protection register (BfS 2025b) were dosimetrically monitored in 2023 (e.g. in mines, show caves, and waterworks), an effective dose above 6 mSv would be determined for 77 individuals instead of the previous 23, and an effective dose above the limit value of 20 mSv would be determined for five

individuals instead of the previous 0 (In the case of show mines and show caves, it should be borne in mind that natural ventilation caused by seasonal temperature variations can create conditions similar to those of forced ventilation; these, in turn, could affect the working environment for those employed there.

Fehler! Ungültiger Eigenverweis auf Textmarke. provides an overview of the number of employees who in 2023 were classified into the categories mentioned above based on entries in the Radiation Protection Register (BfS 2025b).

– Table 4.10 and Table 4.11 in Section 4.2.4.3). When estimating the effective dose, 2,000 working hours per year are usually assumed – a decidedly conservative figure.

– **Are the new RDC compatible with the graded approach and a reference level of 300 Bq m^{-3}?** With a recommended RDC of $F \cdot 15.6$ mSv/(MBq h m^{-3}) (correspondding to 3 mSv/(mJ h m^{-3})) and assuming 2,000 working hours per year at $F = 0.4$, 300 Bq m^{-3} results in an effective dose of 3.8 mSv; this means that 64 % of the dose criterion of 6 mSv for occupational exposure would be reached (based on a conservative assumption regarding working hours). This difference between the reference level and the dose criterion is acceptable. However, for certain workplaces, a recommended RDC of $F \cdot 31.3$ mSv/(MBq h m^{-3}) (corresponding to 6 mSv/(mJ h m^{-3})) and an assumed 2,000 working hours per year at $F = 0.4$ would mean that 300 Bq m^{-3} corresponds to an effective dose of 7.5 mSv. This means that the graded approach would make sense only if this second workplace category were abandoned or if the reference level were reduced.

In principle, the link between the cumulative radon activity concentration and risk could be established without using the RDC. Based on the detriment given in ICRP Publication 103 (ICRP 2007), the lifetime excess absolute risk (LEAR) associated with the dose criterion of 6 mSv effective dose can be estimated at $2.5 \cdot 10^{-4}$. This involves comparing the damage-weighted risk (detriment) with the risk of lung cancer mortality. The same limitations apply as with the epidemiological approach of the ICRP; for example, the detriment has not been determined for alpha radiation. If the risk coefficient of $F \cdot 8 \cdot 10^{-4}$/(MBq h m^{-3}) assumed in ICRP Publication 115 (ICRP 2010) is also used, the lifetime excess absolute risk at 300 Bq m^{-3} for miners (where $F = 0.2$) would be 10^{-4} (i.e. 40 % of the risk associated with the dose criterion of 6 mSv). For indoor workers ($F = 0.4$), the risk would be $2 \cdot 10^{-4}$, which is 80 % of the dose criterion of 6 mSv. This limit would also apply to the many people working in offices in areas where radon is a concern.

According to this model, the dose criterion (6 mSv) can be expressed as

$$C_{Rn} = \frac{0.3}{F \cdot t_a} \text{ MBq m}^{-3} \text{ h a}^{-1} \quad (1)$$

and the limit value (20 mSv) as

$$C_{Rn} = \frac{1}{F \cdot t_a} \text{ MBq m}^{-3} \text{ h a}^{-1} \quad (2)$$

Given the free parameters F (equilibrium factor) and t_a (annual exposure duration), this approach would, in principle, allow for the individualisation of the 6 mSv dose criterion and the limit value with regard to the equilibrium factor and working hours but not with regard to breathing rate or physical activity (exercise).

It can be assumed that, for most indoor workplaces, simple reduction measures would lead to levels below the reference level of 300 Bq m^{-3} so that there is likely no need for further calculations and corresponding additional measures.

Another alternative approach is to change the radiation weighting factor for radon – or even for all sources of alpha radiation – from the current $w_R = 20$ to $w_R = 10$ based on a study by Beck (2024) (cf. Section 4.3.4). This approach represents a variation on the epidemiological approach in that it establishes a relationship between cumulative radon activity concentration and effective dose. Although it does not differ fundamentally from the approach of the ICRP, it results in a modification of the radiation weighting factor w_R for radon rather than a direct modification of the RDC. While this approach would alleviate some of the aforementioned problems regarding the RDC, it would result in the introduction of a radiation weighting factor

in German radiation protection law that deviates from the internationally standardised practice. The SSK does not consider the far-reaching consequences of this to be justified.

A comparison of the respective advantages and disadvantages of the various approaches leads to the following specific recommendations, which are explained in greater scientific detail in Chapter 4:

1) The SSK recommends that, when specifying limit and reference values in the context of radon protection, any reference to dose quantities – in particular to the effective dose – should be omitted entirely. Instead, only exposure parameters (i.e. namely the radon activity concentration or the cumulative radon activity concentration) should be used as reference values. This represents the consistent continuation of the approach already implemented in existing German radiation protection legislation in which this reference is already largely applied with only a few exceptions (e.g. reference level 300 Bq m^{-3}). The radiation protection strategy for radon exposure is thus separated from the usual focus on dose. Nevertheless, it is based on the same principles and standards as those applied to other sources of exposure.

2) With regard to the dose criterion, the SSK recommends changing the assessment basis for the effective dose for workers, which is currently still laid down in radiation protection legislation under Section 130 (2) StrlSchG (2017), to an assessment basis for the cumulative radon activity concentration. It is recommended to replace the value of 6 mSv a^{-1} with $0.3/(F \cdot t_a)$ MBq h a^{-1} m^{-3}. F is the equilibrium factor, and t_a is the annual exposure duration. The risk associated with this value corresponds to the risk arising from other exposure conditions with an effective dose of 6 mSv a^{-1}.

3) The SSK recommends that the limit value applicable under Section 78 (1) StrlSchG (2017) for occupationally exposed persons should also be based on the cumulative radon activity concentration. It is recommended to replace the value of 20 mSv a^{-1} with $1/(F \cdot t_a)$ MBq h a^{-1} m^{-3}. F is the equilibrium factor, and t_a is the annual exposure duration.

4) The SSK recommends using the following sum formula for workplace situations in which employees may be exposed to both radon and other sources of exposure:

$$\frac{E_a}{20\ \text{mSv a}^{-1}} + \frac{C_{Rn}}{\frac{1}{F \cdot t_a}\text{MBq m}^{-3}\ \text{h a}^{-1}} \leq 1 \qquad (3)$$

   Here, C_{Rn} is the (mean) radon activity concentration, and t_a is the annual time spent at the workplace. F is the equilibrium factor, and E_a is the effective dose for the calendar year from other sources of exposure. This ensures that the resulting total risk is not greater than the risk arising from 20 mSv a^{-1} from other exposure sources alone.

5) The SSK recommends using $F = 0.4$ as the standard value for the equilibrium factor introduced under No. 2) and 3). If there are technical reasons why F deviates considerably from 0.4, a correspondingly modified cumulative radon activity concentration must be calculated. This results in cumulative radon activity concentrations of $0.75/t_a$ MBq h a^{-1} m^{-3} instead of 6 mSv a^{-1} and of $2.5/t_a$ MBq h a^{-1} m^{-3} instead of 20 mSv a^{-1}.

6) The SSK recommends that the departure from the procedure proposed in ICRP Publication 137 (ICRP 2017) be limited in time. In the meantime, the SSK is encouraging the German experts within the ICRP to explain the technical background outlined here with a view to initiating a review process within the ICRP. From the perspective of the SSK, it is important that radiation protection remains harmonised at the international level as far as possible. The SSK believes that one way to achieve this is through closer coordination of the national delegations within the ICRP so that German positions can be incorporated into the work of the ICRP in a coordinated manner.

3 Answers to the questions set out in the advisory mandate

3.1 Workplace categories and the effect of breathing rate

"How should the methodologically different approach to dose conversion for radon, which takes into account differentiated workplace categories and new classes of workers with reduced breathing rates, be assessed in comparison with the established approach in radiation protection and general occupational safety, which uses a reference worker for other radionuclides? How could the combined assessment of inhalation doses from radon and other radionuclides at a workplace be effectively carried out and justified despite differences in breathing rates?"

The methodology for deriving inhalation dose coefficients is based on the ICRP human respiratory tract model (HRTM), a morphological model of the human respiratory tract (ICRP 1994). Numerical reference values for the breathing rate and other parameters are input into the model. The dose coefficients are then calculated based on these. This model is exceptionally detailed and highly differentiated. However, from the perspective of the SSK, this situation is associated with a number of problematic consequences:

- In the perspective of the SSK, the high degree of differentiation may give the impression of a correspondingly high degree of accuracy because a wide range of parameters is explicitly taken into account. However, this formal distinction does not allow us to draw any conclusions about the actual reliability of the results because the individual model parameters themselves are subject to uncertainties, some of which are considerable. The SSK already drew attention to this issue in its 2017 recommendation (SSK 2017), and its assessment remains essentially unchanged.
- Even if the parameters and their interrelationships could be determined with great precision, this might, under certain circumstances, allow for a more accurate calculation of the (lung) dose. However, no epidemiological studies are available that reflect the level of detail required for the HRTM. Given the measurement techniques currently available, such studies are also unlikely to be exspected in the near future. While the radon activity concentration in ambient air can be accurately measured, other exposure and model parameters relevant to the HRTM, in particular the concentration of short-lived decay products, the equilibrium factor and the air exchange rate, are considerably more difficult to determine and highly scenario-dependent. Furthermore, the deposition of radon decay products in the human respiratory tract cannot be measured directly; instead, it is modelled in the HRTM using model-based assumptions regarding aerosol sizes, breathing patterns, and physico-biological processes, each of which is subject to considerable uncertainty. It is important to bear in mind that the aim of radiation protection is to limit the risk and not the dose. A more precise determination of the dose does not necessarily mean that the associated risk can be determined with the same degree of precision.
- Not least for practical reasons, not every scientific finding regarding differences among specific subgroups of the population is reflected in full detail in radiation protection. Instead, a conscious effort is made to standardise the system in order to ensure a manageable and consistent protection framework. A particularly striking example of this is that the organ weighting factor for breast cancer was set at the same level for men and women. Other differences between women and men, older and younger people, smokers and non-smokers, and many others are likewise deliberately not represented individually. This reflects the chosen strategy of radiation protection, which is based on

an artificial reference population and accounts for individual variation through appropriatly conservative assumptions.

- The adjustment of the breathing rate introduced for radon leads to methodological inconsistencies when radon exposure is assessed together with exposures to other radionuclides, for which reference assumtions continue to be used. Consistent alternatives are either scientifically complex or impractical and could lead to systematic overestimation of the radon dose, whereas in practice (e.g. office-based work), a relevant combined exposure is unlikely.

For the reasons outlined above, the SSK takes a critical view of the methodological changes proposed in ICRP Publication 137 (ICRP 2017) regarding dose conversion for radon, particularly with regard to differentiated workplace categories.

3.2 Partical size, partical distribution

"In the biokinetic-dosimetric approach, assumptions are made regarding the particle distribution of radon decay products in the workplace. The calculations show that radon decay products in the size range of a few nanometres make a major contribution to the effective dose, thereby resulting in different dose coefficients for indoor workplaces and show caves compared with underground mines. From the perspective of the SSK, is the scientific evidence regarding the dosimetric effects of radon decay products of different particle sizes sufficiently robust to justify the use of different dose conversion factors at different workplaces?"

The SSK considers the scientific evidence for this exceptionally complex process to be insufficiently robust. Particle deposition in the respiratory tract depends heavily on particle size (Smerajec und Vaupotič 2012). Additional effects such as the hygroscopic growth of certain aerosols must also be taken into account (Reineking und Porstendörfer 1988). Similarly, factors such as breathing frequency, geometry, and the velocity of the airflow in the respiratory tract also play a role. This means that particle deposition depends on individual morphological and physiological characteristics as well.

The distribution of activity levels strongly depends on the size distribution of the particles in the ambient air. This can be measured with traceability to national standards only up to a lower limit (aerodynamic diameter) of 10 nm. In particle measurement technology, there is a wide range of innovations with regard to the expansion of measurement ranges, improved quality assurance, and cost reduction. This applies only to a limited extent to the determination of activity distributions. These are required to adapt RDC to different exposure scenarios (indoor workplaces, underground mines and show caves) (ICRP 2017). This procedure can be carried out effectively only if the associated uncertainties are known and the respective distributions differ considerably when these uncertainties are taken into account. If quality assurance and traceability are not possible, this cannot be carried out. The same applies, in principle, to all other parameters included in the modelling.

In the context of radon exposure, the short-lived decay products from the radon decay series, which can adhere to aerosol particles, are particularly important for dose assessment (see Section 4.1.1).

Both the data available for the dosimetric approach and those for the epidemiological approach are subject to considerable uncertainty, which, as is often the case in radiation protection, cannot be quantified. However, the proposed dose coefficients for different particle sizes give the false impression of accuracy that is not supported by the data available. This is because particle size distributions are poorly understood in most of the underlying studies and there are no studies involving a very narrow particle size distribution.

3.3 Epidemiological studies

"What conclusions can be drawn from new scientific findings, in particular the 'Pooled Uranium Miners Analysis' (PUMA) study, regarding the lifetime excess absolute risk (LEAR) assumed in ICRP Publication 137?"

Given the long follow-up periods and the large cohort size, the PUMA study (Kreuzer et al. 2024) is one of the most important epidemiological studies on the health risks associated with radon exposure for miners. The results of the study enable the calculation of radon risk coefficients (i.e. risk estimates per unit of exposure for a reference population). The reference value for the calculated risk parameters is exclusively the cumulative radon activity concentration. The PUMA study considers the lifetime excess absolute risk (LEAR) as a risk measure as a function of the cumulative potential alpha energy concentration (expressed in the old non-SI unit WLM). From the PUMA study, a lifetime excess absolute risk (LEAR) per cumulative radon activity concentration of $F \cdot 8.5 \cdot 10^{-4}/(\mathrm{MBq\,h\,m^{-3}})$ can be derived, whereby the results indicate that the risk is even higher particularly at lower exposures. The assumed risk in ICRP Publication 65 (ICRP 1993), which forms the basis for current regulatory requirements, is thus lower than that suggested by the current, expanded PUMA study.

Because no reference is made to a lung organ dose or an effective dose, the PUMA study, like all other radon epidemiological studies, cannot serve as a basis for calculating radon dose coefficients using the dosimetric approach preferred by the ICRP. However, a comparison based on an epidemiological approach is possible (cf. Section 4.3.3.2).

The PUMA study and other studies on occupational radon exposure or the Darby study on domestic radon exposure (Darby et al. 2005), therefore do not allow for dose calculation or the determination of dose coefficients based on a dosimetric approach. However, from the perspective of the SSK, its valuable findings can be applied directly and without reference to dose levels to link radon protection directly to the reference parameters used in epidemiological studies, in particular the cumulative radon activity concentration. This leads to the recommendations in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** as alternative solutions. The recommendations are described in detail in the scientific justification (Chapter 4).

3.4 Transfer to other occupational areas

"One approach adopted in European countries is to apply the dose coefficient of 3 mSv/mJ h m^{-3}, which is recommended in ICRP Publication 137 and derived from calculations for people in predominantly sedentary occupations, to other – or even all – workplaces. Can a sufficiently conservative level of protection for all affected persons be achieved in Germany using a similar approach, taking into account all uncertainties in dose assessment for radon and the graded approach established in Germany?"

The European Commission (EC 2024) essentially recommends the use of two ICRP dose coefficients for different workplace conditions. However, it also allows for different values in 'site-specific' situations, particularly for different workplaces. The recommendation therefore allows a certain degree of flexibility, which is used differently across European countries so that its implementation is handled in various ways. Some countries have adopted both ICRP values unchanged while others use modified RDCs with the corresponding categorisation of workplaces. Only Italy and Finland have, in principle, committed to a single RDC, namely 3 mSv/(mJ h m^{-3}), see Section 4.2.4.2.

In Northern European countries, particularly in Sweden, a classification is carried out based on the cumulative radon activity concentration (see Section 4.2.4.2). From the perspective of the

SSK, this approach offers a number of advantages (in particular the direct risk reference) and is being pursued in order to overcome the conceptual difficulties that the SSK identifies in principle with dose conversion (see also the explanations in Section 4.2.1).

In radiation protection, it is often necessary to strike a balance between being 'sufficiently conservative' and 'as realistic as possible' (cf. SSK 2005). In the case of radon exposure, it can be assumed that people who engage in 'substantial physical activity' are exposed to approximately twice the level of internal exposure as those with 'predominantly sedentary occupations' simply because of their breathing rate. In this respect, focusing solely on people whose work involves mainly sedentary occupations and failing to take into account work environments involving greater exercise would not be strictly conservative. However, even when radiation exposure is the same, the risk ranges for different occupational sectors or different population groups often vary by a factor of more than two. Such differences are not always reflected in radiation protection yet an adequate level of protection is still achieved. From the perspective of the SSK, this can also be achieved in radon protection, even if only one category of workplace is taken into account. The alternative approach proposed in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** allows for different workplace conditions to be taken into account by setting limits on annual exposure duration or by using the equilibrium factor as a tool in the optimisation process. In this respect, it proves to be flexible and practical, thereby ensuring that a sufficiently conservative level of protection is achieved for all those affected.

The decision regarding the type and number of different workplace categories thus touches on a fundamental issue in the concept of radiation protection: As explained in Section 4.2.1, the approach proposed by the SSK largely avoids any potential subdivision into specific subgroups of the population out of practical considerations. This reflects the fact that radiation protection is sufficiently robust to account for known or unknown differences in radiation risk for specific subgroups or individuals. With regard to radon a deliberate decision not to distinguish between smokers and non-smokers has been made even though the differences in risk and dose between these two groups are considerable. A similar line of reasoning could be used to define just one workplace category.

3.5 Graded approach in radon protection

"The aim of the graded approach set out in radiation protection legislation is to ensure adequate radon protection for workers, including compliance with the annual exposure limits for occupational exposure. From the perspective of the SSK, how can adequate radiation protection at workplaces be ensured in situations where a radon activity concentration of 300 Bq m^{-3} is not exceeded but the effective dose is not negligible from an occupational radiation protection perspective (e.g. because an effective dose of 6 mSv per year is exceeded)? The situation of persons under the age of 18 (trainees) and the limit of 1 mSv applicable to them (with a maximum of 6 mSv per calendar year subject to approval by the competent authority) should also be taken into account here."

The graded approach used in radon protection involves a hierarchy linked to the potential risk (increasing risk) of radon exposure with protective measures becoming progressively more extensive and stringent at each stage. In their current form, the individual stages are defined as a 'combination of reference parameters' relating either to activity concentrations or to dose values, whereby a graduation can be identified only by comparing the associated risk values (see Section 4.2.5). The concept underlying the risk classification system defines the lowest stage (lowest risk) of the graded approach as the detection of a level exceeding the reference level of 300 Bq m^{-3}. In this framework, exceeding 6 mSv in a calendar year triggers the next higher stage, which is associated with a higher risk than the lowest stage (cf. Section 4.2.5). Thus, under a graded approach, a situation in which "*a radon activity concentration of*

300 Bq m^{-3} is not exceeded, but the effective dose of 6 mSv per year is exceeded" should not arise. However, if the ICRP dose coefficients for radon were adopted, such cases would certainly be possible; for example, if the ICRP radon dose coefficients were applied to predominantly physical activities or if an equilibrium factor of more than 0.5 had to be assumed for predominantly sedentary occupations (cf. Section 4.2.5). The possibility of such cases also forms the background to the question raised in the advisory mandate. The application of the ICRP dose coefficients for radon would not reflect the increase in risk intended by the graded approach. Given the importance of the graded approach within the broader context of radiation protection, the SSK does not therefore consider it appropriate to adopt the ICRP dose coefficients for radon.

The SSK identifies a further critical issue in the comparison of the risks associated with the different stages: both dose-based (6 mSv) and activity-based (300 Bq m^{-3}) criteria are applied. When deriving dose estimates and applying RDC, certain parameters that are independent of the specific situation regarding radon exposure arise (e.g. DDREF, detriment model). It is difficult to understand how the applicability of the graded approach currently established in radiation protection legislation for radon protection could depend on parameters that do not relate to radon but are associated with other types of radiation, other affected organs, and other exposure conditions.

From the perspective of the SSK, incorporating the ICRP radon dose coefficients into the existing radiation protection system would also have negative consequences for the radiation protection system as a whole. In Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, the SSK therefore recommends an alternative approach that consistently continues the principle of separating radon protection from other areas of radiation protection; this principle is already largely implemented in radiation protection. This approach is described in detail in the Scientific justification (Chapter 4) (see in particular Figure 4.7).

4 Scientific justification

4.1 Basic information about the advisory mandate

The following introductory section sets out the key concepts relevant to addressing the questions raised in the advisory mandate. In particular, this addresses the measurement quantities used in ICRP Publication 137 (ICRP 2017), the assumptions regarding the reference worker, the parameters of respiration, and the exposure environment.

4.1.1 Radon and ist short-lived decay products

Among naturally occurring radionuclides, radon (^{222}Rn) is the only gaseous radionuclide in the ^{238}U decay series and is of particular relevance[3]. The half-life of around 3.8 days is sufficiently long to allow it to penetrate into living spaces from the bedrock beneath buildings, being it an inert noble gas. This can lead to elevated radon activity concentrations that, if inhaled along with its short-lived decay products, can result in radiation exposure when people are present.

Radon and its short-lived decay products account for more than half of the mean natural radiation exposure of the population in Germany. More than 95 % of radiation exposure to radon and its short-lived decay products is attributable to the short-lived decay products of radon, which are inhaled as particles. By contrast, radon gas plays only a minor role in radiation

[3] The analysis presented here is limited to the radon isotope ^{222}Rn. The radon isotopes ^{220}Rn from the ^{232}Th decay series and ^{219}Rn from the ^{235}U decay series are not addressed here.

exposure. Figure 4.1 contains a diagram of the decay chain of ^{222}Rn showing its short-lived decay products down to the long-lived ^{210}Pb. The short-lived decay products of radon are heavy metals.

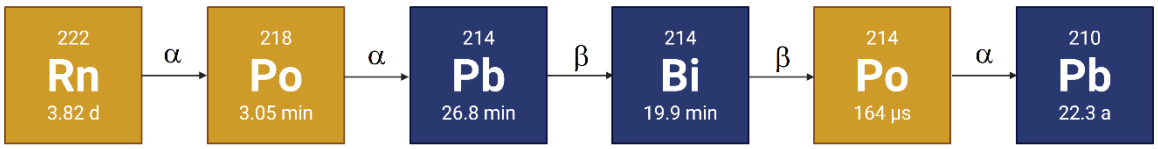

Figure 4.1: Illustration of the decay chain of ^{222}Rn and its short-lived decay products down to the long-lived ^{210}Pb (Created with BioRender.com).

The diagram in Figure 4.2 illustrates the processes that take place following the decay of radon and the role of aerosols in relation to the short-lived radon decay products. According to the ICRP and ICRU classifications, a distinction is made between unattached and attached decay products (ICRP 2017, ICRU 2015).

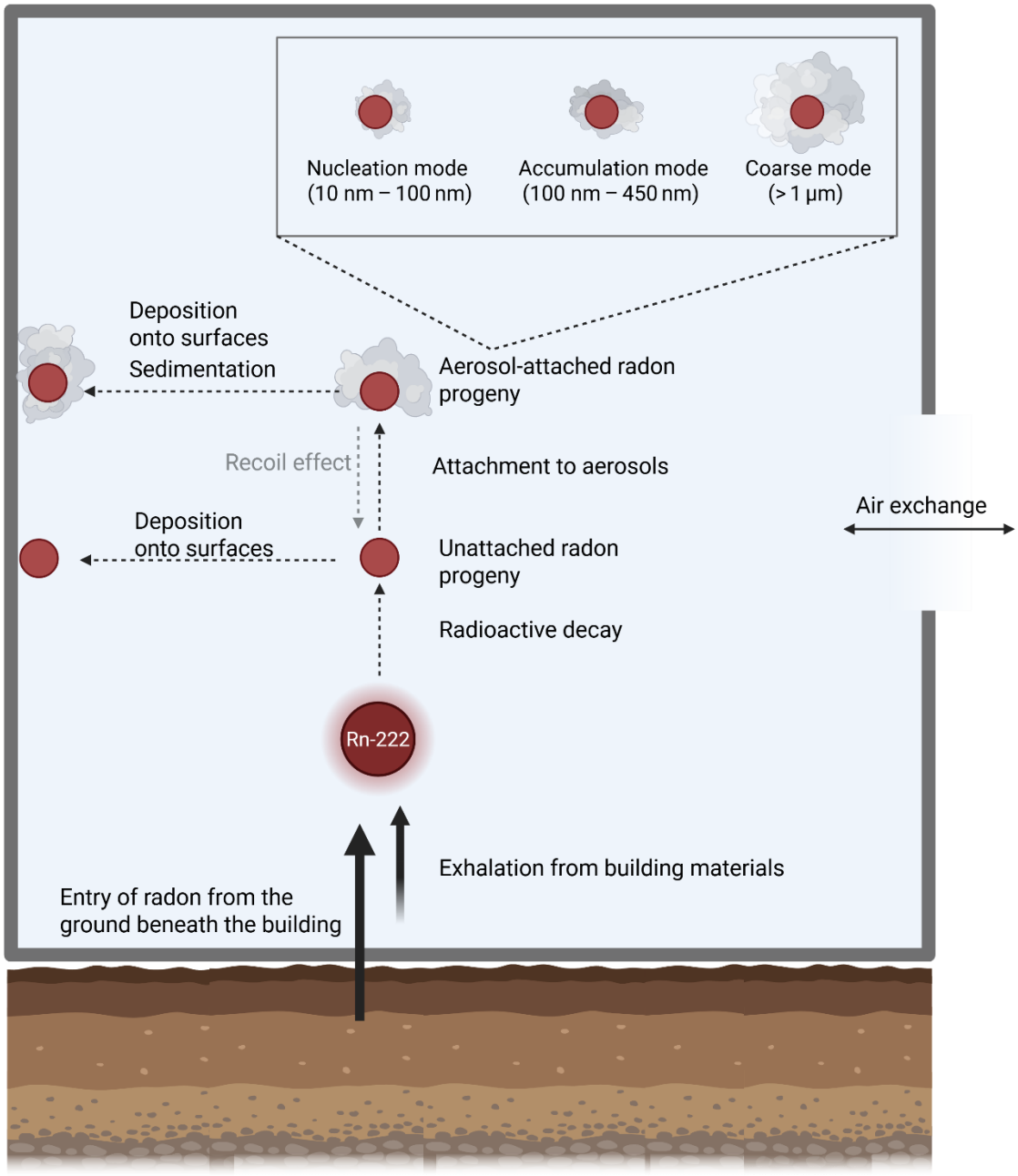

Figure 4.2: Schematic illustration of the behaviour of radon and its short-lived decay products in indoor air, including their attachment to aerosols[4] and deposition onto surfaces (Created with BioRender.com).

When radon decays, 88 % of the products are positively charged ^{218}Po ions and 12 % are neutral ^{218}Po atoms (Wellisch 1913, Henderson 1916). Within the first second of decay, radioactive particles ranging from 0.5 nm to 5 nm are produced through reactions with trace gases and water vapour; these are generally referred to as unattached decay products (ICRP 2017). Over the next 1–100 s, the decay products may adhere to existing aerosols (Porstendörfer 1994), thereby causing the particle size to change and range from 10 nm up to several micrometers. Particles of these size fractions are referred to as attached decay products (ICRP 2015, ICRP 2017). The

[4] During the alpha decay of ^{218}Po, the recoil energy of the helium nucleus can cause the resulting ^{214}Pb to detach from aerosols, a phenomenon referred to as the 'recoil effect'.

attached decay products exhibit a trimodal activity distribution; this means they can be classified into the nucleation mode (AMTD[5] 10–100 nm) (Knutson et al. 1984, Kulmala et al. 2004), the accumulation mode (AMTD 100–450 nm) (Porstendörfer und Reineking 1992, Shimo und Saito 2000), and the coarse mode (AMAD[6] > 1 µm) (Becker et al. 1984, Reineking und Porstendörfer 1988). The size distribution in ambient air can vary considerably and is influenced by relative humidity and the concentration of other trace gases and aerosols (ICRP 2017).

In practice, the activity concentrations of short-lived radon decay products in the air are always lower than the radon activity concentration itself. The deposition of radon decay products onto surfaces reduces their activity concentration in the air. The processes involved are complex. The smaller the particles are, the greater their diffusivity and thus their deposition rate. The state of charge also affects the deposition process on surfaces. In the case of larger particles, sedimentation plays a role. For example, the bulk of the activity of the radon decay products ^{214}Pb and ^{214}Bi is generally present in the accumulation mode (El-Hussein und Ahmed 1995, Cheng et al. 1997, Mohammed 1999) because the deposition rate is minimal for particles of this size.

A high air exchange rate in rooms can also result in considerably lower activity concentrations of radon decay products compared with radon itself because the radon does not have enough time to decay (i.e. the radon decay products do not have time to build up) (ICRP 2017, p. 449). A measure of the degree of imbalance between radon and its short-lived decay products is the equilibrium factor *F*, which is defined in Section 4.1.3.

As a rule, high concentrations of aerosols in the air result in a high proportion of attached radon decay products. This case is typical of the situation in active mines. If, on the other hand, the aerosol concentration is low, the proportion of unattached radon decay products may increase.

The unattached fraction[7] (f_p) of radon decay products is defined as the ratio of the potential alpha energy concentration (*PAEC*) (see Section 4.1.2 for the definition) of the unattached radon decay products to the sum of the potential alpha energy concentrations of the unattached and attached radon decay products.

For dosimetric purposes, certain activity ratios are assumed for the short-lived radon decay products (ICRP 2017, p. 473). Accordingly, for attached nuclides, ^{218}Po : ^{214}Pb : ^{214}Bi are in the ratio 1.0 : 0.75 : 0.60 and for unattached nuclides in the ratio 1.0 : 0.1 : 0.0.

4.1.2 Exposure levels of radon decay products and equilibrium factor

4.1.2.1 Derivation of the equilibrium factor F from the potential alpha energy concentration

In a radioactive decay process, the total number of decays, $N_{ges,}$ is given by the ratio of the initial activity, $A_{0,}$ of a radionuclide to its decay constant λ:

$$N_{ges} = \frac{A_0}{\lambda} \tag{4}$$

where the decay constant λ is related to the half-life $T_{½}$ as follows:

$$\lambda = \frac{ln(2)}{T_{1/2}} \tag{5}$$

[5] AMTD: Activity median thermodynamic diameter
[6] AMAD: Activity median aerodynamic diameter
[7] Also known as the free portion

The total energy E_{ges} released by this process is the product of the energy per decay E and the total number of decays N_{ges}:

$$E_{ges} = E \cdot N_{ges} = E \cdot \frac{A_0}{\lambda} \quad \text{or normalised to the activity:} \quad \frac{E_{ges}}{A_0} = \frac{E}{\lambda} \qquad (6)$$

In the case of a decay chain, the total energy is the sum of the energies of all decays of the parent nuclide and all decays of the daughter nuclides (decay products).

The lung dose results mainly from the alpha decay of short-lived radon decay products that are inhaled and deposited in the respiratory tract. However, these are not in radioactive equilibrium with the parent nuclide in the air we breathe. The potential alpha energy *PAE* of such a short-lived radon decay product in the radon decay chain is the total alpha energy released during the decay of this radionuclide and all its subsequent short-lived decay products down to the long-lived ^{210}Pb (Table 4.1). In this context, each of these radionuclides is considered separately as a parent nuclide together with all its decay products.

For example, in the decay chain of ^{214}Bi, which itself does not undergo alpha decay, only the radionuclide ^{214}Po, which has an alpha decay energy of 7.69 MeV per decay, contributes to the potential alpha energy *(PAE)*, whereas ^{218}Po contributes to the *PAE* both as the parent nuclide with 6 MeV per decay and, with ^{214}Po as one of its decay products, with 7.69 MeV per decay (= 13.69 MeV per decay). In the case of radioactive equilibrium

$$A(^{222}\text{Rn}) = A(^{218}\text{Po}) = A(^{214}\text{Pb}) = A(^{214}\text{Bi}) = A(^{214}\text{Po}) \qquad (7)$$

the *PAE* normalised to the activity can be aggregated into a total *PAE* per activity. This corresponds to the energy per activity that can be released into the lung tissue in the case of radioactive equilibrium through the alpha decay of short-lived radionuclides and their respective decay products (Table 4.1, Columns 6 and 7). In practice, this case does not occur but rather represents a construct to relate the *PAE* of a mixture of radon decay products not in equilibrium to the *PAE* under equilibrium conditions (cf. ‘equilibrium equivalent concentration’, EEC below).

Table 4.1: Nuclide-specific data for calculating the potential alpha energy (cf. Table A.1 in (ICRP 2017) and Table A1 in (SSK 2000))[8].

Nuclide	**Half-life $T_{½}$**	**Decay constant λ [s^{-1}]**	**Potential alpha energy *PAE***				
			Per decay		**Per activity**		
			[MeV]	**[10^{-12} J]**	**[MeV/Bq]**	**[10^{-10} J/Bq]**	**Ratio**
^{222}Rn	3.82 d	$2.1 \cdot 10^{-6}$					
^{218}Po	3.05 min	$3.8 \cdot 10^{-3}$	13.69	2.19	3,615	5.79	0.105
^{214}Pb	26.8 min	$4.3 \cdot 10^{-4}$	7.69	1.23	17,840	28.6	0.516
^{214}Bi	19.9 min	$5.8 \cdot 10^{-4}$	7.69	1.23	13,250	21.2	0.379
^{214}Po	164 µs	$4.3 \cdot 10^{3}$	7.69	1.23	$2 \cdot 10^{-3}$	$3 \cdot 10^{-6}$	
				Total: *(Radioactive equilibrium)*	34,710	55.6	1

The potential alpha energy concentration *PAEC* is the sum of the individual *PAE* per decay of any mixture of short-lived radon decay products (unattached and attached) present in a given volume of air. The SI unit of the *PAEC* is J m^{-3}.

The equilibrium equivalent concentration (EEC) C_{eq} with the unit Bq m^{-3} (cf. Chapter 7 Glossary of terms) is defined as the activity concentration of radon in equilibrium with its short-lived decay products that has the same potential alpha energy concentration *PAEC* as the actual mixture of short-lived decay products that is *not* in equilibrium:

$$PAEC(C_{eq}) = 55.6 \cdot 10^{-10}\,\mathrm{J\,Bq^{-1}} \cdot C_{eq} \qquad (8)$$

Given any mixture of the activity concentrations of the short-lived decay products, the equilibrium equivalent concentration is given by:

$$C_{eq} = 0.105 \cdot C_{Po-218} + 0.516 \cdot C_{Pb-214} + 0.379 \cdot C_{Bi-214} \qquad (9)$$

The weighting factors for the respective nuclide activity concentrations are derived from the relative proportions in the radioactive equilibrium (Table 4.1, Column 8). If, for example, the following distribution of activity concentrations is present:

$$\begin{aligned} C_{Po-218} &= 200\ \mathrm{Bq\,m^{-3}} \\ C_{Pb-214} &= 150\ \mathrm{Bq\,m^{-3}} \\ C_{Bi-214} &= 120\ \mathrm{Bq\,m^{-3}} \end{aligned} \qquad (10)$$

this mixture (ratio 1.0 : 0.75 : 0.60; cf. attached nuclides in Section 4.1.1) yields the same *PAEC* as a radon activity concentration C_{eq} in radioactive equilibrium:

$$\begin{aligned} C_{eq} &= (0.105 \cdot 200 + 0.516 \cdot 150 + 0.379 \cdot 120)\ \mathrm{Bq\,m^{-3}} = 144\ \mathrm{Bq\,m^{-3}} \\ PAEC(C_{eq}) &= 55.6 \cdot 10^{-10}\,\mathrm{J\,Bq^{-1}} \cdot C_{eq} = 8 \cdot 10^{-7}\,\mathrm{J\,m^{-3}} \end{aligned} \qquad (11)$$

[8] A comparison with BIPM-5 (BIPM 2010) yields slightly different values. However, to ensure consistency with the SSK values and the SSK glossary, reference is made to the SSK statement ‘Guideline on measurements of radon, thoron and their decay products’ (SSK 2000).

The equilibrium factor F is the ratio of the equilibrium equivalent concentration C_{eq} of the radon decay product mixture to the actual radon activity concentration C_{Rn}:

$$F = \frac{C_{eq}}{C_{Rn}} = \frac{PAEC(C_{eq})}{PAEC(C_{Rn})} \quad (12)$$

F thus describes the ratio of the potential alpha energy concentration $PAEC(C_{eq})$ of a given mixture of radon decay products to the potential alpha energy concentration $PAEC(C_{Rn})$ that a given radon activity concentration would have.

Assuming for the above example (in which the short-lived radon decay products are not in radioactive equilibrium) a radon activity concentration of $C_{Rn} = 200\ \mathrm{Bq\ m^{-3}}$ and an equilibrium equivalent concentration of the radon decay products of $C_{eq} = 144\ \mathrm{Bq\ m^{-3}}$, this results in an equilibrium factor of $F = 144/200 = 0.72$.

The integral of the $PAEC$ over the exposure time is the cumulative potential alpha energy concentration (P_{PAEC}) with the unit $\mathrm{J\ h\ m^{-3}}$ and serves in occupational radiation protection as the basic reference quantity for dose and risk.

Using these definitions, the cumulative potential alpha energy concentration P_{PAEC} can be converted into the cumulative radon activity concentration P_A (cf. Table 4.1 Column 7 and Table 4.2):

$$\frac{P_{PAEC}}{P_A} = F \cdot 55.6 \cdot 10^{-10}\ \frac{\mathrm{J\ h\ m^{-3}}}{\mathrm{Bq\ h\ m^{-3}}} = F \cdot 5.6 \cdot 10^{-3}\ \frac{J}{\mathrm{MBq}} \quad (13)$$

Radon dose coefficients (RDC, see Section 4.1.2.2) are used to convert exposure quantities into dose quantities, in particular for conversion into effective dose. Various quantities and units are used to express exposure; this can make things somewhat confusing. Reference quantities for exposure are the cumulative radon activity concentration P_A with the unit $\mathrm{Bq\ h\ m^{-3}}$ and the cumulative potential alpha energy concentration P_{PAEC} with the unit $\mathrm{J\ h\ m^{-3}}$ or the historical unit WLM ('working level month', 1 WLM corresponds to a $PAEC$ of $2.08 \cdot 10^{-5}\ \mathrm{J\ m^{-3}}$ over a monthly working period of 170 h). All exposure values can be converted into one another without ambiguity (Table 4.2).

Table 4.2: Conversion of the various units for exposure to radon and its decay products. A factor by which a value in the row unit must be multiplied to obtain the value in the column unit (without units).

	P_A: MBq h m^{-3}	P_{PAEC}: J h m^{-3}	WLM
P_A: MBq h m^{-3}	1	$F \cdot 5.6 \cdot 10^{-3}$	$F \cdot 1.56$
P_{PAEC}: J h m^{-3}	$F^{-1} \cdot 178$	1	286
WLM	$F^{-1} \cdot 0.64$	$3.5 \cdot 10^{-3}$	1

In practical application as well as in the legal texts of the StrlSchG (2017) and the StrlSchV (2018), exposure is specified both as cumulative radon activity concentration P_A in units of Bq h m^{-3} and as cumulative potential alpha energy concentration P_{PAEC} with the unit J h m^{-3}. The recommendations of the ICRP on RDCs as well as epidemiological studies on occupational radon exposure refer primarily to the cumulative potential alpha energy concentration P_{PAEC}. The historical unit WLM, which is still used primarily in epidemiological literature, is not an SI unit and is therefore no longer permitted. In this document, WLM is used only when a direct reference to the original literature is necessary. The unit conversion from J h m^{-3} to WLM is carried out solely by means of a numerical factor, whereas the conversion to Bq h m^{-3} includes the equilibrium factor F.

4.1.2.2 Derivation of radon dose coefficients

The effective dose resulting from a given occupational exposure (cumulative radon activity concentration P_A or cumulative potential alpha energy concentration P_{PAEC}) is calculated using radon dose coefficients (RDC). The basic calculation of these RDCs is based on two different approaches: the epidemiological approach and the dosimetric approach. Both approaches are described in more detail below.

Epidemiological approach

The epidemiological approach to deriving RDCs forms the historical basis for assessing radon exposure in radiation protection. It is based on an analysis of observed links between exposure to short-lived radon decay products and the incidence of lung cancer. Key findings come from epidemiological studies of occupationally exposed groups, primarily those working in uranium mines.

The relationship between exposure and disease risk is usually modelled using the excess relative risk (ERR = RR − 1), which is assumed to be proportional to exposure. The risk coefficient is determined by statistical adjustment to the observational data, taking into account temporal modifiers, age at exposure, time since exposure, duration of exposure, and the rate of exposure.

To calculate the increase in the lifetime excess absolute risk (LEAR) due to occupational exposure, the assessed RR is projected to a defined reference population (of working age 18 to 65 years). It is assumed that the relative risk is applied to the respective age-specific baseline incidence rates for lung cancer in the reference population. By integrating the exposure over the working lifetime, the LEAR for lung cancer resulting from occupational exposure to radon is obtained and is generally expressed as a risk coefficient $LEAR/P_A$ with the unit 1/(MBq h m^{-3}) or $LEAR/P_{PAEC}$ with the unit 1/(mJ h m^{-3}).

The link to the effective dose is established by equating the risk caused by radon exposure with the detriment-weighted risk associated with the dose in the general radiation protection system.

Dosimetric approach

The dosimetric approach is used to quantitatively calculate the radiation exposure caused by radon and its short-lived decay products using physical and biological models. The starting point is the inhalation of the decay products and their deposition in the human respiratory tract. To this end, respiratory models that divide the respiratory tract into anatomically defined regions are used. For each region, the deposition of the decay products, their residence time, and the energy released by the emitted alpha radiation are modelled. The absorbed dose is calculated in the target cells assumed to be radiation-sensitive, taking into account assumptions regarding the spatial distribution of these cells and the range of the alpha particles. The absorbed dose is converted to the equivalent dose by applying the radiation weighting factor for alpha radiation. The effective dose is calculated taking into account the tissue weighting factor for the lungs.

The particle size distribution of the inhaled short-lived radon decay products and the breathing rate have a considerable influence on the RDC values determined using the dosimetric approach. The deposition of short-lived radon decay products occurs via size-dependent mechanisms such as diffusion, sedimentation, and inertia. This results in different regional deposition patterns in the respiratory tract with varying radiation effects. The breathing rate determines the energy intake per unit of time and is therefore approximately proportional to the resulting RDC.

4.1.3 Anatomical and physiological bases for the definition of reference worker according to ICRP

The ICRP has developed comprehensive models and reference levels to assess radiation exposure resulting from the inhalation of radioactive substances. A central component of these models is the definition of the breathing rate of the reference worker.

4.1.3.1 Historical background of the reference individuals

Reference individuals for dosimetric purposes have been used since 1949. The first ICRP reference individual was known as the ‘Standard Man’. In 1963, the ‘Standard Man’ was renamed the ‘Reference Man’ (ICRP 1975). This model represented a typical worker and provided information on the anatomical, morphological, and physiological characteristics relevant to the biokinetics and dosimetry of the internal deposition of radionuclides. In 1984, the ‘Reference Man’ was revised to reflect the substantial increase in available information on radionuclide biokinetics and dosimetry, as well as the growing emphasis on the exposure of members of the public. This led to an increased need for reference models for children and other subgroups of the population. With regard to the development of various biokinetic models and their dosimetric implications, the ICRP subsequently published the following key papers:

- ICRP Publication 66 (ICRP 1994): “Human Respiratory Tract Model for Radiological Protection” – This publication contains detailed guidelines for determining respiratory parameters.
- ICRP Publication 70 (ICRP 1995): “Basic Anatomical and Physiological Data for Use in Radiological Protection: The Skeleton”.
- ICRP Publication 88 (ICRP 2001): “Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother”.
- ICRP Publication 89 (ICRP 2002): A review of the information from Publication 23 (ICRP 1975); this provides additional details on individual differences among normal persons, including differences in age, gender, and ethnic group.

– ICRP-Publication 115 (ICRP 2010): “Lung Cancer Risk from Radon and Progeny and Statement on Radon”.

ICRP publications in the Occupational Intakes of Radionuclides (OIR) series:

– ICRP Publication 130 (ICRP 2015): Part 1
– ICRP Publication 134 (ICRP 2016): Part 2
– ICRP Publication 137 (ICRP 2017): Part 3
– ICRP Publication 141 (ICRP 2019): Part 4
– ICRP Publication 151 (ICRP 2022): Part 5

4.1.3.2 Definition and role of the reference worker[9]

The reference worker is a theoretical model that reflects the average physiological and behavioural characteristics of an adult worker (Figure 4.3). The adult reference person is used to define the reference worker in conjunction with the biokinetic and dosimetric reference models. The relevant parameter values are defined within the OIR series (ICRP 2015). This model is designed to provide consistent and standardised assessments of radiation exposure. Relevant parameters include anatomical and physiological characteristics, such as the ventilation/breathing rate (ICRP 2002) and activity patterns, i.e. sitting, light and heavy exercise.

The reference worker is situated in an environment characterised by physical parameters. These were described in Section 4.1.2.

Where there are known deviations from the reference assumptions, high calculated doses or doses exceeding the dose limits, the ICRP recommends deriving and using more detailed dose coefficients provided that sufficient data are available.

[9] The *reference worker* as defined by the ICRP is conceptually gender-neutral, but many of its parameters are still based on the male reference model.

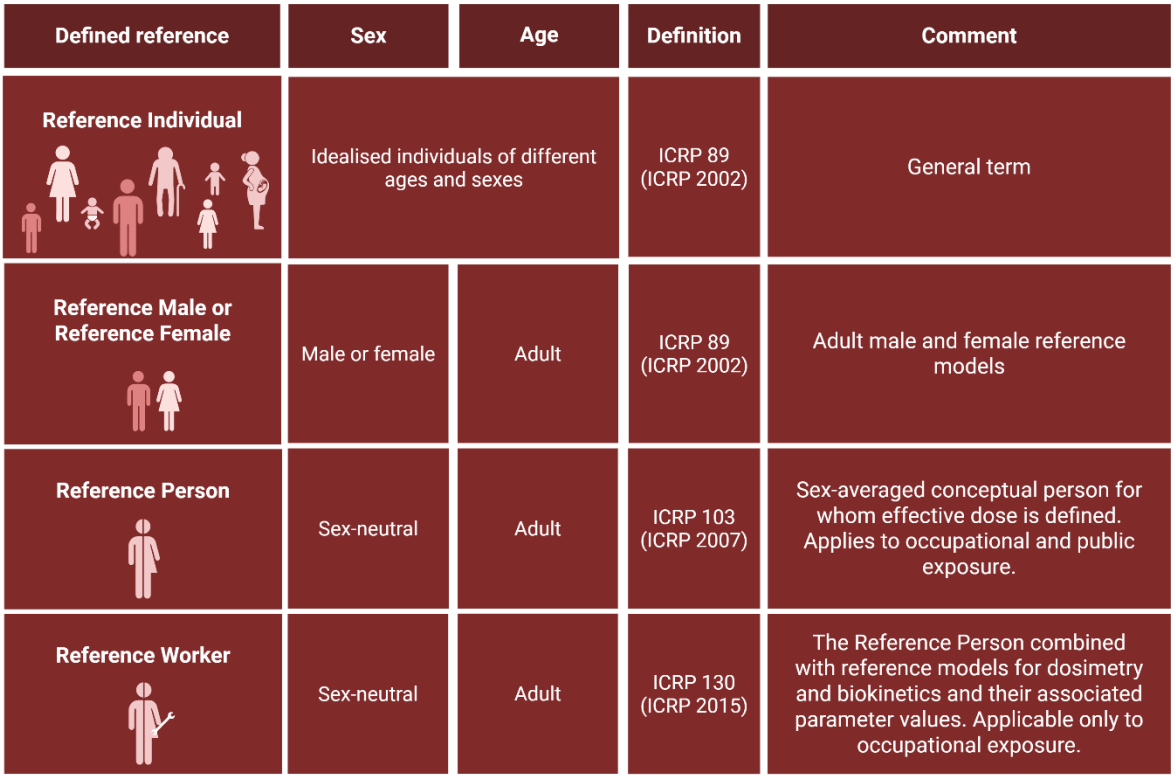

Figure 4.3: Overview of the definitions of reference individual, reference male, reference female, reference person, and reference worker[10] (Created with BioRender.com).

4.1.3.3 Respiratory physiological parameters

A basic distinction is made between two categories of respiratory physiological parameters: lung-specific parameters and respiratory parameters.

Lung-specific parameters depend on factors such as age, height, weight, gender, ethnic origin, and general health. These include total lung capacity, the volume of air at maximum inhalation, functional residual capacity, and the volume of air remaining after a normal exhalation (ICRP 1994, Appendix B, Figure B.1A, p. 169). Using values for these and other biometric parameters (e.g. lung volume, ICRP 1994, Appendix B, Tables 6 and 7, p. 189 ff.), which are based on measurements from the 1970s and earlier (ICRP 1951, Stuart 1976, Stuart 1984, ICRP 1994, SSK 2017), the part of the ICRP lung model dealing with deposition mechanisms ('deposition model') was used to calculate specific deposition values for the lung model as a function of particle size. The values for the parameters are given for six different reference groups (age groups) (ICRP 1994, Appendix A, Table A3, p. 139, and Appendix B, p. 173 ff.).

The following parameters describe various aspects of breathing:

– The breathing mode determines how the air inhaled is distributed between the nose and the mouth.

– The breathing frequency is the number of breaths per minute while tidal volume measures the volume of air per breath (ICRP 1994, Appendix B, p. 179 ff).

[10] http://icrpaedia.org/ICRP_Glossary

– The breathing rate, i.e. the volume of air inhaled per unit of time, is the product of the breathing frequency and the tidal volume.

Both the latter parameters, the breathing frequency and the breathing rate, vary depending on body size, age, gender as well as the health status of the respiratory system, and the level of exercise (ICRP 1994, p. 22, ICRP 2002). In addition, there are various breathing patterns: Most people breathe through their nose when at rest and switch to a combination of nasal and mouth breathing during moderate exercise. Some people habitually breathe through their mouths while others always breathe through their noses or do not have a consistent breathing pattern.

4.1.3.4 Values for the breathing rate of the reference worker

– Reference parameters for the breathing of workers have been established since the 1950s (see Age and health status: The most important factors affecting respiration in the model are age and the level of exercise (ICRP 2002, Tables 2.31 to 2.35, (177)–(179)). The reference worker is regarded as a healthy adult who breathes through their nose (ICRP 2002, p. 89, ICRP 1994). ICRP Publication 130 defines the healthy reference worker as a non-smoker (ICRP 2015, p. 59 and p. 130). However, the potential influence of smoking or the extent of cigarette consumption was not incorporated into the revised model (ICRP 2015, p. 164).

Table 4.3). These parameters are reviewed at appropriate intervals and, where necessary, updated in line with new scientific findings.

The model assumptions for the reference worker used in ICRP Publication 137 (ICRP 2017) are based predominantly on the parameters specified in the Human Respiratory Tract Model (HRTM, ICRP 1994).

Key reference parameters for the respiration of the reference worker include:

– Breathing rate (the product of tidal volume and breathing frequency): These parameters vary depending on the type of exercise being carried out. The ICRP takes into account conservative assumptions regarding various physical activity levels such as those typically encountered in the workplace or at home:
  - sleeping: 0.45 $m^3\,h^{-1}$
  - sitting (at rest): 0.54 $m^3\,h^{-1}$
  - light exercise: 1.5 $m^3\,h^{-1}$
  - heavy exercise: 3.0 $m^3\,h^{-1}$.
– Reference values for the temporal distribution of daily physical activity levels (‘time budgets’ [$h\,d^{-1}$] depending on age for indoor and outdoor exercise as well as sleep and waking periods, see (ICRP 2002, Table 2.33 and 2.34, p. 26 and (177), p. 99) and for the distribution of working time: Reference values for the daily volume of air inhaled have been established both for the general population (ICRP 2002, Table 2.32, p. 25 and (178), p. 100) and for workers (ICRP 2002, Table 2.35, p. 27 and Table (179), p. 101). For defining the breathing rate of the reference worker an activity pattern of 2.5 $h\cdot d^{-1}$ of sedentary occupations and 5.5 $h\,d^{-1}$ of light exercise is applied in ICRP Publication 137 (ICRP 2017). This equates to roughly one-third of working hours spent sitting and two-thirds spent doing light exercise. This pattern is already described in ICRP Publication 103 (ICRP 2015, p. 59) in relation to the reference worker. In earlier publications, it also served as the basis for the definition of ‘light work’ (ICRP 1994, p. 23) or the ‘sedentary worker’ (ICRP 2002, p. 27) (see Age and health status: The most important factors affecting respiration in the model are age and the level of exercise (ICRP 2002, Tables 2.31 to 2.35, (177)–(179)). The reference worker is regarded as a healthy adult who

breathes through their nose (ICRP 2002, p. 89, ICRP 1994). ICRP Publication 130 defines the healthy reference worker as a non-smoker (ICRP 2015, p. 59 and p. 130). However, the potential influence of smoking or the extent of cigarette consumption was not incorporated into the revised model (ICRP 2015, p. 164).

– Table 4.3). In addition, ICRP publications define different exercise patterns for strenuous physical work and light office work (see Age and health status: The most important factors affecting respiration in the model are age and the level of exercise (ICRP 2002, Tables 2.31 to 2.35, (177)–(179)). The reference worker is regarded as a healthy adult who breathes through their nose (ICRP 2002, p. 89, ICRP 1994). ICRP Publication 130 defines the healthy reference worker as a non-smoker (ICRP 2015, p. 59 and p. 130). However, the potential influence of smoking or the extent of cigarette consumption was not incorporated into the revised model (ICRP 2015, p. 164).

– Table 4.3).

– Age and health status: The most important factors affecting respiration in the model are age and the level of exercise (ICRP 2002, Tables 2.31 to 2.35, (177)–(179)). The reference worker is regarded as a healthy adult who breathes through their nose (ICRP 2002, p. 89, ICRP 1994). ICRP Publication 130 defines the healthy reference worker as a non-smoker (ICRP 2015, p. 59 and p. 130). However, the potential influence of smoking or the extent of cigarette consumption was not incorporated into the revised model (ICRP 2015, p. 164).

Table 4.3: Reference values for breathing rates [$m^3 h^{-1}$] and the total volume of air inhaled during an eight-hour working day [m^3] for different activities of the adult reference worker in accordance with ICRP recommendations (1951–2017).

Exercise	ICRP	Breathing rate [$m^3 h^{-1}$]	Volume of air inhaled [m^3] per working day	Exercise patterns
'At Work'	1951	1.25	10	NA
'Working - light exercise'	1975	1.2	9.6	NA
'Occupational light work'	1994	1.2	9.6	2.5 h sitting, 5.5 h light exercise
'Sedentary worker'	2002	1.2	9.6	1/3 sitting, 2/3 h light exercise
'Reference worker'	2015	1.2	9.6	2.5 h sitting, 5.5 h light exercise
'Reference worker'	2017	1.2	9.6	2.5 h sitting, 5.5 h light exercise
'Heavy work'[a]	1994	1.7	13.5	7 h light exercise, 1 h heavy exercise
'Heavy work'[a]	2002	1.7	13.5	7/8 light exercise, 1/8 heavy exercise
'Sedentary – office work'[b]	2017	0.89	7.1	2/3 sitting, 1/3 light exercise

[a] Examples of 'heavy work' cited in (ICRP 2002, p. 100) are occupations such as firefighters, construction and agriculture workers.

[b] Data from Harrison und Marsh (2012), cited in ICRP Publication 137 (ICRP 2017), published in the Proceedings of ICRP 2011.

4.1.3.5 Influence of respiratory parameters on dose calculation

Respiratory parameters are used in the Human Respiratory Tract Model (HRTM) and other dosimetric models to calculate the dose. Fluctuations in these parameters can have a considerable effect on the radiation exposure calculated using the model because they influence the distribution and deposition of radionuclides in the respiratory tract as well as their transport within the body. As shown by the data presented in Sections 4.1.3.3 and 4.1.3.4, breathing parameters and lung-specific physiological parameters vary substantially with the level of physical activity and between individuals (ICRP 2002, p. 96 ff).

In Publication 66 (ICRP 1994, Table 31), the ICRP proposes a weighting scheme for the relative radiation sensitivity of tissues in the respiratory tract (**Fehler! Ungültiger Eigenverweis auf Textmarke.**).

Table 4.4: Summary: Weighting factors assigned for the partition of radiation detriment among respiratory tract tissues in accordance with Table 31 of ICRP Publication 66 (ICRP 1994).

Tissue	**Assigned fractions (A) of w_T**
Extrathoracic region	
ET_1 (anthrior nose)	0.001
ET_2 (posterior nasal passages, larynx, pharynx, and mouth)	1
LN_{ET} (lymphatics)	0.001
Thoracic region	
BB (bronchial)	0.333
bb (bronchiolar)	0.333
AI (alveolar-interstitial)	0.333
LN_{TH} (lymphatics)	0.001

The weighting factor $w_T = 0.12$ for the lungs is used to weight the equivalent dose to the lungs when calculating the effective dose. The extrathoracic region is included among the 'other tissues'[11], which collectively have a weighting factor of $w_T = 0.12$. This set of parameters can be used to estimate the respective cancer risk following deposition in various parts of the respiratory tract. The quality of the data on which this ICRP partition is based cannot be assessed here[12].

Various uncertainties associated with the dosimetric concepts and the calculated dose coefficients were already highlighted in (SSK 2017) and in a summary of Makumbi et al. (2024). In addition to individual variability and environmental conditions, these uncertainties include, in particular, the deposition values of radon decay products in the lung region (particle deposition model), the mechanical transport mechanisms of the attached radon decay products (particle transport model), the absorption rate from the respiratory tract into the blood (absorption model), and the definition and location of radiation-sensitive cells.

– Reference values for respiratory parameters are defined in Chapter 3 of ICRP Publication 66 (ICRP 1994) for both the reference worker and the general public. In accordance with the definition of the reference worker in (ICRP 2017), it is assumed that a volume of 9.6 m^3 of air is inhaled during an eight-hour working day (Age and health status: The most important factors affecting respiration in the model are age and the level of exercise (ICRP 2002, Tables 2.31 to 2.35, (177)–(179)). The reference worker is regarded as a healthy adult who breathes through their nose (ICRP 2002, p. 89, ICRP 1994). ICRP Publication 130 defines the healthy reference worker as a non-smoker (ICRP 2015, p. 59 and p. 130). However, the potential influence of smoking or the extent of cigarette consumption was not incorporated into the revised model (ICRP 2015, p. 164).

Table 4.3). This corresponds to an average breathing rate of 1.2 $m^3\,h^{-1}$ (one third sedentary occupations and two thirds light work) (ICRP 2017, (665)). This specification served as the basis for calculating dose conversion coefficients.

[11] Adrenal glands, upper respiratory tract, gall bladder, heart, kidneys, lymph nodes, muscle tissue, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix.

[12] A discussion of the uncertainties in the model regarding the inhalation of uranium-containing particles can be found in (HPA 2007).

When calculating the dose from radon exposure using the HRTM, a distinction is made between the intake of radon gas and radon decay products. Various physical and physiological parameters are taken into account to calculate the incorporated activity. For the absorbed radionuclides, these include the activity concentration of radionuclides in the ambient air, the exposure time, the activity concentrations of the decay products, and the breathing rate.

The dose modelling is further complemented by a detailed consideration of physical processes such as particle filtration and deposition as well as biologically influenced clearance mechanisms in the respiratory tract.

Filtration models describe the deposition of aerosols in the various sections of the respiratory tract; this varies depending on the size, shape and physical properties of the particles. These processes are influenced by the polydispersity of the aerosols because in real-world environments, aerosols typically consist of a mixture of particles of varying sizes.

Hygroscopic aerosols represent an additional influencing factor because they grow after inhalation as a result of the humidity within the respiratory tract. A hygroscopic growth factor is used to model the resulting increase in particle size, which in turn affects deposition in the different regions of the respiratory tract.

4.1.4 Parameters of the exposure environment and their effect on radon exposure

Exposure to radon in the workplace is determined primarily by the distribution of activity levels of radon decay products; this is influenced by various physical and environmental parameters (cf. Section 4.2.2). The particle concentration is the primary parameter determining the activity size distribution of radon decay products within a room. Particle concentration and size distribution depend largely on the presence of aerosols or aerosol sources (e.g. cigarette smoke, particles from exhaust fumes), humidity, the room configuration (volume and internal surface area of the room), air exchange rates, and air movement within the room.

In general, the proportion of unattached radon decay products decreases with increasing particle concentration, while the proportion of attached radon decay products and the particle concentration are directly correlated.

The volume and internal surface area of a room influence the deposition rate of radon decay products; this is also dependent on particle size. Particles of different sizes have considerably different deposition velocities. The mean deposition velocity of unattached radon decay products is thus approximately two orders of magnitude higher than the deposition velocity of radon decay products attached to aerosols.

At low particle concentrations, where there is a correspondingly higher proportion of unattached radon decay products, the equilibrium factor F is generally low. The presence of aerosols and radon decay products attached to them is associated with higher values of the equilibrium factor F. Lower values of the equilibrium factor may occur, particularly at high ventilation rates.

In practice, reliable measurement data are not available for many workplaces where radon protection is a concern. ICRP Publication 137 (ICRP 2017) compiles results from various studies for selected types of workplaces and uses these to validate the underlying model assumptions. This overview alone makes it clear that the reported figures vary considerably. The following section briefly outlines the types of workplaces described in ICRP Publication 137 along with the associated assumptions regarding the exposure environment.

Indoor workplaces

The parameter values for the activity distribution of radon decay products at indoor workplaces (see Table A3 in ICRP 2017) are based primarily on measurements of Porstendorfer (2001) as well as on the results of studies conducted in residential buildings. The value of the equilibrium factor is influenced mainly by the indoor ventilation rate, which is controlled by the opening and closing of windows and the use of electric fans, air conditioning systems, and dehumidifiers. The average value of the equilibrium factor in schools, nurseries, offices, nuclear power plants, factories, and cafés is typically between 0.3 and 0.6. In 2000, UNSCEAR adopted an equilibrium factor of 0.4 for indoor environments (UNSCEAR 2000, Appendix B, (127)). The unattached fraction (f_p) of radon decay products is inversely proportional to the aerosol concentration in the indoor air and is therefore strongly influenced by ventilation and aerosol sources. For indoor workplaces, a mean value of $f_p = 0.08$ is assumed based on measurements from Porstendorfer (2001) and other studies in residential buildings (ICRP 2017, (A40)).

Mines

Characterising aerosol parameters in mines is difficult because of highly variable conditions such as different mining methods (use of diesel- or electrically powered equipment), varying ventilation rates, and the type of heating used during the winter months (ICRP 2017, Appendix A.5.2).

Under mining conditions, the inverse correlation between the equilibrium factor F and the unattached fraction of radon decay products f_p is less consistent than in indoor environments and tourist caves.

Tourist caves

In tourist caves (also known as show caves), mechanical ventilation is often avoided and air exchange occurs primarily through natural ventilation. Minimising air movement and air exchange is desirable to protect the cave environment, including its flora and fauna, geological formations, and cultural heritage. As a result, the radon activity concentration can reach levels of several thousand Bq m^{-3}. The equilibrium factor F varies widely and ranges from approx. 0.2 to 0.7 depending on the season, air exchange, and aerosol concentration. For modelling purposes, the ICRP specifies representative values of $f_p = 0.15$ and $F = 0.4$. These are considered to be moderate, realistic assumptions for tourist caves (ICRP 2017, Appendix A.5.3).

Waterworks and spas

Exposure conditions in water abstraction facilities and thermal spas are described in detail in the annex to ICRP Publication 137 (ICRP 2017), although reference parameter values are not provided. High levels of radon may occur in the air at water abstraction, treatment, and distribution facilities that treat or store groundwater with a high radon activity concentration. Relative humidity in such facilities has been reported to approach 100 % (ICRP 2017, Appendix A.5.4).

Thermal spas are used both as medical therapy and rehabilitation centres and for recreational purposes. Radon that escapes from thermal sources represents an additional radiation exposure for employees, patients and other visitors. Measurements have shown that the dominant pattern of radon release to air occurs during the filling of the bathtub. The average values for F and f_p have been reported for different types of thermal baths and vary depending on the location and specific operating conditions.

4.1.5 Reasons for the change of radon dose coefficients in ICRP Publication 137

The discussion in Sections 4.1.3 and 4.1.4 explains the large number of influencing factors, some of which are poorly characterised, that can affect the lung dose at given radon activity concentrations. This results in considerable uncertainty in the dose estimates. In the case of radon, the availability of large-scale epidemiological studies makes it possible to assess the plausibility of the assumptions made in the epidemiological model. In ICRP Publication 65 (ICRP 1993), an RDC of 1.4 mSv/(mJ h m^{-3}) or $F \cdot 7.8$ mSv/(MBq h m^{-3}) for workers was originally established based on epidemiological data from miner studies.

ICRP Publication 115 (ICRP 2010) took into account recent epidemiological data, particularly that relating to subgroups with relatively low exposure levels within various cohorts of miners. Furthermore, the dosimetric model was recommended as the preferred model for determining the RDC. This resulted in an almost doubling (by a factor of 1.82) of the radon risk coefficient ('nominal risk coefficient'). By applying this revised nominal risk coefficient of $F \cdot 8 \cdot 10^{-4}$/(MBq h m^{-3}) (cf. Figure 4.8) and taking into account the detriment from ICRP Publication 103 (ICRP 2007), a new RDC of $F \cdot 18.8$ mSv/(MBq h m^{-3}) or 3.3 mSv/(mJ h m^{-3}) was derived for workers in mines (ICRP 2017, (664)–(665)). The changes to the RDC in ICRP Publication 137 (ICRP 2017) were justified on the grounds that the derivation should be standardised in line with that for other radionuclides and should therefore be based not on epidemiological data but rather, by analogy, on the biokinetic and dosimetric model. However, this change has not yet been incorporated into German radiation protection legislation. One of the main arguments against its adoption was that, at that time, updated risk assessments for other major cohorts, particularly the Wismut cohort, were still pending (SSK 2017).

Table 4.5: Radon dose coefficients according to various ICRP publications/models for occupational exposure.

Radon risk coefficient for lung cancer mortality (lifetime excess absolute risk)		**Total detriment**	**Dose coefficient**		**Multiplier factor compared with ICRP Publica-tion 65**
1/(MBq h m^{-3})	1/(mJ h m^{-3})	1/mSv	mSv/ (MBq h m^{-3})	mSv/ (mJ h m^{-3})	
ICRP Publication 65 (ICRP 1993)		ICRP Publication 60 (ICRP 1991)			
$F \cdot 4.4 \cdot 10^{-4}$	$8.0 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$F \cdot 7.8$	1.43	-
ICRP Publication 115 (ICRP 2010)		ICRP Publication 60 (ICRP 1991)			
$F \cdot 8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$5.6 \cdot 10^{-5}$	$F \cdot 14.1$	2.5	1.7
ICRP Publication 115 (ICRP 2010)		ICRP Publication 103 (ICRP 2007)			
$F \cdot 8 \cdot 10^{-4}$ (cf. Figure 4.8)	$1.4 \cdot 10^{-4}$	$4.2 \cdot 10^{-5}$	$F \cdot 18.8$ (cf. Figure 4.8)	3.3	2.4
Biokinetic and dosimetric models (ICRP 2017) assuming a breathing rate of 1.2 m^3 h^{-1}					
HRTM, reference worker, mines			$F \cdot 18.8$	3.3	2.4
HRTM, reference worker, indoor workplaces			$F \cdot 31.3$	5.7	4.0
HRTM, reference worker, tourist caves			$F \cdot 37.5$	6.7	4.7
Recommendations in ICRP Publication 137 (ICRP 2017)					
Majority of all workplaces			$F \cdot 15.6$	3	2.1
tourist caves, heavy physical work			$F \cdot 31.3$	6	4.2

A distinction based on workplace categories was first made in ICRP Publication 137 (ICRP 2017) (Table 2.1 in SSK 2017). For the reference worker, a pattern of physical activity comprising approximately one-third of the working day spent sitting and two-thirds undertaking light physical activity is assumed. This results in a time-weighted mean ventilation rate of approximately 1.2 m^3 h^{-1} (ICRP 2017, (665)). For exposure in mines, this value is similar to the average breathing rate of 1.3 m^3 h^{-1}, which was derived from a study of 620 underground miners carrying out heavy work in a gold mine in South Africa (ICRP 1994, (B76)). This is also consistent with the breathing rates derived by Ruzer et al. (1995) for personnel (0.9 ± 0.4) m^3 h^{-1}, assistant drillers (1.1 ± 0.5) m^3 h^{-1}, and drillers (1.4 ± 0.5) m^3 h^{-1} who worked underground in an ore mine in Tajikistan (ICRP 2017, (A83)).

In ICRP Publication 137 (ICRP 2017), values of 5.7 mSv/(mJ h m^{-3}) for the reference worker indoors and 6.7 mSv/(mJ h m^{-3}) for show caves are calculated. In both cases, the same breathing rate as for miners was assumed but with an equilibrium factor of 0.4 instead of 0.2, and an 8- to 15-fold higher unattached fraction (0.08 (indoor workplaced), 0.15 (show caves) instead of 0.01 (mines)) (Figure 4.4). The higher equilibrium factor is due to the fact that mines have long been equipped with highly effective ventilation systems, whereas in indoor workplaces and in

show caves, air exchange and air movement occur to a far lesser extent. In these cases, the RDC with respect to cumulative radon activity concentration is $F \cdot 33$ mSv/(MBq h m^{-3}).

However, Harrison und Marsh (2012) suggest that the reference ventilation rate is too high for sedentary occupations such as office work. Assuming a lower breathing rate of 0.86 m^3 h^{-1} (two thirds of the time spent sitting and one third of the time in light exercise) would reduce the dose coefficient for radon and radon decay products with unchanged aerosol characteristics from $F \cdot 33$ mSv/(MBq h m^{-3}) or 5.7 mSv/(mJ h m^{-3}) to approx. $F \cdot 24$ mSv/(MBq h m^{-3}) or 4.1 mSv/(mJ h m^{-3}) (see Figure 4.4, Harrison und Marsh 2012). Dosimetric calculations using the same method result in a value of 3.7 mSv/(mJ h m^{-3}) for members of the public living in dwellings with high radon activity concentrations. Although this is mentioned in (ICRP 2017, (665)), no explicit reference is made to it in the 'Recommendations' chapter.

After rounding and simplification, ICRP Publication 137 (ICRP 2017) recommends two different RDCs: For mines and most radon exposure situations in buildings a coefficient of 3 mSv/(mJ h m^{-3}) or $F \cdot 17$ mSv/(MBq h m^{-3}) is to be assumed without further consideration of the specific aerosol characteristics (ICRP 2017, (667)). For indoor workplaces where workers are engaged in substantial physical activities (corresponding to the reference worker) and for workers in show caves, the doubled value of 6 mSv/(mJ h m^{-3}) or $F \cdot 33$ mSv/(MBq h m^{-3}) is considered appropriate (ICRP 2017, (668)).

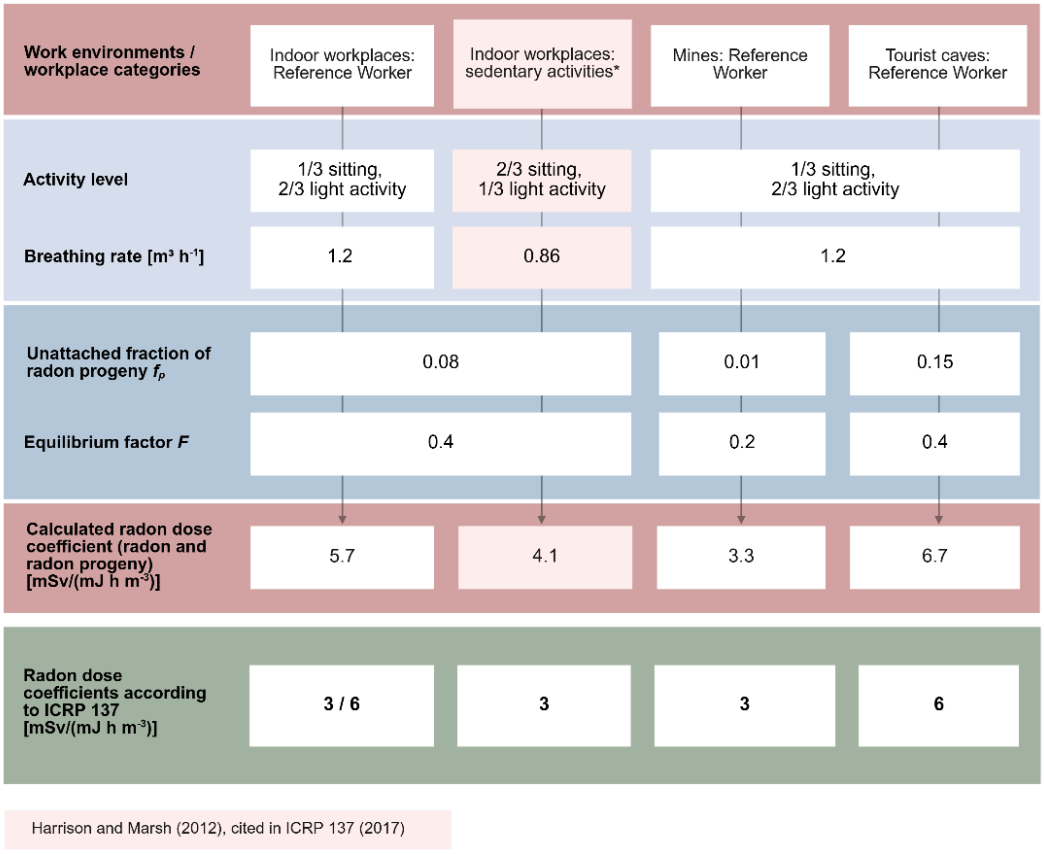

Figure 4.4: Overview of ICRP Publication 137: exposure situations, activity levels, and environmental parameters used to calculate radon dose coefficients (RDCs) according to the biokinetic/dosimetric model. The RDCs recommended in ICRP Publication 137 are highlighted in green: 3 mSv/(mJ h m^{-3}) for the majority of workplaces and 6 mSv/(mJ h m^{-3}) for tourist caves and indoor workplaces involving substantial physical activity (Created with BioRender.com).

No further justifiation is provided for the recommendation that the lower dose coefficient should be applied in all cases in which no further information on aerosol conditions is available (ICRP 2017, (667)).

Although the appendix discusses the specific situation in waterworks, there is no more detailed discussion of this point in ICRP Publication 137 (ICRP 2017). Specific model calculations for determining RDC for persons performing significant physical activity with a breathing rate of $1.7\ m^3\ h^{-1}$ are also not included in ICRP Publication 137.

The ICRP points out that, in cases where aerosol conditions differ considerably from those typically assumed and reliable aerosol data are available, the calculated dose requires detailed consideration. In such cases, site-specific dose coefficients may be calculated as explained in more detail in Appendix A of ICRP Publication 137 (ICRP 2017, (669)).

4.2 Scientific justification for answering the questions set out in the advisory mandate

4.2.1 Workplace categories and the effect of breathing rate

Because more than 95 % of the effective dose is attributable to the lung dose, physiological parameters related to respiration (see Sections 4.1.3.3, 4.1.3.4, and 4.1.3.5) as well as the parameters of the exposure environment (see Section 4.1.4) play a decisive role in the context of exposure to radon and radon decay products. Selecting appropriate reference parameters for calculating the RDC using the biokinetic/dosimetric model described in ICRP Publication 137 presents a number of challenges. Unlike regulated radiation protection areas (e.g. medicine, nuclear facilities, research), where exposure conditions are generally well controlled and relatively consistent, typical workplaces with high radon exposure exhibit considerable temporal and spatial variability in exposure conditions (see Section 4.1.4). For the corresponding underlying exposure scenarios (see Section 4.1.4) the modelled RDC differ for example by a factor of 2 with 3.3 mSv/(mJ h m^{-3}) for mines and 6.7 mSv/(mJ h m^{-3}) for tourist caves (Table 4.5).

To provide a practicable approach without requiring separate calculations for every workplace, the recommendation in ICRP Publication 137 distinguishes between only two workplace-specific categories. This difference is reflected in the recommendation in the values for the RDC of 3 mSv/(mJ h m^{-3}) for most workplaces and 6 mSv/(mJ h m^{-3}) for tourist caves as well as indoor workplaces with substantial physical activity. However, it is notable that the recommended values are lower than the corresponding values obtained from the case-specific model calculations (ICRP 2017, (665)).

The RDCs recommend in ICRP Publication 137 for most workplaces are approximately twice as high as those in ICRP Publication 65 (ICRP 1993). For reference workers in mines, the recommended values are consistent with those in ICRP Publication 115 (ICRP 2010). These estimates were based, among other factors, on the higher risk coefficients obtained from updated epidemiological studies of miners compared with those used in ICRP Publication 65.

The question therefore arises to what extent it is justified to assume an RDC of 3 mSv/(mJ h m^{-3}) for additional workplaces or to define workplace categories for which a higher RDC of 6 mSv/(mJ h m^{-3}) should apply.

One possible explanation for the recommendation of a lower RDC could be that it is based on the activity patterns assumed by Harrison und Marsh (2012) for the reference worker. The ICRP notes that the standard breathing rate of $1.2\ m^3\ h^{-1}$ assumed for predominantly sedentary occupations such as office work may be set too high. Studies by Harrison and Marsh suggest that a value of $0.89\ m^3\ h^{-1}$ would be more plausible for indoor office workplaces. If this reduced

breathing rate were applied, a lower dose coefficient of 4.1 mSv/(mJ h m^{-3}) would result for indoor workplaces. This adjustment of the breathing rate is not explicitly mentioned in the final recommendation for the RDC of 3 mSv/(mJ h m^{-3}) but is explained earlier in the chapter on the use of dosimetric data. The ICRP also states that for workers with increased physical activity, the higher RDC of 6 mSv/(mJ h m^{-3}) should be applied. This suggests that the reduction of the breathing rate may have contributed to the selection of lower RDC of 3 mSv/(mJ h m^{-3}) for most workplaces. Despite these adjustments, the reduced breathing rate alone does not fully explain the recommendation for a lower RDC of 3 mSv/(mJ h m^{-3}). Other factors that contributed to the formulation of the recommendation are not explicitly stated; making a detailed scientific assessment difficult.

The ICRP states that deviations from the reference conditions should be taken into account where sufficient data are available. However, in practice, the breathing frequency of workers is not recorded individually when determining radon exposure; this means that no specific measurement data are available for assessment. Different reference conditions can therefore be defined only for generalised reference scenarios. This raises the question of whether the new reference scenario for sedentary office work is more representative for assessing radon exposure at most workplaces than the previous scenario of predominantly standing light work.

Studies indicate that the proportion of office workplaces is steadily increasing as a result of digitalisation and automation. In 2022, around 18 million people (approx. 50 % of the working population) in Germany worked at office and computer workplaces (VBG 2022). Studies on sedentary occupations conducted in 2023 found that office workers spend an average of 7 h (80 % of their working hours) sitting down (Nöscher et al. 2023).

Based on the findings of these studies, the assumption of a reference worker with a pattern of physical activity comprising two-thirds light exercise and only one-third sitting no longer appears to apply to many modern workplaces in Germany. The reduced breathing rate proposed by Harrison und Marsh (2012) for predominantly sedentary occupations could therefore provide a more realistic basis for calculating exposure levels in most workplaces. This means that the estimated breathing rate is more reliable and less prone to fluctuations than the environmental parameters included in the model.

Directive 2013/59/Euratom (Euratom 2014) also expanded the range of workplaces subject to radiation protection requirements relating to radon. This affects many workplaces where radon exposure is not directly linked to the work being carried out; these include, presumably, many office workplaces.

Applying different dose coefficients according to the level of physical activity represents a departure from previous practice and would require a practical and consistently applicable methodology.

Unlike radon, the general reference worker for light work should continue to be used for dose conversion for other radionuclides without making any specific adjustments for different activities and, in particular, without reducing the breathing rate for sedentary office work. This presents an inconsistency in cases in which a uniform assessment of the inhalation doses of different radionuclides is required.

One possible solution could be to determine specific dose coefficients for other radionuclides as well based on adjusted breathing rates. This would be in line with the philosophy of the ICRP, according to which recognised deviations from the reference conditions should be taken into account. From a scientific point of view, this would be a consistent approach provided that the breathing rate on which the RDC is based is known. Implementing this would involve

considerable effort because a separate dose coefficient would have to be calculated for each nuclide based on the respective breathing rate.

Alternatively, in cases where exposure to radon must be assessed together with other radionuclides, a conservative dose coefficient for radon based on the reference worker breathing rate of 1.2 $m^3 h^{-1}$ could be assumed in order to allow doses to be formally added without inconsistent assumptions. If the radon dose coefficient derived for reduced breathing rates better reflects actual exposure conditions, the radon dose would be overestimated by a factor of two; this could lead to more extensive radiation protection measures that may not be proportionate to the actual need. However, in practice, it is reasonable to assume that, in the case of office work, simultaneous exposure to other radionuclides is likely to be very rare if it occurs at all.

4.2.2 Partical size, partical distribution

4.2.2.1 Introduction

According to simulations by Sakoda et al. (2010) based on the biokinetic model of Leggett et al. (2013), only about 1 % of inhaled radon gas enters the bloodstream so that under normal environmental conditions (e.g. without active filtration of decay products), more than 95 % of the effective dose in radon exposure is caused by the inhaled decay products (ICRP 2017). When inhaled, radon decay products accumulate in the respiratory tract and are transported or cleared via various mechanisms such as mucociliary transport, the lymphatic system, and the bloodstream. The transport rates for most of the decay products deposited in the respiratory tract are so low that, because of the short half-lives of the individual radon decay products (ICRP 2015), the decay products are not effectively absorbed into the body before the daughter nuclides in the respiratory tract have decayed. Combined with the high organ weighting factor for the lungs, the lung equivalent dose thus accounts for over 95 % of the effective dose from radon exposure (Khursheed 2000, Sakoda et al. 2012).

The following sections therefore examine in more detail the relationship between the size distribution of radon decay products and the influence of particle size on deposition in the respiratory tract. To this end, the nuclides ^{218}Po, ^{214}Pb, and ^{214}Bi are examined in more detail.

4.2.2.2 Human Respiratory Tract Model (HRTM)

A morphological model of the human respiratory tract (HRTM: Human Respiratory Tract Model) is described in ICRP Publication 66 (ICRP 1994) and updated in ICRP Publication 130 (ICRP 2015). In this classification, the respiratory tract is divided into five regions (Figure 4.5): the extrathoracic region (ET) is further subdivided into ET_1 (anterior nose) and ET_2 (oral and pharyngeal cavities, larynx). The thoracic regions are divided into bronchial (BB: trachea and bronchi), bronchiolar (bb, bronchioles), and alveolar–interstitial (AI, gas exchange region).

In each region, the efficiency of particle deposition can be estimated using various mechanisms depending on the particle size. The three dominant deposition mechanisms are: a) inertial impaction, b) sedimentation, and c) diffusion (Figure 4.6).

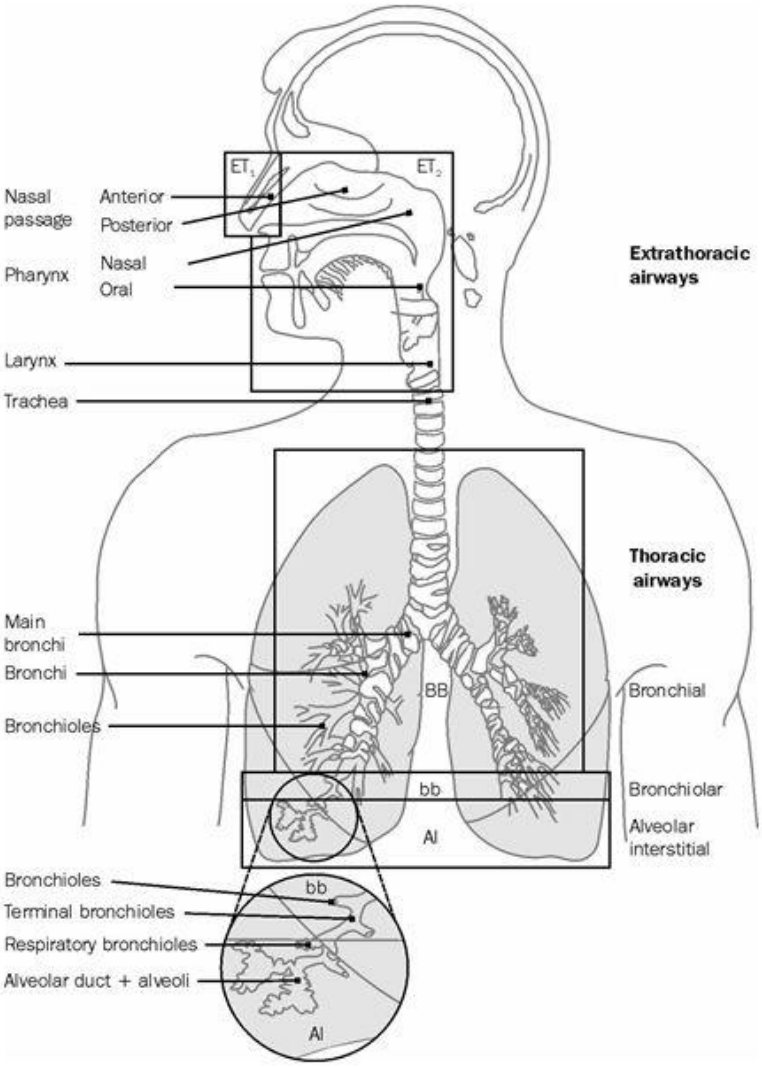

Figure 4.5: Anatomical regions of respiratory tract (ICRP 1994)

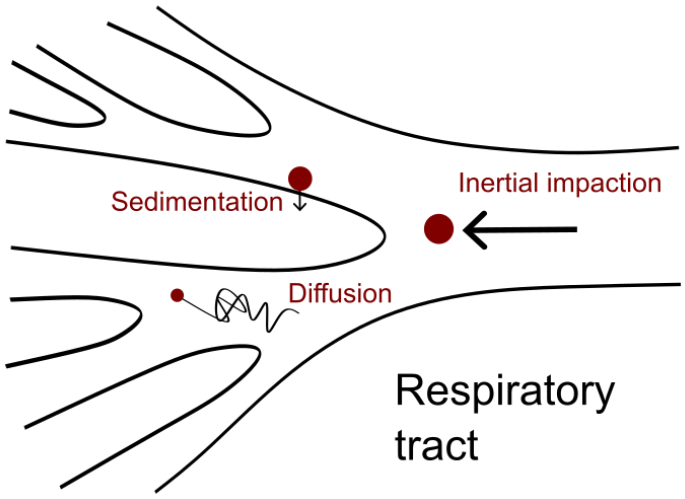

Figure 4.6: Schematic illustration of the deposition mechanisms in the respiratory tract

a) Inertial impaction occurs for particles with a diameter of 2–20 µm, primarily in the upper respiratory tract (ET_1, ET_2, partially BB) (see Figure 4.5).

b) Sedimentation during transport through the respiratory tract occurs with particle sizes of 0.1–50 µm. Larger and heavier particles are already captured in ET_2 and BB at high airflow velocities while lighter particles with diameters of 0.1–10 µm are captured in AI only at lower airflow velocities.

c) Diffusion occurs for particles with a diameter of less than 0.2 µm, whereby the mechanism becomes increasingly relevant as particle size decreases. Very small particles such as unattached decay products are deposited directly in the upper regions of the respiratory tract (ET_1, ET_2) because of their high diffusion coefficient. Larger particles (5–200 nm), which mainly fall within the nucleation mode 10–100 nm), are increasingly deposited in the alveolar region of the lung (AI) via diffusion at lower flow velocities (Stuart 1984, Hofmann 2011, Carvalho et al. 2011).

Particles with a diameter of 0.2 µm to 0.5 µm exhibit the lowest deposition rates, as they are too light for deposition processes such as inertial impaction, but too large to be effectively absorbed by diffusion.

The deposition model describes the deposition of aerosols in each of these regions and for different aerosol sizes ranging from 0.1 nm to 100 µm. In the extrathoracic regions, deposition probabilities measured for this purpose were correlated with parameters such as particle size and airflow and subsequently scaled against anatomical parameters in order to obtain deposition probabilities for other conditions. For the thoracic regions, a theoretical model of gas transport and particle deposition was used to determine the deposition in each of the regions. Deposition parameters are specified for three reference scenarios (sitting, light exercise, heavy exercise). A distinction is also made between occupational exposure and the general population broken down into different age groups (3-month-olds; children aged 1, 5, 10, and 15; and adults).

With regard to the inhalation of radionuclides by workers, the reference is taken to be an adult male performing light work who breathes through his nose. For occupational exposure, a value of 5 µm is recommended for the 'active median aerodynamic diameter' (AMAD). In this case, the regional distribution is shown in **Fehler! Ungültiger Eigenverweis auf Textmarke.**.

Table 4.6: Regional deposition of inhaled aerosols for the reference worker for an AMAD of 5 µm (values rounded).

Region	**Deposition [% of inhaled activity]**
ET_1	34.0
ET_2	40.0
BB	1.8
bb	1.1
AI	5.3
Total	82.2

The HRTM describes several *clearance* mechanisms of the respiratory tract. In the ET_1 area, particles are released into the external environment (e.g. through sneezing). In other regions, this occurs through transport mechanisms into the digestive tract or lymph nodes combined with absorption into the bloodstream. In this context, the transport rates for transport and absorption are considered independently of one another.

This assumes that the transport rates are the same for all materials. Where possible, reference values for transport constants were derived from studies involving humans because these vary considerably between different species.

In contrast, absorption depends on the physical and chemical state of the deposited material. It is assumed that this occurs at the same rate in all regions with the exception of ET_1, where no absorption is assumed.

Absorption is a two-stage process: Dissociation into substances that can be absorbed into bodily fluids (*dissolution*) and the absorption into bodily fluids itself (*uptake*). The clearance rates for these two processes may vary over time.

It is recommended that material-specific absorption rates be used for compounds for which reliable experimental data are available. For other compounds, standard values are recommended depending on whether absorption is fast (Type F), moderate (Type M), or slow (Type S).

The absorption types can be described in terms of approximate half-lives:

- Type F: 100 % absorption with a half-life of 10 minutes. Almost all of the deposited material is absorbed very rapidly in BB, bb, and AI and 50 % of the deposited material in ET_2 . The remaining 50 % from ET_2 is transported to the digestive tract via transport mechanisms.
- Type M: 10 % absorption with a half-life of 10 minutes and 90 % with a half-life of 140 days. There is very rapid absorption of approx. 10 % of the deposition products in BB and bb and 5 % of the deposition products in ET_2. Around 70 % of the deposition products in AI are excreted into bodily fluids.
- Type S: 0.1 % absorption with a half-life of 10 minutes and 99.9 % with a half-life of 7,000 days. There is virtually no absorption in ET, BB, or bb; approx. 10 % of the deposition products in AI pass into body fluids.

The small proportion of the deposition products that passes into the lymph nodes is subsequently absorbed into the bodily fluids at the same rate as in the respiratory tract.

For radionuclides inhaled as particles, the HRTM assumes that total and regional deposition in the respiratory tract depends on the size distribution of the aerosols.

The situation is different for gases and vapours; in this case, deposition depends solely on the chemical form. In this context, deposition refers to the amount of the inhaled substance that remains after exhalation because almost all inhaled gas molecules are exhaled again with the exception of those that dissolve in or react with the surface. The proportion of inhaled gases or vapours deposited therefore depends on their solubility and reactivity.

4.2.2.3 Dose coefficients

According to ICRP Publication 137 (ICRP 2017), different dose coefficients apply to radon decay products depending on the aerosol size distribution in the environment (see **Fehler! Ungültiger Eigenverweis auf Textmarke.**). The underlying aerosol size distributions for the different scenarios (indoor workplaces, underground mines, and show caves) and the resulting deposition in the different regions of the respiratory tract (which is ultimately decisive for the calculated dose coefficients) are given in Table 4.8.

Table 4.7: Dose coefficients for inhaled radon decay products. Values are given for different particle sizes in accordance with Section 4.1.1 (u: unattached mode, n: nucleation mode, a: accumulation mode) (ICRP 2017).

		Effective dose coefficients [Sv Bq^{-1}]		
Exposure scenario	**Mode**	**^{218}Po**	**^{214}Pb**	**^{214}Bi**
All	u	1.1E-08	6.1E-08	
Indoor workplace	n	3.8E-09	1.8E-08	1.5E-08
	a	1.3E-09	6.7E-09	5.9E-09
Mine	a	1.4E-09	6.7E-09	5.6E-09
Tourist cave	a	1.6E-09	7.9E-09	6.6E-09

Table 4.8: Deposition of inhaled radon decay products in various regions of the respiratory tract (ICRP 2017).

		Deposition in regions [%]*					
Exposure scenario	**Mode**	**ET_1**	**ET_2**	**BB**	**bb**	**AI**	**Total**
All	u	51.91	27.96	7.93	10.05	0.59	98.43
Indoor workplace	n	3.85	2.08	0.93	6.53	27.90	41.29
	a	10.68	5.75	0.60	1.42	9.05	27.51
Mine	a	3.16	1.70	0.41	2.16	9.94	17.37
Tourist cave	a	3.42	1.84	0.47	2.61	11.94	20.28

* The degree of precision of the values is given for computational purposes and does not reflect the certainty with which they are known.

The deposition of the decay products by means of the various mechanisms described above gives the values shown in Table 4.8. Because of the high diffusion constant, almost 100 % of the unattached decay products are deposited in the upper respiratory tract. Particles formed via nucleation are deposited mainly in the alveolar region through sedimentation while larger particles are deposited in the upper respiratory tract via inertial impaction and in the alveolar region via sedimentation.

ICRP Publication 115 (ICRP 2010) also refers to three major epidemiological studies on domestic exposure in Europe (Darby et al. 2005), North America (Krewski et al. 2006) and China (Lubin et al. 2004). The increased relative probabilities of developing lung cancer identified in the domestic and mining studies (see Section 4.2.3) are consistent with one another. However, these studies do not include any information regarding particle size distribution. Anyway, under these exposure conditions, monodisperse size distributions are not to be expected. Because these epidemiological studies involve different exposure scenarios, comparability of the results is limited (Müller et al. 2016).

4.2.2.4 Dose assessment according to ICRP-Publikation 137

The deposition of radionuclides depends on particle properties (e.g. size distribution) and the proportion of unattached decay products as well as on physiological conditions (e.g. tidal volume, breathing frequency, age of the person). The combination of these parameters results

in the characteristic deposition of radionuclides in the respiratory tract. The dose values for the radiation-sensitive areas of the respiratory tract are calculated together with the clearance rates. The volume-weighted mean of the energy dose applied to lung regions BB, bb, and AI gives the lung dose. The lung equivalent dose in Sv is calculated by multiplying by the radiation weighting factor for alpha particles, which is 20 (ICRP 2017).

As a general rule, the absorbed dose is inversely correlated with particle diameter because a smaller particle diameter leads to more effective energy deposition in the lower regions of the respiratory tract, see Appendix A.8.2 in ICRP Publication 137 (ICRP 2017). However, this does not apply to particles smaller than 3 nm; because of their higher diffusion coefficient, these are deposited in the less radiation-sensitive nasal and pharyngeal cavities. From there, they are removed via mucociliary transport at relatively high rates (Hopke 1996).

4.2.3 Epidemiological studies

Quantitative risk assessments in radiation protection are generally based on epidemiological studies. For most exposure conditions, the organ-specific dose-response relationships derived from the Life Span Study (LSS) (e.g. Ozasa et al. 2012 and Grant et al. 2017), i.e. the sum of all studies on Japanese atomic bomb survivors, form the main basis for determining quantitative risk variables, such as risk coefficients. These risk coefficients are specified for individual organs (e.g. including the lungs) and relate to external acute exposure consisting mainly of gamma radiation and a neutron component that can be modelled accurately; as a result, the exposure is distributed more or less uniformly, thereby leading to the same organ energy doses across all organs of the body. In contrast, the LSS does not provide any data on alpha radiation.

For radon exposures, however, the situation is significantly different. For radon, no dose-response relationship is known. Instead, epidemiological studies on radon risk are almost exclusively based on effects relationships related to radon exposure (in units of $\mathrm{Bq\,h\,m^{-3}}$, $\mathrm{J\,h\,m^{-3}}$, or WLM) or radon activity concentration (in units of $\mathrm{Bq\,m^{-3}}$), but not on radon dose (e.g. Darby et al. 2005 and Richardson et al. 2022).

Unlike most other internal exposures to individual radionuclides and their decay products, there are well-established exposure-response relationships for radon exposure derived from epidemiological studies; from these, a radon risk coefficient can be determined – at least in principle. However, this does not refer to a dose level but rather to the activity concentration or radon exposure. A radon dose is neither defined nor required in these studies.

The largest and most important study series on the occupational risk of radon is the pooled investigation of lung cancer among miners, the so-called PUMA studies, the current evaluation of which dates back to 2024 (Kreuzer et al. 2024). These studies primarily include the largest single cohort, the German Wismut cohort.

The ‘Pooled Uranium Miners Analysis’ (PUMA) study is the largest cohort of uranium miners and comprises 119,709 miners, 4.3 million person-years at risk, and 7,754 deaths from lung cancer. Using this dataset, estimates of the excess relative risk (ERR) of lung cancer mortality per cumulative exposure (in units of WLM) could be calculated. The ERR was analysed separately for groups by attained age, time since radon exposure, age at radon exposure, and exposure rate. In addition to the overall cohort, a ‘1960+’ subcohort was examined; this comprises miners who were recruited in 1960 or later and experienced chronically low radon exposures and exposure rates.

The lifetime excess absolute risk (LEAR) per cumulative radon activity concentration P_A was determined using different risk models but with identical evaluation methods: risk projection up to an age of < 95 years, an exposure scenario of approx. $1.3/F\ \mathrm{MBq\,h\,m^{-3}}$ per year (in the original literature 2 WLM per year) between the ages of 18 and 64, and mortality rates

representing a mixed European, American, and Asian population. The estimated $LEAR/P_A$ in the full PUMA cohort was approx. $8.5 \cdot 10^{-4} \cdot F/(\text{MBq h m}^{-3})$ (in the original literature: depending on the model choice, LEAR/WLM = $5.38 \cdot 10^{-4}$ or LEAR/WLM = $5.57 \cdot 10^{-4}$) and $LEAR/P_A = 11.8 \cdot 10^{-4} \cdot F/(\text{MBq h m}^{-3})$ in the '1960+' subcohort (in the original literature: depending on the model choice, LEAR/WLM = $7.50 \cdot 10^{-4}$ or LEAR/WLM = $7.66 \cdot 10^{-4}$)[13]. The LEAR estimates per radon exposure derived from risk models based on earlier publications of uranium miner studies range from $4 \cdot 10^{-4} \cdot F/(\text{MBq h m}^{-3})$ to $14 \cdot 10^{-4} \cdot F/(\text{MBq h m}^{-3})$. The risk assumed in ICRP Publication 65 (ICRP 1993) and which forms the basis for the RDC currently established in radiation protection legislation was only about half as high as suggested by the latest, expanded PUMA study.

The authors of the latest PUMA study rightly state that "*PUMA strengthens knowledge on the radon-related lung cancer LEAR, a useful way to translate models for policy purposes*". However, as is generally the case with all epidemiological studies on radon, the risk estimates from the PUMA studies always refer to exposure levels rather than dose levels. They can therefore certainly provide reliable risk estimates for the risk limitation required in radiation protection; however, they do not provide a link to the dose and thus do not form a basis for an RDC based on a dosimetric approach. The observation that the generally less exposed '1960+' subcohort yields higher risk estimates than the overall cohort, which includes higher exposure prior to 1960 (inverse dose effect), can, particularly at lower exposures, be used to support the assumption that the RDC currently established in radiation protection legislation has under-estimated the radon-associated risk.

It should be noted, however, that the findings of the PUMA studies on radon risk coefficients, while providing a valuable basis for risk estimations, were not based on a dosimetric approach for the determination of dose coefficients.

The LEAR values of the above-mentioned PUMA study can be converted to WLM using the following formula:

$$1\ \text{WLM} = \frac{0.64}{F}\ \text{MBq h m}^{-3} \tag{14}$$

This gives the *LEAR* per cumulative radon activity concentration P_A for the overall cohort and for the '1960+' subcohort:

$$LEAR/P_A = F \cdot 8.5 \cdot 10^{-4}/(\text{MBq h m}^{-3})$$

or

$$LEAR/P_A = F \cdot 11.8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) \tag{15}$$

In particular, the value for the full cohort corresponds remarkably closely to the corresponding value from ICRP Publication 115 (ICRP 2010), which is given there as $5 \cdot 10^{-4}$/WLM and can be converted to $F \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3})$. Using these values and based on certain assumptions regarding the duration of exposure and the equilibrium factor *F*, a risk coefficient for radon can be calculated.

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[13] Unfortunately, most international studies, including the PUMA study discussed here, use the highly cumbersome (and inadmissible) non-SI unit WLM. The conversion to permissible exposure limits can be found in the glossary. Furthermore, there is an incorrect mixing of quantities and units (LEAR is a quantity, and WLM is a unit). To be correct, the relationship quoted in brackets in the original should be stated as follows: $LEAR/P_{PAEC} = 5.38 \cdot 10^{-4}$/WLM. In the text that follows, the relevant terms are reproduced accurately.

The above-mentioned epidemiological studies indicate risks for uranium miners and can be extrapolated to people in indoor environments with radon exposure; this finding is also supported by the results of indoor studies (Darby et al. 2005). However, according to the ICRP, the risk coefficient is applicable only to light physical activities carried out indoors. There are no relevant epidemiological studies for 'heavy physical work' carried out indoors or for work in show caves for which the ICRP recommends the use of different risk coefficients; given the relatively small number of people employed in these sectors, such studies are unlikely to be available in the foreseeable future. However, the SSK considers it justified to apply the radon risk coefficient (risk per unit of exposure) derived from studies of miners and people engaged in light exercise indoors to the other occupational situations mentioned as well. On one hand, the epidemiological data from which the risk coefficient used here was derived are subject to uncertainty (see, for example, the differences within the PUMA study between the overall cohort and the '1960+' cohort). On the other hand, the alternative to a broader application of the risk coefficient established for certain groups would be to estimate risks using the ICRP radon dose model, which, in the opinion of the SSK and as discussed in more detail elsewhere in this document, is based on a number of inadequately justified assumptions and has considerable margins of uncertainty.

4.2.4 Transfer to other occupational areas

A key question is whether the RDC of 3 mSv/(mJ h m^{-3}) set for the majority of all workplaces is sufficiently conservative, given that case-specific modelling consistently yields higher values (ICRP 2017, (665)).

The wide variations in environmental parameters highlight the fact that the assumptions underlying the model are subject to considerable uncertainty. Given the variability observed, the RDCs calculated could be considerably higher in many cases.

The model results of the ICRP (see Table 4.5) yielded higher values in many cases than the stated RDC value of 3 mSv/(mJ h m^{-3}) for most workplaces so that insufficient conservatism could be assumed. By contrast, epidemiological data from studies of miners and on domestic exposure suggest that this figure is reasonable in the context under consideration.

Against this background, the question arises whether a uniform 'worst-case scenario' RDC of 6 mSv/(mJ h m^{-3}) represents a practical approach.

Using an RDC of 6 mSv/(mJ h m^{-3}) would lead to considerably higher risk estimates than can be derived from epidemiological studies (ICRP 1993, ICRP 2010, cf. Table 4.5). However, epidemiological data are available only for uranium mining and for indoor environments without 'substantial physical activity' and therefore not for those exposure situations for which the higher RDC is recommended. The assumption of the higher RDC therefore depends to a large extent on the robustness of the ICRP dose model.

It should also be borne in mind that with such a high RDC, the calculated doses associated with radon would increase significantly – by a factor of 4.2 compared to the current dose conversion. This could entail the risk of overregulation and have far-reaching consequences for practical radiation protection.

In summary, it can be concluded that, when considering exclusively the underlying data used by the ICRP for model derivation, neither an RDC of 3 mSv/(mJ h m^{-3}) nor an RDC of 6 mSv/(mJ h m^{-3}) alone represents a fully convincing approach for a uniform radon dose conversion. While a lower value may not be sufficiently conservative, a higher value may lead to systematically enhanced dose estimations and potential overregulation. Against this back-

ground, the question arises as to whether the introduction of multiple dose conversion coefficients, as opposed to the use of a single RDC, provides an additional level of safety that justifies the associated methodological and regulatory burden.

Furthermore, the question arises whether the approach of using a single RDC is appropriate given the considerable variations in environmental parameters (e.g. aerosol characteristics) or a more nuanced assessment would be advisable. However, it would also be necessary to check whether there is sufficient reliable data available to support such a distinction. In practice, this proves to be virtually impossible for most workplaces because collecting detailed aerosol data involves considerable effort and high costs.

Studies have shown that assessing exposure conditions by categorising workplaces according to activity or industry sector is not particularly effective (Schulz et al. 2024, Martin-Gisbert et al. 2023, Lee et al. 2023). It has become apparent that these categories do not adequately reflect the actual influencing factors because exposure to radon and its decay products depends on numerous variable factors. The study by (Schulz et al. 2024) found that it is not possible to distinguish between indoor workplaces based on the properties of the materials or processes involved. The key factors determining exposure are, rather, the ingress of radon-containing air into the building, ventilation practices (e.g. opening doors and windows or the use of active ventilation systems) and, in some cases, work processes that generate dust (Lee et al. 2023). The authors therefore concluded that classifying indoor workplaces by industry sector or occupational group would not be effective. They propose using ventilation conditions as a relevant criterion and the specific location of the workplace within a building to assess the exposure environment.

From the above, an approach that enables effective protection against radon without requiring complex site-specific calculations for every workplace must be identified. On the other hand, it is clear that the parameters underlying the RDC can be standardised only to a limited extent. The aim of radiation protection is to provide the best possible protection for those exposed. The purpose of determining the RDC is ultimately to estimate risk by calculating the dose.

As shown above in Section 4.1.5, two different dose coefficients for radon are recommended in ICRP Publication 137 (ICRP 2017). For mines and buildings ‘in most cases’ a coefficient of 3 mSv/(mJ h m^{-3}) is to be assumed (see (667)). For indoor workplaces where workers are engaged in substantial physical activity and for workers in show caves, the doubled value of 6 mSv/(mJ h m^{-3}) is considered appropriate (see (668)).

However, the ICRP also points out that, in cases where the aerosol properties deviate considerably from typical conditions, sufficient and reliable aerosol data are available, and the estimated doses require more detailed consideration, site-specific dose coefficients may be calculated (see (669)).

Section 4.2.4.2 outlines how dose coefficients have been implemented in accordance with ICRP Publication 137 in a number of European countries. The existing workplace categories in Germany that are to be covered by an SSK recommendation are listed in Section 4.2.4.3.

In this situation, ignoring a factor of 2 (applying 3 instead of 6 mSv/(mJ h m^{-3})) would indeed not be ‘conservative ’. As explained above, the coefficient of 3 mSv/(mJ h m^{-3}) is supported by epidemiological studies for both miners and individuals living in dwellings with elevated radon levels. However, no relevant studies have yet been conducted on workers in show caves or in indoor settings involving higher levels of exercise. Given the small number of people affected, the statistical quality of such studies would be hardly comparable to that of studies on miners. The higher dose coefficient is therefore subject to even greater uncertainty from the models used to calculate internal doses than the lower one.

4.2.4.1 (International) statement and perspectives

In its recommendation 2024/440 (EC 2024), the European Commission has stated that the latest ICRP publications and all the dose coefficients contained therein should be used as a basis for estimating the effective dose and the equivalent dose resulting from internal exposure within the meaning of Directive 2013/59/Euratom (Euratom 2014). The recommendation was made based on the opinion of the Article 31 Euratom Treaty Expert Group on the updated dose coefficients. In its statement of 28 June 2023 (EC 2024, (6)), the expert group emphasised that the series of ICRP publications are unique at the international level in terms of their advanced methodology and their application to a wide range of radionuclides and that they represent the state of the art in this field. The expert group therefore recommended the use of the updated dose coefficients. The expert group acknowledged that ICRP Publication 137 (ICRP 2017) contains changes to the methodology and dose coefficients for certain radionuclides, such as radon; these may present challenges in practical implementation and necessitate further discussion and an exchange of experiences regarding these challenges.

In 2020, the Inter-Agency Committee on Radiation Safety (IACRS) published information on 'Managing Exposure due to Radon at home and at work'[14]. The key messages and summary state, among other things, the following points with regard to the use of the dose coefficients:

- *The October 2019 IAEA Technical Meeting on the Implications of the new DCFs[15] for radon, recommended the use of a DCF of 10 mSv per working level month (WLM) (ICRP 2017) as the default for workplaces unless a different DCF is justified by specific aerosol characteristics.*
- *For planned exposure situations, where worker dose assessment is required for ensuring compliance with the dose limits provided in GSR Part 3, national authorities may choose to use a DCF that most accurately reflects the actual situation in the respective workplace, in particular taking into account the most relevant equilibrium factor F and aerosol characteristics.*
- *It is up to individual national authorities to decide if and when to implement this new DCF for radon. This could be done immediately, but it may be practical to do so once the full set of revised DCFs for workers are available to ensure a consistent approach for all radionuclides. Alternatively, national authorities may decide to apply a DCF other than that recommended by ICRP justified by specific aerosol characteristics.*

The IACRS therefore refers to the fact that the IAEA recommends the RDC of ICRP Publication 137 of 10 mSv/WLM (corresponding to 3 mSv/(mJ h m^{-3})) as the default value for workplaces. This approach is recommended unless specific aerosol characteristics justify the use of a different dose coefficient. It also states that national authorities will decide whether and when the new RDCs for radon should be implemented and that other factors may also be justified by specific aerosol concentrations. The deviation from the ICRP 'standard' RDC refers here solely to the aerosol characteristics. Differences relating to breathing rates or physical activity indoors are not discussed here.

For Member States of the European Union, the implementation of Directive 2013/59/Euratom (Euratom 2014) is mandatory; the relevant recommendations of the European Commission thus take precedence over those of the IACRS.

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[14]http://www.iacrs-rp.org/products/IACRS%20Radon%20Information%20Overview%20FINAL%20-%2024_07_2020.pdf

[15]The RDC is referred to by the IACRS as the 'dose conversion factor' (DCF).

4.2.4.2 Situation in other European countries

The WG3-S3 working group of the European Radiation Dosimetry Group (EURADOS) has launched a survey on the national status regarding the RDCs in use as well as radon reference and limit values in workplaces and buildings. The survey ended in February 2024 and was completed by respondents from 14 countries: Austria (AT), the Czech Republic (CZ), Finland (FI), France (FR), Germany (DE), Hungary (HU), Italy (IT), Poland (PL), Serbia (RS), Slovenia (SI), Sweden (SE), Spain (ES), Switzerland (CH), and the United Kingdom (UK). With the exception of Serbia and Sweden, all countries have established a reference level of 300 Bq m^{-3} for workplaces (see Table 4.9). In addition to the reference level of 300 Bq m^{-3} for workplaces, Switzerland has defined a threshold value of 1,000 Bq m^{-3} that applies at radon-exposed workplaces.

The general limit value for the effective dose is usually 20 mSv a^{-1}. In seven countries, the specified dose coefficients are based on ICRP Publication 137 (ICRP 2017); however, these are applied differently, and workplaces are classified differently. Other ICRP publications used include ICRP 65, ICRP 115, and ICRP 103 (see Table 4.9). Further details on the implementtation of ICRP Publication 137 in individual countries are provided below.

Austria

In Austria, the Radon Protection Ordinance (BMK 2020b, Annex 3 C) laid down the procedures for dose estimation and ongoing dose assessment in accordance with the Radiation Protection Act (BMK 2020a) in 2020. For the dose coefficients to be used, reference is made to ICRP Publication 137 (ICRP 2017), and states that for most cases, when calculating the effective dose at an equilibrium factor of 0.4, a dose coefficient of $6.7 \cdot 10^{-6}$ mSv/(Bq h m^{-3}) is to be applied. This facilitates a simple application in most cases involving workplaces subject to these requirements (indoor workplaces, waterworks, underground workplaces) where no more detailed information or measurement data is available (e.g. the equilibrium factor or breathing rates). However, the regulation also allows the use of other dose coefficients for show caves and workplaces with increased physical activity as recommended in ICRP Publication 137 or for workplace-specific dose coefficients determined under particular conditions. This is also set out and recommended in the explanatory notes to the Radon Protection Ordinance.

In Austria, dose estimation or dose assessment must be carried out by authorised, accredited monitoring bodies responsible for assessing workplace conditions and selecting the appropriate dose coefficient for the calculation. Of course, the authorities can also make decisions or issue guidelines on this matter.

The Czech Republic

In the Czech Republic, all workplaces with a potential for increased radon exposure and where employees work at least 100 h per year are required to carry out a radon measurement.

In 2022, the dose coefficients from ICRP Publication 137 (ICRP 2017) were published in a notice issued by the State Office for Nuclear Safety (SONS). It specifies a dose coefficient of 6.7 nSv/(Bq h m^{-3}) for workplaces with sedentary occupations and for mines, and 13 nSv/(Bq h m^{-3}) for workplaces with increased physical activity and for caves.

Table 4.9: Overview of reference levels and their relationship to ICRP guidelines for dose coefficients in various European countries (based on a survey conducted by the EURADOS WG3-S3 working group in February 2024).

	AT	**CZ**	**FI**	**FR**	**DE**	**HU**	**IT**	**PL**	**RS**	**SI**	**SE**	**ES**	**CH**	**UK**
Reference level [Bq m^{-3}]	300	300	300	300	300	300	300	300	1 000	300	200	300	300, 1,000 (Thres-hold value)	300
Reference for RDC	ICRP 137	ICRP 137	ICRP 137	ICRP 137	ICRP 65	ICRP 137	ICRP 137	ICRP 65	ICRP 65	ICRP 137	ICRP 115, ICRP 103	ICRP 137	ICRP 115	ICRP 65
Implementation of ICRP Publication 137 – Distinction based on workplace category	per-mitted	yes	per-mitted	yes		yes	no			yes		yes		

A guideline of the State Office for Nuclear Safety (SONS) provides a more detailed characterisation of workplace types. For the 'indoor' workplace type, different equilibrium factors are applied depending on the nature of the workplace: standard environment ($F = 0.4$), dusty environment ($F = 0.7$), environment with forced ventilation ($F = 0.4$), and caves (with low aerosol concentration, 'dust-free environment', $F = 0.4$). The classification here is based on the type of workplace or environmental conditions rather than the nature of the work (e.g. predominantly sedentary). There is no information regarding specific breathing rates at the classified workplaces. The guideline is to be incorporated into the next revision of the legal provisions in 2025.

France

In France, a new decree published in November 2023 sets out the procedures for calculating effective doses and equivalent doses resulting from human exposure to ionising radiation; it also regulates the radon dose coefficients (MTE 2023).

The dose coefficient depends on the type of workplace and is divided into two categories:

- Indoor workplaces where employees mainly carry out sedentary occupations (e.g. tertiary sector/services, offices): 3 mSv/(mJ h m^{-3}).
- Indoor workplaces where workers predominantly perform non-sedentary occupations (substantial physical activity such as construction work, maintenance, and repair work): 6 mSv/(mJ h m^{-3}).

The distinction here is therefore based on the nature of the work (predominantly sedentary or non-sedentary) and does not classify the workplaces themselves. The regulation makes no mention of specific breathing rates or the equilibrium factor.

Hungary

In Hungary, the application of the dose coefficient is governed by a regulation published by the Hungarian Atomic Energy Authority. The decree sets out the following requirement: When calculating the dose resulting from the inhalation of radon and its decay products, the latest version of the relevant ICRP publications must be used. In this case, it is ICRP Publication 137 (ICRP 2017).

Radon dose is monitored at only a few workplaces in Hungary using the latest RDCs recommended by the ICRP. Where necessary, working hours in the relevant work areas were reduced as a measure to ensure compliance with the annual dose limit.

Italy

In Italy, the dose coefficient of $6.7 \cdot 10^{-6}$ mSv/(Bq h m^{-3}) (corresponding to 3 mSv/(mJ h m^{-3})) from ICRP Publication 137 (ICRP 2017) at an equilibrium factor of 0.4 was incorporated into legislation (DPC 2020) in 2020. No other situations are specified, and no classification or characterisation of workplaces is carried out. A dose estimation or calculation is carried out only if the radon activity concentration in the workplace cannot be reduced below the reference value.

Slovenia

In Slovenia the dose coefficient of 3 mSv/(mJ h m^{-3}) or $6.7 \cdot 10^{-6}$ mSv/(Bq h m^{-3}) from ICRP Publication 137 (ICRP 2017) is applied without additional consideration or adjustment of aerosol characteristics for most indoor workplaces and underground mines. For indoor workplaces where workers perform substantial physical activity and for tourist caves the coefficient of 6 mSv/(mJ h m^{-3}) or $1.4 \cdot 10^{-5}$ mSv/(Bq h m^{-3}) is used.

Where the exposure of workers may exceed an effective dose of 6 mSv, additional measurements of aerosol characteristics are always carried out in order to assess whether these differ considerably from typical conditions. If the conditions do not correspond to typical conditions, the measured parameters are used to calculate the dose. This also takes into account the type of work (e.g. breathing rate).

Specific location-dependent coefficients based on additional measurements of aerosol characteristics have been calculated for two tourist caves in Slovenia (Postojnska jama and Škocijanska jama), where dose coefficients of 4.5 mSv/(mJ h m^{-3}) or $1.0 \cdot 10^{-5}$ mSv/(Bq h m^{-3}) are applied.

Spain

In Spain, the Nuclear Safety Council signed and published a resolution setting out the dose coefficients for internal exposure in April 2024. This stipulates that the effective dose coefficients for internal exposure from ICRP Publications 130, 134, 137, 141, and 151 (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022) are to be used for workers exposed to radiation in the course of their work. Specific criteria for the use of effective dose coefficients for internal radon exposure are set out in the annex to the document.

The following radon dose coefficients should be used as standard for radon exposure:

- 3 mSv/(mJ h m^{-3}) in most indoor environments (workplaces and apartments).
- 6 mSv/(mJ h m^{-3}) in tourist caves and at workplaces where workers perform intensive physical activity (e.g. manual shovelling or manual handling of loads).

If the characteristics of aerosol distribution in the air differ considerably from the norm, the Nuclear Safety Council may authorise the use of workplace-specific dose coefficients based on ICRP Publication 137, Part 3.

Spain has thus adopted the recommendation of the European Commission of February 2024 (EC 2024) on the use of ICRP dose coefficients for estimating effective dose and equivalent dose within the framework of Directive 2013/59/Euratom (Euratom 2014). With regard to radon, Spain has adopted ICRP Publication 137 (ICRP 2017), which specifies a dose coefficient for most cases and sets a specific value for tourist caves and workplaces involving heavy exercise. Where aerosol distribution differs, the use of workplace-specific dose coefficients must be approved by the competent authority. Specific breathing rates are not discussed.

Examples of countries that refer to radon exposure rather than effective dose

Sweden (from Finne et al. 2024 and Turtiainen et al. 2024)

In Sweden a radon activity concentration of 200 Bq m^{-3} applies as the reference level for workplaces in existing buildings (SFS 2018a). If the concentration at a workplace exceeds the reference level and cannot be reduced to below the reference level even with the implementation of measures, a report must be submitted to the Swedish Radiation Safety Authority (SSM).

Because the calculated mean annual radon activity concentration derived from long-term measurements may overestimate the radon activity concentration during working hours (e.g. where ventilation is used less frequently or not at all outside working hours), an assessment of the radon activity concentration during working hours may be carried out if the reference level is exceeded. To this end, a follow-up measurement is carried out at one or more points. The measurement is carried out using a time-resolved measuring device capable of recording and distinguishing between radon activity concentrations during and outside working hours. The measurement period must be at least seven days, five of which must be working days. This can

then be used to calculate the mean annual radon activity concentration during working hours (C_a):

$$C_a = c_1/c_2 \cdot C_{LT}$$

c_1: mean radon activity concentration during the working hours of the follow-up measurement.

c_2: mean radon activity concentration over the entire duration of the follow-up measurement.

C_{LT}: mean radon activity concentration from passive long-term radon measurement (measurement period of at least two months).

If the reference level is exceeded, the annual radiation exposure to radon must be assessed for each employee.

These values must then be compared with the maximum permitted levels or hygiene limits (AFS 2018). These depend on the type of workplace:

- Underground work (e.g. mines, underground construction work, rock caverns, tunnels): 2.1 MBq h m^{-3}.
- Other underground works (e.g. rooms carved into the rock, cellars): 0.72 MBq h m^{-3}.
- Above ground: 0.36 MBq h m^{-3}.

If the calculated annual radon exposure of employees at a respective workplace exceeds the hygiene limit, measures must be taken to reduce exposure (in accordance with AFS 2018). Further optimisation of radon exposure must be carried out in accordance with (SFS 2018b).

Notification to the authority is required if the reference value or a radon exposure of 0.72 MBq h m^{-3} is exceeded.

To establish a link to dose, the regulation for radon at workplaces (SSM 2018), which is based on ICRP Publication 103 (ICRP 2007) and ICRP Publication 115 (ICRP 2010), assumes that the annual dose of 6 mSv used for assessment in the European Basic Safety Standards (EU-BSS, Euratom 2014) corresponds to an annual radon exposure of 0.72 MBq h m^{-3} at an equilibrium factor of $F = 0.4$.

For most workplaces, it is not necessary to calculate an effective dose. Nevertheless, for workers carrying out activities in planned exposure situations, radon exposure must be taken into account when determining the total annual effective dose for comparison with the effective dose limit (EC 2020).

Sweden has not (yet) specified any dose coefficients in its regulations. As of June 2024, SSM was still in the process of evaluating the various dose coefficients proposed by the ICRP and UNSCEAR and had not yet made a final decision on which coefficient to use.

(SSM 2018) indicates that the radon dose can be calculated in various ways. However, there is neither a requirement nor a recommendation regarding which dose coefficients should be used nor how the effective dose from radon exposure should be estimated. The dose estimation should be carried out by the body responsible for monitoring the workplace in the planned exposure situation (Turtiainen et al. 2024).

Finland (from Finne et al. 2024 and Turtiainen et al. 2024)

In Finland, the reference level for workplaces is 300 Bq m^{-3} if the working time at the workplace exceeds 600 h per person per year. If the working time per person at a workplace is less than 600 h per year, the radon activity concentration may exceed 300 Bq m^{-3}, and the assessment is then based on radon exposure. The reference level for radon exposure is 0.5 MBq h m^{-3} per year.

If a ventilation system exists at the workplace which is operated outside working hours with low performance or not operated at all, an additional time-resolved measurement with a measurement period of one week may be carried out in addition to the original integrated measurement. The radon activity concentration during working hours (C_a) is then calculated from the following, including the correction factor of 0.9 specified in the legal text:

$$C_a = c_1/c_2 \cdot C_{LT} \cdot 0.9$$

c_1: mean radon activity concentration during the working hours of the follow-up measurement over a one-week measurement period.

c_2: mean radon activity concentration over the entire measurement period (one week) of the follow-up measurement.

C_{LT}: mean radon activity concentration from passive long-term radon measurement (measurement period of at least two months).

If the radon activity concentration cannot be reduced below the reference level, the operator must apply for a 'safety licence' in line with the requirements for planned exposure situations. Licensing is already required when the reference value is exceeded and not only from 6 mSv a^{-1} as provided for in Article 35 (2) of the EU-BSS (EC 2020, Turtiainen et al. 2024). In these planned exposure situations, a limit of 20 mSv for the effective dose is applied. Where there are several licensed activities (including radon), these are considered together, and the doses are summed (EC 2020).

Finland has adopted ICRP Publication 137 (ICRP 2017), and Annex 3 of the Government Decree on Ionising Radiation (1034/2018) (Finlex 2018) sets out the methods for dose assessment. A dose coefficient of 3 mSv/(mJ h m^{-3}) is specified for workplaces and dwellings. Other dose coefficients may be used if supporting studies or international guidelines indicate that they are justified. The ICRP recommendation of 6 mSv/(mJ h m^{-3}) for substantial physical activity has not been adopted in (Finlex 2018, Turtiainen et al. 2024).

As of May 2024, only one workplace had been granted a licence to exceed the reference level for radon exposure (Turtiainen et al. 2024).

Belgium

In Belgium the assessment of whether an employee is classified as occupationally exposed to radiation is carried out either based on an annual radon exposure of 0.6 MBq h m^{-3} (2,000 h at 300 Bq m^{-3}) or an effective dose of 6 mSv per year (FÖD 2001, Art. 20.3). As a first step, exposure is normally calculated, and, if the limit is exceeded, measures are taken to reduce it. The obligated persons may also calculate the dose if they can justify the use of a specific equilibrium factor or have measured it.

For dose calculation, it is planned to use the RDC from ICRP Publication 137 (ICRP 2017) (specified in Annex 3, FÖD 2001, currently under revision), namely 3 mSv/(mJ h m^{-3}), unless additional available aerosol data or specific conditions (e.g. intensive physical activity) justify a different factor.

For tourist caves, Belgium does not currently follow the recommendation of ICRP Publication 137 to use a dose coefficient of 6 mSv/(mJ h m^{-3}) because there are not yet sufficient data to confirm or justify the conditions underlying the calculations (equilibrium factor, 'unattached fraction') for Belgium. For this reason, exposure is also used here to assess and regulate the working conditions of staff in show caves (see above). Because the radon activity concentration in these properties cannot usually be reduced, exposure is managed by limiting the time spent there.

4.2.4.3 Workplaces in Germany subject to mandatory radon measurement and dose assessment

According to Section 127 StrlSchG (2017), the requirement for an initial radon measurement applies only to a selection of workplaces in Germany (see also Section 4.3.3.1): on the ground floor and in basements in radon precautionary areas and in workplaces listed in Annex 8 of the Radiation Protection Act.

The radon precautionary areas in Germany were designated by the federal states in accordance with the provisions of Section 153 StrlSchV (2018). Radon precautionary areas exist only in the federal states of Baden-Württemberg, Bavaria, Lower Saxony, Saxony, Saxony-Anhalt, and Thuringia and affect just 210 municipalities in Germany (approx. 2 % of all municipalities covering around 2.4 % of the country's total area). It is likely that radon activity concentrations exceeding the reference level will occur only at some workplaces. Based on experience to date (in accordance with the radon measurement data portal of the BfS with approx. 24,000 reports), the reference level is exceeded in around 16 % of the indoor workplaces measured. For indoor workplaces, it will, in most cases, be possible to reduce exposure levels below the reference level through (structural) measures. It is therefore likely that dose estimation – and thus the application of a dose coefficient – will be required only for a small number of indoor workplaces.

It is very difficult to estimate which workplaces are located on the ground floor and in the basement in radon precautionary areas, what conditions prevail there, and what types of work or activities are carried out (sedentary, non-sedentary, breathing rates, aerosol distribution, equilibrium factors).

The areas where measures are mandatory throughout Germany (including outside radon precautionary areas) also include facilities for water abstraction, treatment, and distribution. In this regard, ICRP Publication 137 (ICRP 2017) does not indicate any specific dose coefficients. However, there is a section on studies and findings in waterworks (IRCP 2017, Appendix A.5.4), see Section 4.1.4, particularly in Germany. Radon activity concentrations in water supply facilities have been studied in detail in Bavaria (Trautmannsheimer 2002). Although equilibrium factors and aerosol concentrations were not investigated, the final report does cite an average equilibrium factor of 0.5 from the literature.

Because water supply facilities can contain quite high radon activity concentrations, it is likely that dose estimations will need to be carried out and a dose coefficient applied. However, the time spent in these parts of the facilities is often short for control purposes and is decreasing further with increasing automation. In some cases (e.g. when carrying out cleaning work in larger facilities), the level of physical exercise may well be higher, and a higher dose coefficient may be justified for these activities. In the study conducted in Bavaria cited in ICRP Publication 137 (Trautmannsheimer 2002), workers were also monitored with personal exposimeters during tank cleaning operations. High radon exposures (approx. 2 MBq h m^{-3}, the value considered as the intervention reference level at that time) were found in only two of the 19 water supply facilities investigated while all others were below 0.2 MBq h m^{-3}. The report also includes details of mean times of stay in various parts of the facility. The entries in the Radiation Protection Register (BfS 2023, BfS 2025b) show that approximately one quarter of monitored individuals or those with measurable exposure at radon workplaces are employed in water abstraction and water treatment facilities (In the case of show mines and show caves, it should be borne in mind that natural ventilation caused by seasonal temperature variations can create conditions similar to those of forced ventilation; these, in turn, could affect the working environment for those employed there.

Fehler! Ungültiger Eigenverweis auf Textmarke. provides an overview of the number of employees who in 2023 were classified into the categories mentioned above based on entries in the Radiation Protection Register (BfS 2025b).

Table 4.10).

According to the European Association of Radon Spas (EURADON), there are nine radon spa resorts in Germany. Although ICRP Publication 137 (ICRP 2017) does not recommend any specific dose coefficients for thermal spas or spas, it does include a section on studies (A 5.4, see Section 4.1.4) that demonstrate equilibrium factors in the range of 0.15 to 0.6. In radon spas, radon activity concentrations may well exceed the reference level; however, the principle that radon exposure for workers must be kept as low as reasonably achievable naturally applies here too. However, in certain areas (radon tunnels), the assumption of higher dose coefficients could result in doses close to the limit.

The workplaces subject to monitoring in underground work areas can, in part, be assigned to the DeStatis workplace category 'Mining and quarrying', which comprises 1,945 companies with approx. 39,400 employees. There are still 13,700 insured employees in underground and opencast mining in Germany. The figures available do not indicate what proportion of these workers are still working in underground or opencast mining. At least for those working underground, it can generally be expected that radon exposure is combined with external gamma exposure from the surrounding rock. However, external gamma exposure cannot be ruled out even for surface workers. With regard to underground work areas, ICRP Publication 137 (ICRP 2017) discusses dose coefficients and conditions in active mines with forced ventilation for which an equilibrium factor of 0.2 is specified and the breathing rate of the reference worker is assumed. As for indoor environments, a dose coefficient of 3 mSv/(mJ h m^{-3}) is recommended here. For other underground workplaces with the exception of caves, there are no specific details regarding dose coefficients and no further discussion on this matter.

According to Wikipedia, there are around 160 show mines[16] in Germany; these are also subject to radon protection requirements under the Radiation Protection Act (StrlSchG). In the case of show mines, it would be necessary to assess whether the environmental conditions and breathing rates in these mines in Germany are more akin to those found in (active) mines or to those found in caves and which scenarios in ICRP Publication 137 (ICRP 2017) they most closely correspond to.

According to the German Speleological Federation (VdHK), there are 53 tourist caves in Germany, most of which are karst caves[17]. For caves, a higher dose coefficient of 6 mSv/(mJ h m^{-3}) is recommended in ICRP Publication 137 (ICRP 2017) because of the specific environmental conditions (high unattached fraction).

In the case of show mines and show caves, it should be borne in mind that natural ventilation caused by seasonal temperature variations can create conditions similar to those of forced ventilation; these, in turn, could affect the working environment for those employed there.

Fehler! Ungültiger Eigenverweis auf Textmarke. provides an overview of the number of employees who in 2023 were classified into the categories mentioned above based on entries in the Radiation Protection Register (BfS 2025b).

[16]List of show mines in Germany: https://de.wikipedia.org/wiki/Liste_von_Schaubergwerken_in_Deutschland

[17] List of show caves in Germany: https://www.vdhk.de/fileadmin/pdf/data/schauhoehlenliste.pdf

Table 4.10: Number of employees monitored and with measurable exposure at radon workplaces in 2023 (BfS 2025b).

Radon workplaces		
Category of activity	Employees under monitoring	Employees with measurable exposure
Radon total	391	236
Underground mines, excluding uranium mining	54	41
Underground visitor facilities	34	28
Water abstraction and treatment facilities	99	52
Cross-sectional activities relating to radon	204	115

For these employees, the BfS calculated effective doses using the currently valid radon dose coefficients (RDCs) as well as those recommended in ICRP Publication 137 (ICRP 2017), see Table 4.11.

Table 4.11: The number of employees who would exceed an annual dose of 6 mSv or 20 mSv if the exposures measured in 2023 were converted into effective doses using different models (BfS 2025b).

Interval	**Radon workplaces**	**Radon workplaces option a**	**Radon workplaces option b**	**Radon workplaces option c**
	With previously valid RDC: 1.4 mSv/ (mJ h m^{-3})	Categories of underground mining with RDC: 3 mSv/(mJ h m^{-3}), visitor facilities, water works with RDC: 6 mSv/(mJ h m^{-3})	All activitiy categories with RDC: 3 mSv/(mJ h m^{-3}), only underground visitor facilities with RDC: 6 mSv/(mJ h m^{-3})	All activitiy categories with RDC: 3 mSv/(mJ h m^{-3})
Monitored	391	391	391	391
Number of employees exposed to more than 6 mSv	23	111	82	77
Number of employees exposed to more than 20 mSv	0	30	17	5

Show caves, show mines, and, in some cases, small water supply facilities are often run by volunteers and therefore do not constitute a traditional professional occupation.

Since autumn 2021, the BfS has been receiving measurement results and further information from monitored workplaces via a digital measurement data reporting portal. On 22 July 2025[18], the BfS-dataset of radon measurements taken at workplaces used for the following analysis comprised 24,833 records. This refers to data from measurements carried out in accordance with Sections 127–128 StrlSchG (2017) (i.e. prior to official notification and prior to dose estimation).

These data were also used to estimate threshold exceedances: Depending on the choice of RDC and, in particular, without knowledge of the effectiveness of a reduction measure to be implemented following measurement in accordance with Section 128, it is possible to determine how many persons might be expected in the event of a change in the legal provisions. For the estimation, the two dose coefficients under consideration, 3 mSv/(mJ h m^{-3}) and 6 mSv/(mJ h m^{-3}), were used. For comparison, the resulting effective dose has also been calculated using the previous dose coefficient (1.4 mSv/(mJ h m^{-3})).

These estimates for waterworks are presented in Table 4.12 and are based on different exposure durations (working hours per year) and different dose coefficients (RDC).

Table 4.12: Exceedances of limit values in the dataset in Annex 8 StrlSchG (2017) – Waterworks – assuming different radon dose coefficients (RDC). The data used are those submitted up to 22 July 2025 regarding the mean annual radon activity concentration (BfS 2025a).

RDC [mSv/mJ h m^{-3}]	Exposure time [h]	Number of employees	Number > 6 mSv	% > 6 mSv	Number > 20 mSv	% > 20 mSv
1.4	2,000	1,423	414	29.09	143	10.05
6.0	2,000	1,423	881	61.91	477	33.52
3.0	2,000	1,423	642	45.12	253	17.78
1.4	1,600	1,423	318	22.35	137	9.63
6.0	1,600	1,423	802	56.36	416	29.23
3.0	1,600	1,423	569	39.99	204	14.34

For the dataset "RVG – indoor workplaces" with 23,410 data points, the following exceedances result for the dose coefficients considered (**Fehler! Ungültiger Eigenverweis auf Textmarke.**).

[18]The date of the data set differs from the reference date of this recommendation (31 December 2024) because the working group had access only to figures from a data extract dated 22 July 2025.

Table 4.13: Exceedances of limit values in the dataset for radon precautionary areas – indoor workplaces – assuming different radon dose coefficients (RDC). The data used are those submitted up to 22 July 2025 regarding the mean annual radon activity concentration (BfS 2025a).

RDC [mSv/mJ h m^{-3}]	Exposure time [h]	Number of employees	Number > 6 mSv	% > 6 mSv	Number > 20 mSv	% > 20 mSv
1.4	2,000	23,410	443	1.89	16	0.07
6.0	2,000	23,410	5,335	22.79	774	3.31
3.0	2,000	23,410	2,032	8.68	110	0.47
1.4	1,600	23,410	236	1.01	11	0.05
6.0	1,600	23,410	4,011	17.13	465	1.99
3.0	1,600	23,410	1,314	5.61	40	0.17

No information was collected regarding physical activity for indoor workplaces.

4.2.5 Graded approach in radon protection

The measures for radon protection in the workplace provide for a graduated procedure in accordance with a graded approach shown in Figure 4.7. For workplaces on the ground floor or in the basement within a radon precautionary area there is an obligation to measure the radon activity concentration over a period of 12 months as part of Stage 1 within 18 months of the designation of the area. The measurement period may also be shortened if it is apparent that the mean annual radon activity concentration exceeds the reference level (Section 155 (1), StrlSchV (2018)). In most cases, the radon precautionary areas were designated in the first quarter of 2021. Measurements at the workplaces therefore had to be largely completed by the second half of 2022. If the mean value over this period remained below the reference level of 300 Bq m^{-3}, no further action was required. In principle, the provisions of the graded approach apply also to workplaces in underground mines, radon spas and tunnels, and water abstraction facilities[19].

The risk associated with this reference level therefore represents the first stage of the graded approach. Using the currently well-established radon risk coefficient k_R from ICRP Publication 115 (ICRP 2010), it is possible to estimate the associated mean risk for a specific duration of exposure for a reference population (cf. Figure 4.8):

$$k_R = LEAR/P_A = F \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) \quad (16)$$

The radon risk coefficient k_R is derived from epidemiological studies of miners and was, as described in Section 4.2.3, largely confirmed in the Pooled Uranium Miners Analysis (PUMA) study (Kreuzer et al. 2024). For miners, ICRP Publication 137 (ICRP 2017) assumes an equilibrium factor of $F = 0.2$. With a maximum exposure of 2,000 hours per calendar year, this results in an additional lifetime excess absolute risk (LEAR) of:

$$LEAR = 300\text{Bq m}^{-3} \cdot 0.2 \cdot 2{,}000\text{ h} \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) = 10^{-4} \quad (17)$$

Epidemiological data for estimating lifetime risk are also available for indoor environments. Marsh und Bailey (2013) indicate that the risks associated with indoor exposure are approx. 10 % higher per unit of exposure than those for miners. If, for the sake of simplicity, we apply

[19] The obligation to monitor the radon situation already applied to these workplaces since the Radiation Protection Ordinance of 2001 (StrlSchV 2001).

the same risk coefficient here as for miners, we obtain the following for work involving no particular physical exertion ('sedentary worker') for which $F = 0.4$ is assumed:

$$LEAR = 300\text{Bq m}^{-3} \cdot 0.4 \cdot 2{,}000\text{ h} \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) = 2 \cdot 10^{-4} \qquad (18)$$

If the reference level of 300 Bq m^{-3} has been exceeded, measures must be taken to reduce the radon activity concentration. Within 30 months of the measurement results becoming known, the measures must be implemented, and their effectiveness must be demonstrated by subsequent control measurements (Stage 2 of the graded approach). In other words, after the measures have been taken, the activity concentration must be determined as the mean over a period of 12 months and remain below the reference level of 300 Bq m^{-3}.

Section 128 (4) StrlSchG (2017) nevertheless takes into account circumstances in which measures may be waived. This applies where such measures would be impossible or the effort required would be disproportionately high (i.e. where there are other specific reasons unrelated to radiation protection such as occupational health and safety considerations or factors arising from the nature of the workplace). Such reasons include the hygiene requirements for drinking water treatment in waterworks; these requirements can make it difficult to provide additional ventilation in the relevant rooms. Similarly, in some cases, structural conditions may make it considerably more difficult or even impossible to carry out such measures. In the case of radon therapy tunnels, reducing the concentration is actually incompatible with the nature of the activity. In such cases, Stage 2 of the control strategy is skipped.

If these exceptional cases do not apply, the workplaces concerned must be registered with the competent authority in Stage 3 of the concept (Figure 4.7), and a workplace-specific estimation of the effective dose for the employees concerned is required. If the assessment indicates that the effective dose cannot exceed 6 mSv in a calendar year, the radon protection measures taken may be regarded as sufficiently effective in this case. However, exposure to radon should be checked regularly. If the estimated dose exceeds 6 mSv in the calendar year, the corresponding provisions for occupational radiation protection apply (Stage 4 of the graded approach).

In this graded approach, the harm-weighted risk associated with an effective dose of 6 mSv per calendar year thus represents a further graduation of measures to be taken: A greater (estimated or anticipated) risk requires stricter or more extensive measures. The risk associated with 6 mSv per calendar year can be calculated using the harm-weighted risk coefficient k_D ('detriment') of the ICRP for the adult population over a calendar year as follows (Figure 4.8):

$$k_{D,2} = 4.2 \cdot 10^{-2}/\text{Sv} \qquad (19)$$

$$\Rightarrow \quad LEAR = 6\text{ mSv} \cdot 4.2 \cdot 10^{-5}/\text{mSv} = 2.5 \cdot 10^{-4}$$

According to ICRP Publication 103 (ICRP 2007), this includes the application of a dose and dose rate effectiveness factor (DDREF) of 2. If the recommendation of the SSK (SSK 2014), namely not to apply a DDREF or to set DDREF = 1 is followed, the harm-weighted risk (detriment) is calculated as follows:

$$k_{D,1} = 8.4 \cdot 10^{-2}/\text{Sv} \qquad (20)$$

$$\Rightarrow \quad LEAR = 6\text{ mSv} \cdot 8.4 \cdot 10^{-5}/\text{mSv} = 5 \cdot 10^{-4}$$

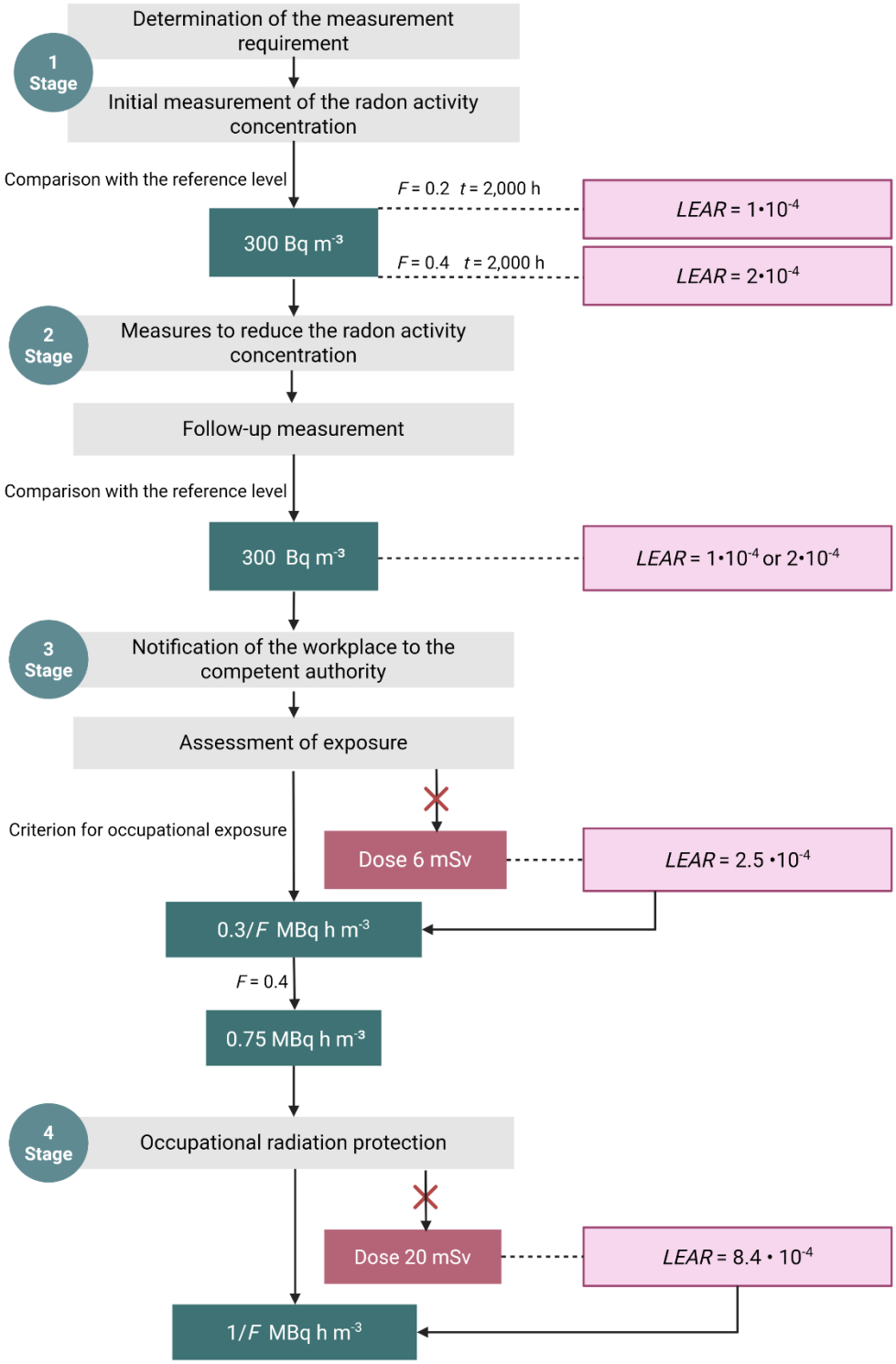

Figure 4.7: Graded approach to measures for radon protection in workplaces pursuant to Section 126 et seq. of the German Radiation Protection Act (StrlSchG) (Created with BioRender.com).

Classification as an 'occupationally exposed person' as a consequence of Stage 4 of the graded approach and the associated application of occupational radiation protection entails that a limit value of 20 mSv effective dose in the calendar year applies to that person (i.e. a reference to a 'maximum tolerable risk' corresponding to a further graduation of risk and the associated radiation protection measures).

If the risk associated with a dose of 20 mSv is again calculated using a DDREF of 2 and a DDREF of 1, the following results are obtained:

$$LEAR = 20\ \text{mSv} \cdot k_{D,2} = 8.4 \cdot 10^{-4}$$

$$LEAR = 20\ \text{mSv} \cdot k_{D,1} = 17 \cdot 10^{-4} \quad (21)$$

If one compares the risks corresponding to the graduations, it can be seen that, according to the internal logic of the ICRP recommendations, the risk expected at the reference level of 300 Bq m^{-3} for miners is considerably below that at 6 mSv, whereas for workers with sedentary indoor occupations, it is only slightly below this risk:

Stage 1: 300 Bq m^{-3} $LEAR = 1 \cdot 10^{-4}$ bzw. $2 \cdot 10^{-4}$

Stage 3: 6 mSv $LEAR = 2.5 \cdot 10^{-4}$

Stage 4: 20 mSv $LEAR = 8.4 \cdot 10^{-4}$ (22)

On the other hand, assuming a DDREF of 1 (instead of 2) results in a more evenly distributed graduation of approximately 2.5 to 5 in each case:

Stage 1: 300 Bq m^{-3} $LEAR = 1 \cdot 10^{-4}$ bzw. $2 \cdot 10^{-4}$

Stage 3: 6 mSv $LEAR = 5 \cdot 10^{-4}$

Stage 4: 20 mSv $LEAR = 17 \cdot 10^{-4}$ (23)

A comparison of the respective risk values is relevant because the primary objective of radiation protection is to limit the stochastic risk (rather than the dose) to a tolerable level; consequently, a meaningful graduation of *risks* is the key criterion for the graded approach.

However, when applying the RDC d_R for radon currently recommended by ICRP Publication 137 (ICRP 2017), this uniformity of the graduation is thrown out of balance. In this case, under otherwise identical conditions as above, the reference level for radon activity concentration of 300 Bq m^{-3} corresponds to:

$$d_R = F \cdot 17\ \text{mSv}/(\text{MBq h m}^{-3}) \quad (24)$$

Effective Dose:

$$E = 300\ \text{Bq m}^{-3} \cdot 0.4 \cdot 2{,}000h \cdot 17\ \text{mSv}/(\text{MBq h m}^{-3}) = 4\ \text{mSv} \quad (25)$$

and:

$$LEAR = E \cdot k_{D,1} = 3.4 \cdot 10^{-4} \quad (26)$$

According to ICRP Publication 137, this applies to sedentary occupations carried out indoors. In this context, an equilibrium factor of $F = 0.4$ and a maximum exposure duration of 2,000 hours per year have been assumed. As can be seen, the risk associated with Stage 1 is very close to that of Stage 3. At an equilibrium factor of $F = 0.5$ or higher or when applying the ICRP dose coefficient for radon for indoor environments with predominantly physical activity from equation

$$d_R = F \cdot 33\ \text{mSv}/(\text{MBq h m}^{-3}) \quad (27)$$

the risk associated with Stage 1 would be even greater than that of Stage 3. Thus, even for activity concentrations at the workplace of less than 300 Bq m^{-3}, an annual risk exceeding that associated with 6 mSv in the calendar year would be possible. This would therefore no longer constitute a meaningful graduation; in fact, it would reverse the graduation, thereby rendering the entire graded approach unusable. If, in order to avoid this and to restore an appropriate graduation, the 6 mSv criterion were changed (e.g. raising it to 10 mSv per calendar year), this would result in a considerable departure from the approach taken for other exposures and would

conflict with the general concept of radiation protection in a way that would be difficult to accept.

For occupationally exposed persons under the age of 18, a limit value of 1 mSv in the calendar year applies in accordance with Section 78 (3) StrlSchG (2017) deviating from the limit value for adults while no separate provision exists for this group regarding the reference level for radon activity concentration (300 Bq m^{-3}). There is also no dose value for Stage 3 of the graded approach that has been adapted for people under the age of 18. A risk comparison such as the one above would, in any case and for any dose coefficient considered, indicate the highest risk as early as Stage 1. The graded approach must therefore generally be regarded as not appropriate for occupationally exposed persons under 18 years of age.

The comparative calculations shown above were based on a maximum of 2,000 working hours per year; however, this is rarely the case in practice. If, on the other hand, a more realistic figure of 1,000 working hours per year is assumed, an appropriate risk classification can initially be achieved again but only if DDREF = 1 is set and the risk coefficient

$$k_{D,1} = 8.4 \cdot 10^{-2}/\mathrm{Sv}$$

is applied. However, that would mean that the ICRP would have to endorse the recommendation of the SSK to abolish the DDREF (SSK 2014).

4.3 General principles on radon dose conversion

Chapter 3 of this document addresses the questions set out in the advisory mandate in detail and, where possible, provides answers. However, it becomes apparent that there are unresolved issues in each of the questions under consideration and that a satisfactory answer is achieved only to a limited extent and not in a fundamental way.

Therefore, the SSK considers it necessary to identify issues of a fundamental and conceptual nature arising from radon dose conversion, and to discuss the associated radiation protection principles.. Based on these considerations, the SSK goes beyond the exclusive treatment of the advisory mandate and sets out further recommendations in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** of this document outlining ways in which radon protection can be appropriately implemented as a consistent continuation of the procedures already established in existing German radiation protection legislation. This is explained in more detail below.

The primary objective of radiation protection is to limit the stochastic risk caused by ionising radiation to an acceptable level (e.g. SSK 2018, SSK 2020, and SSK 2023). The basis for determining such an acceptable level of risk is generally provided by dose-response relationships derived from studies in radiation epidemiology. For most exposure conditions, the organ-specific dose-response relationships derived from the LSS (e.g. Ozasa et al. 2012 and Grant et al. 2017), i.e. the sum of all studies on Japanese atomic bomb survivors, form the main basis for determining risk coefficients. These risk coefficients are specified for individual organs (e.g. including the lungs) and relate to external acute exposure consisting mainly of gamma radiation and a neutron component that can be modelled accurately; as a result, the exposure is distributed more or less uniformly, thereby leading to the same organ energy doses across all organs of the body. In contrast, the LSS does not provide any data on alpha radiation.

4.3.1 The situation for radon

Unlike most other exposure conditions, no dose-response relationship is known for radon. Epidemiological studies on radon risk are instead based almost exclusively on response relationships with respect to cumulative radon activity concentration (in units of Bq h m^{-3}),

cumulative potential alpha energy concentration (in units of mJ h m^{-3} or historically WLM), or radon activity concentration (in units of Bq m^{-3}) and thus not on radon dose (e.g. Darby et al. 2005 and Richardson et al. 2022). Accordingly, for the purpose of limiting risk, a radon dose is not initially necessary, and instead the relationship to exposure or activity concentration established in epidemiological studies could be used directly as a measure of risk.

In fact, this approach has largely been followed in radon protection to date. The current provisions on radon protection in accordance with StrlSchG (2017) generally refer either to a value for activity concentration in ambient air or to a quantity for cumulative radon activity concentration (activity concentration multiplied by exposure time). For example, the reference level for radon in living spaces and at workplaces is set at an activity concentration of 300 Bq m^{-3}. A radon-related dose is not calculated in this context. Although the radiation protection concept for radon exposure is thus separated from the usual focus on dose, it is nevertheless based on the same principles and standards for existing exposure situations as those applied to other sources of exposure. An exception is currently provided by the regulations on occupational radiation protection (StrlSchG 2017) concerning radiation exposure to radon for which reference to the effective dose is required and is provided for both in ICRP Publication 103 (ICRP 2007) and in the German regulatory framework.

For occupational internal exposure, the ICRP has published a series of five publications containing comprehensive calculations for converting activity levels into dose values for virtually all relevant radionuclides (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022). The calculations of these dose coefficients take into account numerous incorporation parameters, various biokinetic models, and many other assumptions regarding the relevant metabolic processes. For most internal exposure situations, this ‘dose conversion’ is, strictly speaking, unproblematic. However, the extent to which the dose calculations, some of which are highly accurate, based on these dose coefficients actually correspond to the risk implicitly associated with them can be epidemiologically substantiated only in exceptional cases. A precise indication of the dose does not necessarily imply an equally precise indication of the risk. Unlike internal exposure to most other radionuclides, a number of epidemiological risk studies are available for radon. Whilst these provide a sufficiently reliable basis for estimating the radon *risk*, they do not provide any information on the radon dose (cf. Section 4.2.3).

The ICRP follows a ‘dosimetric approach’ for radon as well (ICRP 2010, ICRP 2014, ICRP 2017), which, however, leads to some serious difficulties. The ICRP lung model HRTM (Human Respiratory Tract Model), which forms the basis of biokinetic modelling, takes into account the uptake, deposition, residence time, transport, exchange, and release of the relevant radionuclides for the individual compartments of the lung. The model therefore includes numerous parameters, some of which can be determined only with a high degree of uncertainty. Along with a number of other factors, this circumstance leads to considerable uncertainty when calculating the RDC. This was one of the reasons why the SSK, at the time, chose not to recommend incorporating the then-new dose coefficients of the ICRP into German radiation protection legislation but instead advocated retaining the existing values (SSK 2017). With regard to the objective of limiting the risk from radon exposure, the SSK considers that determining the effective dose in relation to radon is unnecessary or even inappropriate.

4.3.2 The specific nature of radon dose assessment

Unlike most other internal exposures to individual radionuclides and their decay products, there are well-established exposure-response relationships for radon exposure derived from epidemiological studies; from these, a radon risk coefficient can be determined – at least in principle. As mentioned above, this refers to the radon activity concentration or the cumulative radon activity concentration. A radon dose is neither defined nor required in these studies.

However, if a radon dose is calculated using the ICRP dose conversion factors, this can, in principle, be linked to the epidemiological findings. The ICRP had indeed adopted this 'epidemiological approach' in the past but subsequently set it aside in favour of the dosimetric approach (ICRP 2017).

Figure 4.8 schematically illustrates the pathway from a cumulative radon activity concentration (activity concentration C_{Rn} multiplied by exposure time t) to the determination of radon risk (*LEAR* per cumulative radon activity concentration). In the first step, the HRTM (the ICRP 'dosimetric approach') provides the energy dose to the lungs. The effective dose is calculated from this value using the radiation weighting factor w_R (Step 2) and the organ weighting factor for the lungs w_{Lunge} (Step 3). Overall, this leads to the RDC from ICRP Publication 115 of $F \cdot 18.8$ mSv/(MBq h m^{-3}) (here, by way of example, without explicit workplace category[20]) for occupational exposure (ICRP 2010). This value is approximately twice that of ICRP Publication 65 from 1993 (ICRP 1993). Using the general risk coefficient of 4.2 % Sv^{-1} for stochastic radiation effects in the adult population from ICRP Publication 103 (ICRP 2007), the final step yields the radon risk *LEAR* per cumulative radon activity concentration. This final step is independent of radon and is based on the data set as well as the assumptions and models used to determine the general stochastic risk. This includes, in particular, the detriment model, the dose and dose effectiveness factor DDREF = 2, and the risk coefficients taken primarily from the LSS publications concerning acute exposure to gamma radiation and neutrons (i.e. all parameters that do not apply to radon).

[20] Strictly speaking, the radon risk coefficient, which is regarded as central, actually applies *only* to this single value of the radon dose coefficient (RDC).

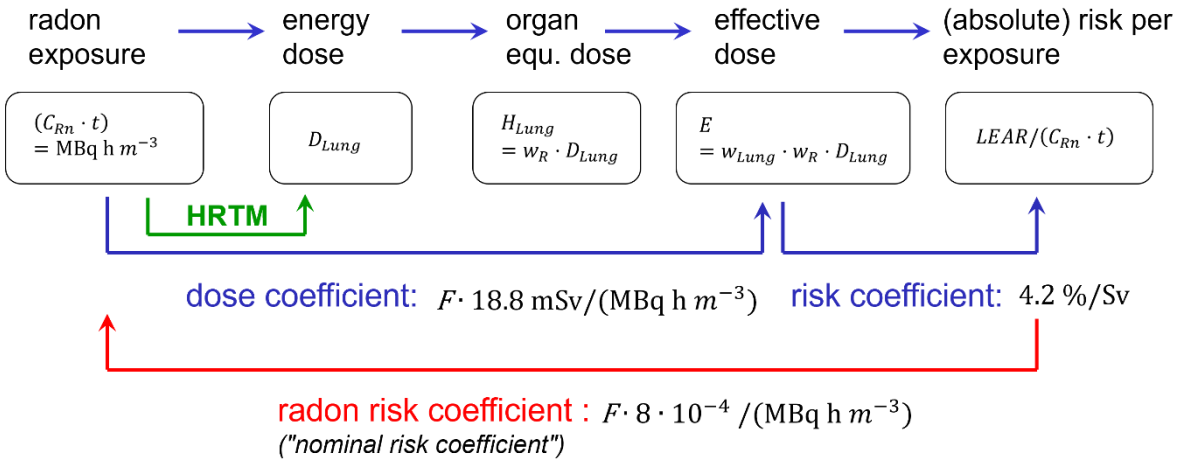

Figure 4.8: Schematic representation of the relationship between cumulative radon activity concentration (referred to as 'radon exposure' in the figure) and radon risk. The individual steps of the calculation are shown, as well as the relationship between the radon dose coefficient and the general risk coefficient, which, when multiplied, yield the radon risk coefficient.

The sequence of steps described essentially sets out the procedure for all radionuclides in the event of internal exposure. The rationale behind this calculation is that any changes to the general risk coefficient for all stochastic radiation effects are unlikely to affect the RDC. For most of the radionuclides considered by the ICRP (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022), this is also implicitly assumed even though it is not possible to verify this because of a lack of epidemiological data.

In contrast, when it comes to radon, the outcome of the entire process can actually be validated by epidemiological findings. This has also been successfully achieved using the radon risk coefficient ('nominal risk coefficient') given in ICRP Publication 115 as $F \cdot 8 \cdot 10^{-4}$/(MBq h m^{-3}) (ICRP 2010). This figure is based primarily on epidemiological studies of miners (cf. Section 4.2.5) and on the Darby study from 2005 (Darby et al. 2005) and indicates the direct link between radon exposure and radon-related risk (Figure 4.8). The fact that this 'epidemiological approach' yielded general agreement had also led the ICPR to regard its radon dose conversion as sufficiently robust.

However, one key conceptual complication is overlooked or ignored in this context: The radon dose coefficient (densely-ionising radiation) is linked to the radon risk coefficient ('nominal risk coefficient') via the risk coefficients for all organs (determined for loosely-ionising radiation). So if there were ever to be a change in how detriment is calculated (e.g. as a result of the work of ICRP Task Group 122 or a re-evaluation of the LSS) or if other models were applied (e.g. a different detriment model or the abolition of the DDREF), this would also result in a change to the RDC because the radon risk coefficient would, of course, have to remain unchanged (Figure 4.8). The SSK recommendation from 2017 (SSK 2017) already states the following on this point: "*It is difficult to see why the effective dose from radon exposure should change if the risk assessment for colorectal cancer from X-ray radiation were revised*." Even if only the lungs were taken into account, this implausibility would still remain (Breckow 2018).

In its current recommendation from 2014 (SSK 2014), the SSK advocates the abolition of the DDREF or setting DDREF = 1. As a consequence, the general risk coefficient for the adult population increases from 4.2 % Sv^{-1} to 8.4 % Sv^{-1}. If the radon risk coefficient of $F \cdot 8 \cdot 10^{-4}$/(MBq h m^{-3}) remains unchanged as the central reference quantity, this would imply

a reduction of the dose coefficient to $F \cdot 9.4\,\mathrm{mSv/(MBq\,h\,m^{-3})}$ for occupational exposure (Figure 4.8). If the SSK accepted a dose-related approach in radon protection, it would either have to recommend dose coefficients that deviate from the ICRP recommendations or contradict its own recommendation regarding the dose and dose rate effectiveness factor (DDREF) (SSK 2014). The SSK considers both of these to be problematic.

4.3.3 Solution

As explained above, calculating the effective dose resulting from radon exposure presents considerable difficulties. Under both international and German radiation protection legislation, radon protection has already been largely decoupled from dose-based approaches through the use of activity concentrations or cumulative exposure metrics. However, it is still applied in some areas at present. Thus, in accordance with StrlSchG (2017), reference to the effective dose is required especially for the regulations on occupational radiation protection in the case of radon exposure. A dose-related assessment is also carried out with regard to radioactive contamination. Section 136 of StrlSchG (2017) defines radioactive contamination sites "*that may cause the reference level for the effective dose of 1 mSv per calendar year to be exceeded for an individual member of the public*". This reference level generally includes the dose attributable to the inhalation of radon and its decay products. In contrast, in a recommendation on this subject (SSK 2022), the SSK advocates excluding radon when considering the reference level of 1 mSv and instead defining separate reference levels for radon based on activity concentrations.

A similar path with exclusive reference to activity concentrations could also be adopted for the regulations on occupational radiation protection. In this case, this would apply not only to the reference levels for existing exposure situations but also to the limit values for planned exposure situations. This would mean that the radiation protection concept for radon would be free of conceptual inconsistencies and completely separate from the usual focus on dose (cf. Figure 4.7). It would nevertheless be based on the same principles and standards as for all other sources of exposure. Above all, this would be in line with the fundamental principle of radiation protection, which states that it is not the dose but rather the risk that should be limited.

4.3.3.1 Workplace categories and activity concentrations

In accordance with European Commission Recommendation 2024/440 (EC 2024), when transposing into national law, the ICRP publications on occupational intakes of radionuclides from the OIR series (Occupational Intakes of Radionuclides) (ICRP 2015, ICRP 2016, ICRP 2017, ICRP 2019, ICRP 2022) and all dose coefficients contained therein should be used for estimating the effective dose and the equivalent dose from internal exposure within the meaning of Directive 2013/59/Euratom (Euratom 2014). With regard to radon exposure, this refers in particular to ICRP Publication 137 (ICRP 2017).

In an advisory mandate dated 6 December 2023, the Federal Environment Ministry commissioned the SSK to provide answers to the questions addressed in Chapter 3 of this statement. The questions focus primarily on the critical aspects and the robustness of the biokinetic-dosimetric approach adopted by the ICRP (particle distribution of radon decay products in the workplace, the influence of radon decay products of different particle sizes on the dose), the conclusions drawn from new scientific findings such as the PUMA study, the conservativeness of the level of protection for all those affected, and the associated assurance of adequate radiation protection in workplaces where radon activity concentrations are even below $300\,\mathrm{Bq\,m^{-3}}$.

However, when it comes to the necessary regulations in StrlSchG (2017) and StrlSchV (2018), a distinction must be made: As explained in detail in the previous chapters, risk assessment is

the key factor in ensuring radon protection in indoor workplaces (in areas covered by Section 121 or Appendix 8 StrlSchG (2017)). Consequently, this means that the graded approach for radon protection set out in StrlSchG (2017) can be structured in a risk-based manner. An estimate of the effective dose is not strictly necessary solely for the purposes of radon protection in the workplace and determining what measures may be required.

Only when compliance with the occupational exposure dose limit of 20 mSv per calendar year must be assessed or when occupational exposures must be added in accordance with Section 166 (1) StrlSchG (2017) and, under No. 2, the contribution associated with radon in the workplace must also be taken into account is the determination of an effective dose for radon at workplaces unavoidable under the currently applicable radiation protection legislation.

The recommendations set out by the SSK in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** mean that the regulations governing measures for (health-related) radon protection (Sections 127 et seq. StrlSchG (2017)) and the necessary provisions for determining occupational exposure (Section 166 (1) StrlSchG (2017)) are to be considered independently or separately from one another. The reference level of 300 Bq m^{-3} according to Section 126 StrlSchG (2017) remains unaffected for the time being.

4.3.3.2 Risk reference of the graded approach

The graded approach described in Section 4.2.5 is retained for Stages 1 to 3. However, within Stage 4, the cumulative radon activity concentration or the cumulative potential alpha energy concentration at the workplace must be estimated within six months of registration, and the determination of the body dose under Section 130 (1) StrlSchG (2017) is waived. The assessment of exposure should take into account workplace-specific conditions and cover workplaces located in areas defined in Section 121 StrlSchG (2017) as well as the categorisation of the fields of work listed in Annex 8.

The individual steps in the sequence of the current graded approach (cf. Figure 4.7) relate either to the radon activity concentration or to the effective dose (i.e. to different reference parameters in each case). However, as explained in Section 4.2.5, the graduation actually intended in radiation protection relates to risks of varying magnitude to which a corresponding hierarchy of measures is assigned. It therefore stands to reason to choose the cumulative radon activity concentration as a standard reference value for which a sufficiently robust risk coefficient k_R is available (cf. Equation (16)):

$$k_R = F \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3})$$

The additional absolute annual risk $LEAR_a$ (with the unit a^{-1}) associated with radon exposure therefore depends on the radon activity concentration C_{Rn}, the annual exposure duration t_a (with the unit h a^{-1}), and the equilibrium factor F:

$$LEAR_a = C_{Rn} \cdot t_a \cdot k_R = C_{Rn} \cdot t_a \cdot F \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) \quad (28)$$

For *Stage 1* of the graded approach, the reference level of 300 Bq m^{-3} currently applies. If this is retained, the risk reference calculated in Section 4.2.5 will also remain unchanged.

The risk reference for Stage 3 has so far been set at an annual dose of 6 mSv. The associated risk was calculated in Section 4.2.5 as

$$LEAR_a = 2.5 \cdot 10^{-4}\ \text{a}^{-1} \quad (29)$$

(cf. Equation (19)). If this risk is also to remain unchanged, the corresponding radon activity concentration is calculated using the following formula:

$$2.5 \cdot 10^{-4}\ \text{a}^{-1} = C_{Rn} \cdot t_a \cdot F \cdot 8 \cdot 10^{-4}/(\text{MBq h m}^{-3}) \quad (30)$$

$$\Rightarrow\ C_{Rn} \cdot t_a \cdot F = 0.3\ \text{MBq m}^{-3}\ \text{h a}^{-1} \tag{31}$$

or:

$$C_{Rn} = \frac{0.3}{F \cdot t_a}\ \text{MBq m}^{-3}\ \text{h a}^{-1} \tag{32}$$

This provides a uniform reference value that still includes the equilibrium factor F and the annual occupancy or exposure duration t_a (unit: h a^{-1}) as free parameters (cf. Figure 4.7).

Equation (32) makes it possible to represent different workplace categories with a single flexible relationship and the two free parameters, all corresponding to the same risk as 6 mSv a^{-1}. From the perspective of the SSK, this approach offers far greater flexibility than the rigid and largely opaque use of various dose coefficients, the determination of which continues to be associated with considerable uncertainty and numerous assumptions. From a practical implementation perspective, this also means that the legally compliant classification of a workplace into a category is simplified, and any necessary assessment of typical workplace conditions would be greatly simplified.

For example, using Equation (32), a radon activity concentration of 375 Bq m^{-3} is obtained for *Stage 3* at a working time of t_a = 2,000 h a^{-1} if F = 0.4 can be assumed (and 750 Bq m^{-3} in mines with F = 0.2). Other exposure situations can be easily accounted for using just a single relationship based on Equation (32) provided that assumptions are made regarding the exposure time and the equilibrium factor.

Building on this and in line with the current requirement to estimate whole-body doses, it could be stipulated that exposure to radon must be checked regularly if the radon activity concentration does not exceed the values given in Equation (32) (analogous to Section 130 (2) StrlSchG (2017)) without reference to a calculated whole-body dose. If it is found that the values given in Equation (32) have been exceeded, the requirements for occupational radiation protection must be met (Section 130 (3) StrlSchG (2017)) in a suitably modified form.

Using the formula in Equation (32), the annual cumulative radon activity concentrations (or the cumulative potential alpha energy concentration) for different workplace categories could be calculated, if required, by applying different equilibrium factors. For indoor workplaces (basements and ground floors) and the workplaces listed in Annex 8 StrlSchG (2017) (with the exception of underground mines), the following applies when F = 0.4:

– 0.75 MBq h m^{-3} or 1.7 mJ h m^{-3}.

In underground mines where F = 0.2, the value is:

– 1.5 MBq h m^{-3} or 1.7 mJ h m^{-3}.

The values stated therefore correspond to a risk equivalent to 6 mSv a^{-1}. Because of specific exposure conditions, these conversion factors may vary and may be determined on a case-by-case basis by the responsible authority using Equation (32). Cumulative radon activity concentrations may also be specified for the areas of work listed in Annex 8 StrlSchG (2017) provided appropriate assumptions are made; however, they are not strictly required under Section 127 (1) StrlSchG (2017).

These values as well as the reference to the cumulative radon activity concentration without the dose criterion of 6 mSv are very similar to the approach adopted in Sweden and other northern European countries (the document mentions Norway and Finland) (cf. Section 4.2.4.2). To establish a link to dose, the regulation for radon at workplaces in Sweden (SSM 2018) assumes that the annual dose of 6 mSv used for assessment in the European Basic Safety Standards (EU-BSS, Euratom 2014) corresponds to an annual radon exposure of 0.72 MBq h m^{-3} at F = 0.4.

The SSK does not consider it necessary to specify separate activity concentration values for specific workplace categories. Instead, as given by Equation (32), a single relationship is recommended for all possible workplace categories. Radiation protection policies and measures should be practical and transparent. Not every scientifically possible distinction regarding specific exposure conditions needs to be implemented in radiation protection. In principle, radiation protection is designed to be robust enough to account for known or unknown differences in radiation risk for specific subgroups or exposure situations while still ensuring an adequate level of protection for the general population. This principle also applies to radon exposure at various workplaces with reference to Equation (32).

The risk reference on which the derivation of the relationship in Equation (32) is based includes the dose and dose rate effectiveness factor DDREF = 2 and therefore does not follow the SSK recommendation (SSK 2014), which recommends the use of DDREF = 1. As explained in more detail in Section 4.2.5, a DDREF of 1 (instead of 2) would also result in a more evenly distributed graduation within the graded approach. However, in order to achieve greater consistency with the international implementation of the ICRP dose conversion and the relevant EU guidelines, this recommendation initially refrains from applying DDREF = 1, not least because the ICRP has not yet endorsed the SSK recommendation (SSK 2014). However, the SSK considers it necessary to continue discussions with the ICRP regarding the reasoning set out in its recommendation (SSK 2014). If the ICRP also endorsed DDREF = 1 (or another modification of DDREF), this would have implications beyond ICRP dose conversion. In this case, the SSK would recommend the more evenly graduated (and more appropriate) graded approach with DDREF = 1 as the basis for a modified version of Equation (32).

According to Section 78 (1) StrlSchG (2017), the limit value for the effective dose for occupationally exposed persons is 20 mSv per calendar year (*fourth* stage in the graded approach). In accordance with Section 131 (1) No. 3 StrlSchG (2017), the dose limits also apply to radon in the workplace. In line with the above considerations, it is recommended that, instead of this dose-related value, an activity-related value be used in accordance with the following equation:

$$C_{Rn} = \frac{1}{F \cdot t_a}\ \mathrm{MBq\ m^{-3}\ h\ a^{-1}} \tag{33}$$

This risk-based assessment could ensure adequate radiation protection against radon in the workplace. This step also follows the practice adopted in Sweden, which does not set a dose limit value for occupational radon exposure.

A value of $F = 0.4$ is recommended as the standard equilibrium factor so that, from Equation (33), a cumulative radon activity concentration of 2.5 MBq h m^{-3} is obtained as the limit value. If there are technical grounds for concluding that F deviates considerably from 0.4, the corresponding cumulative radon activity concentration must be calculated using Equation (32). Equation (33) represents an activity concentration that corresponds to the same risk as 20 mSv a^{-1}.

For workplace situations in which employees may be exposed both to radon and to other exposure sources, it is ensured that the resulting total risk is not greater than the risk corresponding to the limit value of 20 mSv a^{-1} provided that the following summation formula applies:

$$\frac{E_a}{20\ \mathrm{mSv\ a^{-1}}} + \frac{C_{Rn}}{\frac{1}{F \cdot t_a}\ \mathrm{MBq\ m^{-3}\ h\ a^{-1}}} \leq 1 \tag{34}$$

Here C_{Rn} is the (mean) radon activity concentration during the annual occupancy time at the workplace t_a , and E_a is the effective dose in the calendar year because of other exposure sources.

Although the graded approach recommended here is based exclusively on the relationships between risk and (cumulative) radon activity concentration derived from epidemiology and completely disregards dose estimation according to ICRP Publication 115 (ICRP 2010) or ICRP Publication 137 (ICRP 2017), an RDC d_R that would result in the same graduations with regard to radon activity concentration as recommended above can be specified. Providing such information makes it easier to compare the approach with that taken in other European countries. To do this, 20 mSv must be divided by the cumulative radon activity concentration over one year recommended for Stage 4 (cf. Equation (34)):

$$d_R = \frac{E_a}{c_{Rn} \cdot t_a} = \frac{20 \text{ mSv a}^{-1}}{\frac{1}{F} \text{ MBq m}^{-3}} = F \cdot 20 \ \frac{\text{mSv}}{\text{MBq h m}^{-3}} \tag{35}$$

or expressed in terms of cumulative potential alpha energy concentration (cf. Table 4.2):

$$d_R = F \cdot 20 \ \frac{\text{mSv}}{F \cdot 5.6 \text{ mJ h m}^{-3}} = 3.6 \ \frac{\text{mSv}}{\text{mJ h m}^{-3}} \tag{36}$$

where the ICRP gives values of $F \cdot 18.8$ mSv/(MBq h m^{-3}) or 3.3 mSv/(mJ h m^{-3}).

Equation (35) essentially follows the derivation of Equation (32) (there calculated for 6 mSv a^{-1}) and corresponds in principle to the epidemiological approach of the ICRP (cf. Section 4.3.2). The ICRP had indeed followed the epidemiological approach in the past but subsequently set it aside in favour of the dosimetric approach (ICRP 2017).

4.3.4 Change in the radiation weighting factor for radon

Another possible solution approach based on a study by Beck (2024) leads to a change in the radiation weighting factor for radon.

The detriment from ICRP Publication 103 (ICRP 2007) is based, like the previous ones, on the results of the Life Span Study (LSS). Most the dose was due to exposure to gamma radiation (i.e. 'low-LET' radiation). However, when considering exposure of the lungs to radon and its decay products, primarily alpha radiation must be taken into account. Alpha radiation has a higher relative biological effectiveness (RBE) because of its higher linear energy transfer (LET). If the effective dose is calculated as described in Section 4.3.2 using the energy dose $D_{L,R}$ absorbed in the lungs (Index L)

$$E = w_L \cdot w_R \cdot D_{L,R} = w_L \cdot H_L \,, \tag{37}$$

the weighting factor w_R accounts for this circumstance. By definition, for low-LET radiation (gamma, X-ray, beta), $w_R = 1$. For alpha radiation, $w_R = 20$; however, this is not necessarily identical to the RBE of each individual alpha emitter as the ICRP also states ((165) in ICRP 2003). (376) explicitly emphasises the need to derive a more meaningful factor for radon.

The tissue weighting factors w_T are derived from the specific detriment scores for 14 organs and tissues from the LSS study and other data. The detriment k_D (see Section 4.1.5) is a measure of the weighted health damage to a group of individuals and their descendants resulting from their radiation exposure. It depends on risk, mortality, quality of life, and loss of life expectancy.

The two detriments can be considered separately. First, the detriment $k_{D,L,\gamma}$ derived from studies following exposure to low-LET radiation. Second, the hazard ratio $k_{D,R}$ from epidemiological radon studies (e.g. of workers in uranium mining) as a function of exposure. Because these studies do not report the development of cancer in organs other than the lungs as a result of exposure to radon and its decay products, the L index can be omitted.

In ICRP Publication 65 (ICRP 1993), for $k_{D,\gamma}$, the 'nominal mortality' (the risk of death normalised to a standardised age distribution and taking both sexes into account) following exposure to radon and its decay products is used. From ICRP Publication 115 (ICRP 2010), this

is replaced by the use of the LEAR. Under the dose conversion convention, the ICRP compares dose-related detriment with exposure-related detriment. The ICRP uses the total detriment rather than just that for the lungs.

The procedure proposed by Beck (2024) is as follows:

$$k_{D,L,\gamma} \cdot D_{L,\gamma} = k_{D,L,\gamma} \cdot H_{L,\gamma} = k_{R,L} \cdot P_A \tag{38}$$

This equates the organ risks associated with the two types of exposure: on the left for low-LET radiation and on the right for radon and its decay products. In the case of low-LET radiation, $w_R = 1$ and thus numerically $D_{L,\gamma} = H_{L,\gamma}$.

It follows

$$E = w_L \cdot H_L = w_L \cdot \frac{k_{R,L}}{k_{D,L,\gamma}} \cdot P_A \,. \tag{39}$$

Combining equations (37) and (39) yields the radiation weighting factor for radon and its decay products (in lung tissue) as the ratio of the risk coefficients:

$$w_\alpha = \frac{k_{R,L}}{k_{D,L,\gamma}} \cdot \frac{P_A}{D_{L,R}} \tag{40}$$

A similar calculation was already used in ICRP Publication 150 (ICRP 2021) for exposure to uranium and plutonium.

If the energy dose to the lung caused by radon $D_{L,R}$ is replaced by the cumulative radon activity concentration P_A:

$$D_{L,R} = d_k \cdot P_A \tag{41}$$

with d_k (i.e. the radon dose coefficient), the conversion factor of energy dose per exposure is obtained:

$$E = w_L \frac{k_{R,L}}{k_{D,L,\gamma}} \cdot \frac{P_A}{D_{L,R}} D_{L,R} = w_L \frac{k_{R,L}}{k_{D,L,\gamma}} \cdot \frac{1}{d_k} D_{L,R} \tag{42}$$

The lung detriment $k_{D,L,\gamma}$ can be replaced by the total detriment k_{tot}. For this purpose, the relative detriment r_k is defined as the ratio of the organ-specific detriment (in this case, the lungs) to the total detriment

$$r_{k,L} = \frac{k_{D,L,\gamma}}{k_{D,tot,\gamma}} \tag{43}$$

Substituting Equation (40) into (39) yields

$$E = \frac{w_L}{r_{k,L}} \cdot \frac{k_{R,L}}{k_{D,tot,\gamma}} \cdot \frac{1}{d_k} D_{L,R} \tag{44}$$

and, by reearrangement

$$\frac{E}{D_{L,R}} \cdot d_k = \frac{w_L}{r_{k,L}} \cdot \frac{k_{R,L}}{k_{D,tot,\gamma}} \tag{45}$$

Radon exposure cannot be simply converted to dose by considering the ratio of the detriment from low-LET radiation to the detriment from radon. Rather, the relationship between the tissue weighting factor for the lungs, $w_L = 0.12$, and the relative detriment, $r_{k,L}$, must also be taken into account. This takes account of the fact that tissue weighting factors quantify the contribution of the lung dose to the effective dose and are not necessarily the same as the contribution of the organ detriment to the total detriment.

$$w_L = r_{k,L} \tag{46}$$

Table 4.14: Comparison of values for tissue weighting factor as well as coefficients for total radiation detriments and lung-specific radiation detriments according to ICRP 60 and ICRP 103 (source: Beck (2024)).

		Total radiation detriment $(\mathfrak{D}/H)_{tot}$ 10^{-5} mSv^{-1}	Lung-specific values			
			Lung detriment $(\mathfrak{D}/H)_{Lung}$ 10^{-5} mSv^{-1}	Relative detriment $\mathfrak{d}_{rel,Lung}$	Tissue weighting factor ω_{Lung}	Ratio $\frac{\omega_{Lung}}{\mathfrak{d}_{rel,Lung}}$
Whole population	ICRP 60	7.3[a]	0.80[a]	0.110	0.12	1.09
	ICRP 103	5.74[b]	0.903[b]	0.157[b]	0.12	0.76
Working age population	ICRP 60	5.6[a]	0.64[a]	0.114	0.12	1.05
	ICRP 103	4.22[b]	1.207[b]	0.286[b]	0.12	0.42

[a]ICRP 60, Table 4

[b]ICRP 103, Table A.4.1

The values given in ICRP Publication 60 (ICRP 1991) satisfy Equation (46) to a good approximation. With the publication of ICRP Publication 103 (ICRP 2007), the values for $r_{k,L}$ have increased while the tissue weighting factor for the lungs remains unchanged; Equation (46) is thus no longer satisfied. According to Equation (40), the values given in the dose conversion convention in ICRP Publication 65 (ICRP 1993) implicitly corresponded to a weighting factor for the alpha radiation from radon and its decay products of $w_\alpha = 10$ (Harrison und Muirhead 2003).

Later epidemiological studies of workers in uranium mining (NRC 1999, Tomasek et al. 2008) showed a doubling of risk as a function of exposure compared with those underlying ICRP Publication 65 (ICRP 1993). As a result, the nominal risk coefficient in ICRP Publication 115 (ICRP 2010) was increased from $2.83 \cdot 10^{-4}$ WLM^{-1} to $5 \cdot 10^{-4}$ WLM^{-1}. This increased the numerator of Equation (40) – and thus also w_α – by almost a factor of 2.

In ICRP Publication 103, the detriment to the lungs was almost doubled compared with ICRP Publication 60 (see Table 4.14). This increased the denominator of Equation (40) and offset the aforementioned increase in the numerator so that the radiation weighting factor, as given by Equation (41), should return to 10. According to Equation (9), this should also result in a reduction in the RDC. However, this did not occur solely because the dose conversion convention according to which the total (dosimetric) detriment is compared with that from radon exposure was retained.

Adjusting the radiation weighting factor for radon and its decay products to the correct value given by Equation (40), $w_\alpha = 10$, would restore consistency between the dosimetric and epidemiological approaches.

4.3.5 Possible impacts and consequences of implementing the recommendation

The possible impacts of the recommendations (Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**) based on the solution approach favoured by the SSK will become apparent during practical implementation with regard to

- the harmonisation of historical personal data that has been recorded in the radiation protection register following the conversion of radon exposure into an effective dose,
- the necessary adaptation of radiation protection requirements relating to occupational radiation protection insofar as occupationally exposed individuals are exposed to radiation from both radon and other sources of exposure, and
- the calculated effective dose for occupationally exposed individuals who have been exposed to radon while carrying out work outside Germany and for whom an effective

dose has been calculated according to individual, country-specific dose conversion guidelines.

The harmonisation of personal data and data recorded in the radiation protection register could be converted back into radon exposure in a straightforward manner because the currently valid dose conversion has already been applied in StrlSchV (2001).

From a purely practical point of view, the radiation protection requirements for occupational radiation protection can remain largely unchanged when workers are exposed to radon and other sources of radiation. In occupational radiation protection, all measured exposures must be added when assessing exposure limits. This requirement can be met by applying Equation (34). Compliance with the limit of 20 mSv per calendar year is demonstrated if the sum of both terms in this equation is ≤ 1.

Under the Radiation Protection Act, the monitoring of radiation doses for occupationally exposed persons must be traceable across state borders (see Parliamentary Paper 86/17 of 21 July 2017). According to the provisions of the EU Directive (Euratom 2014), the general dose limit for the effective dose is normally 20 mSv per calendar year. As noted in Section 4.2.4, dose coefficients are applied differently, and workplaces are classified differently across EU countries. Regardless of whether German legislation follows the recommendations of the SSK, which relate exclusively to radon exposure, it is difficult to compare regulations from other countries regarding risk assessment based on radon exposure. There are already discrepancies as a result of the different applications of the various RDCs of the ICRP and workplace classifications.

4.3.5.1 Alternative approaches

Various alternatives to the solution proposed here by the SSK were discussed because, as explained above, the preferred approach to protecting against the risks of occupational radon exposure deviates in some respects from the recommendations set out in ICRP Publication 137 (ICRP 2017). Despite all the arguments discussed above, its implementation could lead to certain problems in the context of international cooperation, including with regard to aligning the national system with future developments in the international radiation protection system. If, for this reason, there is a desire to follow the recommendation more closely, some SSK members suggest the following alternative:

Close alignment with the international system and the fullest possible implementation of European Commission Recommendation 2024/440 (EC 2024) would mean applying the ICRP dose conversion factors as they stand. For mines and indoor workplaces without substantial physical activity the recommended coefficient is 3 mSv/(mJ h m^{-3}) or $F \cdot 15.6$ mSv/(MBq h m^{-3}) with $F = 0.2$ typically assumed for mines and $F = 0.4$ for indoor workplaces.

For tourist caves and indoor workplaces with substantial physical activity, a coefficient twice as high is recommended, i.e. 6 mSv/(mJ h m^{-3}) or $F \cdot 31.3$ mSv/(MBq h m^{-3}), generally with $F = 0.4$.

Alternatively, in order to reduce the administrative burden and given the uncertainties in the model as well as the expected small number of workplaces affected, the introduction of the second, higher RDC could be dispensed with.

In other situations such as where ‘site-specific’ *F*-values are known, it should also be permissible to calculate other dose coefficients using the models developed by the ICRP.

The dose coefficients enable the estimation of individual effective doses for people working in areas with radon. This makes it possible to check whether certain employees exceed the dose criterion of 6 mSv per year and must therefore be classified as occupationally exposed to

radiation. Similarly, compliance with the annual limit of 20 mSv for workers exposed to radiation can be verified. The doses caused by radon can easily be combined with effective doses from other exposure pathways (external and internal).

In addition, radiation protection also recognises ‘derived activity concentrations’. They may be calculated for cases in which the exposure situation is essentially determined by a single radionuclide. The term ‘derived activity concentrations’ was first introduced in ICRP Publication 130 (ICRP 2015) and was subsequently used in the other publications in the OIR series (ICRP 2016, ICRP 2017, ICRP 2019). Similarly, StrlSchV (2018) defines ‘maximum permissible activity concentrations’ for the clearance of materials for disposal (Appendix 4, based on SSK Recommendation 2006 (SSK 2006)). In addition, the Radiation Protection Commission has developed derived guideline values for measures to protect individuals in the event of environmental contamination (SSK 2015) as well as reference levels for assessing emissions and immissions in environmental media (SSK 2016). It would therefore not be unusual to express dose criteria and limit values for pure radon exposures in units of $\mathrm{Bq\,m^{-3}}$ multiplied by the exposure time.

The SSK sees the following advantages to the dose-based approach:

- The approach used for decades in radiation protection (which combined risks from all exposure pathways into the effective dose) would not be abandoned in this context (radon protection).
- German radiation protection would thus not diverge from the international system.
- Recommendation 2024/440 of the European Commission (EC 2024) would be fully complied with.
- In the case of radon exposure alone, dose criteria and limit values could nevertheless be expressed as the product of radon activity concentration and exposure time.
- For radon-exposed persons for whom there is at least some plausibility that the same external radon activity concentration leads to a higher internal radiation exposure, correspondingly lower dose criteria and limit values could be specified.

The drawbacks of the dose-based approach were discussed in detail in the scientific justification.

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6 List of abbreviations

AMAD	Activity median aerodynamic diameter
AMTD	Activity median thermodynamic diameter
BfS	Federal Office for Radiation Protection
BSS	Basic Safety Standards
DCF	Dose conversion factor
DDREF	Dose and dose rate effectiveness factor
DeStatis	Federal Statistical Office of Germany
EEC	Equilibrium equivalent concentration
ERR	Excess relative risk
EURADON	European Association Radon Spas eV
EURADOS	European Radiation Dosimetry Group
GSR	General Safety Requirement
HRTM	Human Respiratory Tract Model
IACRS	Inter-Agency Committee on Radiation Safety
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LEAR	Lifetime excess absolute risk
LSS	Life Span Study
OIR	Occupational intakes of radionuclides
PAE	Potential alpha energy
PAEC	Potential alpha energy concentration
PUMA	Pooled Uranium Miners Analysis
RDC	Radon dose coefficient
SONS	State Office for Nuclear Safety (Czech Republic)
SSK	German Commission on Radiological Protection
SSM	Swedish Radiation Safety Authority
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WLM	Working level month

7 Glossary of terms

Active median aerodynamic diameter (AMAD)	AMAD is the abbreviation for Activity Median Aerodynamic Diameter and denotes the median of the activity distribution density as a function of the aerodynamic diameter of aerosol particles. The AMAD is one of the parameters influencing the dose following inhalation of radioactive substances.
Radon activity concentration	The radon activity concentration is the ratio of the radon activity to the volume of air containing radon. The unit of activity concentration is $\mathrm{Bq\,m^{-3}}$. Let A denote the radon activity and V the air volume; the radon activity concentration is then given by: $$C_{Rn}=A/V$$
Attached fraction of radon decay products	The attached fraction of radon decay products is the fraction of the potential alpha energy concentration of short-lived radon decay products that is attached to particles.
Equivalent dose	The ICRP and the ICRU have both stipulated weighting factors for radiation protection purposes which make it possible to take account of the varying biological effectiveness of different radiation types and energies and different radiation sensitivities of various organs and tissues in the dose estimation. Accordingly, the dose term "equivalent dose" used in radiation protection has the general meaning of a product of an ab-sorbed dose and either the radiation weighting factor defined by the ICRP or the quality factor defined by the ICRU. The term "equivalent dose" is used for body doses defined by the ICRP with the radiation weighting factor and for the local and personal dosimetry measurands defined by the ICRU with the quality factor. The equivalent dose is expressed in the same unit as the absorbed dose $\mathrm{J\,kg^{-1}}$. In order to make it clear that this is a weighted dose quantity, as with the effective dose it is expressed in sieverts (Sv) and not in grays (Gy).
Breathing rate	The breathing rate refers to the volume of air inhaled per unit of time. The unit of the breathing rate is $\mathrm{m^3\,h^{-1}}$. Also referred to in the international literature as the "ventilation rate" or "breathing rate".
DDREF	The DDREF (dose and dose-rate effectiveness factor) is an evaluation factor that takes into account, for certain radiation effects, the lower biological effectiveness (per unit of dose) of radiation exposures at low doses and low dose rates. It is the factor by which a dose-response relationship to be described differs from the LNT model. Whether it should continue to be considered in malignant processes is currently under discussion.
Deposition rate	Also referred to in the literature as the 'deposition velocity'. The deposition rate, or deposition velocity, is the ratio of the

mass of airborne radioactive substances deposited per unit of time and area to the mean mass concentration of these substances at vegetation height. The unit of the deposition velocity is m s^{-1}. For the deposition of aerosol particles, the deposition verlocity depends on their particle diameter.

Deposition velocity

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Detriment

The detriment is also referred to as the detriment-adjusted risk. The detriment is the product of the nominal risk coefficient and the detriment quality. It is expressed in Sv^{-1}. The detriment depends on a number of parameters. In particular, the following parameters are included in the calculation for each organ or tissue: the likelihood of incidence, the lethality fraction, the reduction of quality of life and the relative loss of life expectancy.

Dosimetric approach (for radon)

The dosimetric approach is a method used by the ICRP to determine radon dose coefficients (RDC). The dosimetric approach makes use of biokinetic reference models, in particular the ICRP Human Respiratory Tract Model (HRTM). The dosimetric approach makes no reference to epidemiological studies on radon risks.
See also epidemiological approach

Effective dose

The effective dose is the sum of the organ equivalent doses H_T (in relevant tissues and organs) multiplied by the corresponding tissue weighting factors w_T recommended by the ICRP and laid down in the Radiation Protection Ordinance.

$$E = \sum_T w_T \cdot H_T = \sum_T w_T \sum_R w_R \cdot D_{T,R}$$

H_T is the organ equivalent dose in a tissue or organ T; w_T is the tissue weighting factor and w_R the radiation weighting factor. The effective dose is expressed in J kg^{-1}. In order to make it clear that this is a weighted dose quantity, like the effective dose it is expressed in sieverts (Sv) and not in grays (Gy).

Epidemiologic approach (for radon)

The epidemiological approach is a methodology employed by the ICRP to determine radon dose coefficients (RDC). In the epidemiological approach, the ratio of the risk coefficient associated with radon exposure to the overall risk coefficient associated with loosely-ionising radiation (determined prima-

rily from the results of the LSS) is examined. The epidemiological approach does not refer to biokinetic or dosimetric models. See also dosimetric approach

Equilibrium equivalent concentration, EEC (radon)

The *equilibrium equivalent concentration* (EEC) C_{eq} denotes the activity concentration of ^{222}Rn (C_{Rn}) in equilibrium with its decay products that has the same potential alpha energy per unit volume as the actual, non-equilibrium mixture of radon and its short-lived decay products.

$$C_{eq} = 0.105 \cdot C_{Po-218} + 0.516 \cdot C_{Pb-214} + 0.379 \cdot C_{Bi-214}$$

The unit of equilibrium equivalent concentration is Bq m^{-3}.

For indoor environments, 1 Bq m^{-3} EEC corresponds to 2.5 Bq m^{-3} of ^{222}Rn because ^{222}Rn and its decay products are not in equilibrium. This is based on an assumed equilibrium factor of $F = 0.4$. Typical equilibrium factors in domestic premises range from 0.2 to 0.6.

Equilibrium factor *F* (radon)

The equilibrium factor is the ratio of the equilibrium equivalent concentration C_{eq} to the concentration of ^{222}Rn (radon), C_{Rn}. The equilibrium factor F thus represents the ratio of the potential alpha energy concentration $PAEC_{eq}$ – as it would exist in radioactive equilibrium – to the $PAEC_{Rn}$ of a given mixture of ^{222}Rn and its short-lived decay products. An analogous equilibrium factor can be defined for ^{220}Rn (thoron) and its decay products.

$$F = PAEC_{eq}/PAEC_{Rn} = C_{eq}/C_{Rn}$$

In practice, the value of F is always less than 1; typically, for ^{222}Rn, F is 0.4 for indoor air and 0.2 for mechanically ventilated mines.

Half-life, physical

The half-life t_r is the period of time in which the activity of a radionuclide r decreases to half of its original value.

$$t_r = \frac{ln2}{\lambda_r}$$

In this context, λ_r is the decay constant of the radionuclide r. After three half-lives have elapsed, approx. 10 % of the original activity remains, which further decreases to approx. 1 % after seven half-lives and to approx. 0.1 % after ten half-lives. The half-lives of radionuclides range from less than 10^{-12} s to more than 10^{12} a.

Human Respiratory Tract Model (HRTM)

The Human Respiratory Tract Model (HRTM) is a biokinetic model that describes the deposition, translocation, and absorption of inhaled substances in the human respiratory tract. The HRTM forms the basis for the dosimetric approach of the ICRP (ICRP 1994).

Cumulative potential alpha energy concentration P_{PAEC}	The cumulative potential alpha energy concentration P_{PAEC} is the time integral of the potential alpha energy concentration *PAEC* over an exposure time *T*. The unit of cumulative potential alpha energy concentration is J h m^{-3}.
Cumulative radon activity concentration	The cumulative radon activity concentration P_A is the time integral of the radon activity concentration C_{Rn} over an exposure time *T*. The unit of cumulative radon activity concentration is Bq h m^{-3}.
Life Span Study (LSS)	The Life Span Study (LSS) is an epidemiological study of the health effects in survivors of the atomic bombings of Hiroshima and Nagasaki. Epidemiological investigations in this cohort play a pivotal role in radiation epidemiology. Estimates of the dose-dependent cancer risk from this study were used in developping the fundamentals of the current system of radiation protection, for example, when defining limits.
Lifetime Excess Absolute Risk, LEAR	Lifetime Excess Absolute Risk (LEAR). The additional lifetime risk of a stochastic effect (also known as additional absolute probability) is approximated by the number of cases (e.g. lung cancer cases) per number of individuals in a reference population.
Nominal risk coefficient	The nominal risk coefficient is a lifetime risk estimate per dose unit for a representative population, averaged for sex and age at exposure. The lifetime risk is the absolute probability per dose unit of developing a solid cancer or leukaemia (incidence risk) or of dying from cancer (mortality risk). Among other things, nominal risk coefficients are used to determine tissue weighting factors.
Tissue weighting factor	Tissue weighting factors w_T represent an approximation of the contribution to the total health risk from radiation resulting from irradiation of a specific tissue or organ *T* after homogeneous whole-body irradiation. These factors are average values (averaged over men and women and across all age groups) and therefore do not represent specific characteristics of individuals. Tissue weighting factors are used to weight individual organ equivalent doses H_T in calculations of the effective dose *E*. These factors w_T reflect the different sensitivity of various organs, tissues or body parts *T* to stochastic radiation effects (cancer, heritable effects).
Potential alpha energy *PAE*	The potential alpha energy *PAE* is the sum of the alpha energies of ^{222}Rn and its short-lived decay products in radioactive equilibrium. The unit of the *PAE* is J.
Potential alpha energy concentration *PAEC*	The potential alpha energy concentration *PAEC* denotes the alpha energy that is emitted by an arbitrary mixture of short-

	lived ^{222}Rn decay products as they decay from ^{222}Rn to ^{210}Pb in a volume of air V , corresponding to a radon activity concentration C_{Rn}. It is equal to the potential alpha energy divided by the volume. The unit of *PAEC* is J m^{-3}.
Equilibrium, radioactive	Radioactive equilibrium refers to the state in a radioactive decay series in which the half-life of the parent nuclide is longer than those of the daughter nuclides and which is reached after a period that is long compared with the longest half-life of the daughter nuclides. The activity ratios of the elements in the decay series remain constant over time. This state is referred to as dynamic or transient equilibrium. If the half-life of the parent nuclide is much longer than that of all the daughter nuclides (e.g. the ^{238}U and ^{232}Th decay series), the activities of the daughter nuclides are then almost equal (steady-state equilibrium).
Radon dose coefficient, RDC	The radon dose coefficient (RDC, formerly dose conversion coefficient or dose conversion factor) describes the relationship between radiation exposure as a result of inhaling radon-222 and its decay products, expressed in units of mJ h m^{-3} or MBq h m^{-3} (see potential alpha energy concentration (*PAEC*) or radon exposure), and the effective dose, which is expressed in mSv.
Reference worker	The reference person is a hypothetical individual for whom organ doses are calculated by averaging the corresponding dose values for the male and female reference individuals. The organ doses for the reference person are multiplied by the relevant tissue weighting factors in order to calculate the effective dose. In the context of occupational radiation exposure, the reference person is defined in ICRP Publication 130 as reference worker.
Reference individual	'Idealised man' and 'idealised woman', with characteristic features defined by the ICRP for the purposes of radiation protection, i.e. possessing the anatomical and physiological properties speficied in ICRP Publication 89 on the reference human (ICRP 2002).
Reference level	In emergency or existing controllable exposure situations, this represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration.
Risk coefficient	The risk coefficient in radiation protection is a coefficient that is used to calculate the probability of occurrence of a stochastic effect per dose unit. A risk coefficient can be defined for the excess relative risk, the excess absolute risk or for cumu-

	lative risks. The parameter is the product of the risk coefficient and the dose. The unit is Sv^{-1}.
Unattached fraction (radon)	The unattached fraction is the fratction of the potential alpha energy concentration of short-lived radon decay products not attached to particles.
Working Level Month (WLM)	Working Level Month (WLM) is the unit of radon exposure received by a worker during a month (170 working hours) at 1 WL (Working Level). WLM is not an SI unit and should no longer be used.
Decay constant, physical	The decay constant λ_r is the reciprocal of the mean lifetime τ of a radionuclide r, or its half-life t_r, and represents a characteristic quantity for each radionuclide (see radioactive decay). $$\lambda_R = \frac{1}{\tau_r} = \frac{ln2}{t_r}$$ The unit of the decay constant is s^{-1}.
Decay products	The daughter nuclides formed during radioactive decay are referred to as decay products. These can be stable or radioactive. Generally, this term does not refer to the particles emitted by these nuclides (alpha particles, beta particles, photons, neutrinos, neutrons).
Excess relative risk (ERR)	The excess relative risk (ERR) is the ratio of the risk of an event (e.g. disease or death) in an exposed population to that in a non-exposed population, reduced by 1. In radiation epidemiological studies, the excess relative risk can be estimated as the ratio of the event rates in the two groups minus 1. In the literature, this relationship is often not presented, and the 'excess relative risk' is equated with the event rate ratio reduced by 1.