Management of radon: a review of ICRP recommendations

REVIEW

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Abstract
This article proposes a review of past and current ICRP publications dealing
with the management of radon exposures. Its main objective is to identify and
discuss the driving factors that have been used by the Commission during the
last 50 years so as to better appreciate current issues regarding radon exposure
management. The analysis shows that major evolutions took place in very
recent years. As far as the management of radon exposures is concerned, ICRP
recommended, until ICRP Publication 103 (ICRP 2007 *ICRP Publication 103;
Ann. ICRP* **37**), to use action levels and to consider only exposures above
these levels. The Commission has reviewed its approach and now proposes
to manage any radon exposure through the application of the optimisation
principle and associated reference levels. As far as the assessment of the radon
risk is concerned, it appears that the successive changes made by ICRP did not
have a strong impact on the values of radon gas concentration recommended as
action levels either in dwellings or in workplaces. The major change occurred
in late 2009 with the publication of the ICRP Statement on Radon, which
acknowledged that the radon risk has been underestimated by a factor of 2,
thus inducing a major revision of radon reference levels.

1. Introduction

Radon and its progeny are by far the most important source of ionizing radiation among those
that are of natural origin. According to the UNSCEAR, the annual dose from inhalation
of radon gas (and its decay products) represents typically about half of the average human
exposure to natural sources. The typical range of individual annual doses varies from 0.2 to
10 mSv (UNSCEAR 2010).

Radon (^{222}Rn) is a noble gas formed from radium (^{226}Ra) and has a half-life of 3.8 days.
When it is inhaled, ionizing alpha particles emitted by short-lived decay products of radon
(^{218}Po and ^{214}Po) can interact with biological tissue in the lungs leading to DNA damage.

Since the 1980s, it is thus recognised that long-term exposure to radon increases the risk of lung cancer (WHO 1986). Today, estimates of the proportion of lung cancers attributable to radon range from 3 to 14%, depending on the average radon concentration in the concerned country and the calculation methods (WHO 2009).

ICRP recommendations dealing with radon risk assessment successively relied on models representing the lung or on results of epidemiological studies on exposed groups of population (mainly miners). ^{222}Rn presents indeed the specificity to be a very studied radionuclide whose health effects are well characterised: in addition to dosimetric studies that exist for many radionuclides, data coming from epidemiological studies are very numerous and have progressively allowed a better understanding of the associated risk. This accumulation of data is of course of great value but may complicate the evaluations. Approaches and figures retained by ICRP have also varied several times during the last 50 years. The last change occurred in 2009 with the publication of the ICRP Statement on Radon (ICRP 2009) where the Commission acknowledged, according to recent epidemiological findings based on both mine and dwelling exposures, that the radon risk was underestimated by a factor of 2: 'for radiological protection purposes the Commission now recommends a detriment-adjusted nominal risk coefficient for a population of all ages of 8×10^{-10} per Bq h m^{-3} for exposure to radon-222 gas in equilibrium with its progeny (i.e. 5×10^{-4} WLM^{-1})', a value to be compared with 2.8×10^{-4} WLM^{-1} (ICRP 1993).

In parallel, ICRP has also addressed the management of radon risk. It had adopted quite a stable approach over the last 50 years, recommending a management of radon exposures through the use of action levels. However, a major change occurred recently with ICRP Publication 103. It is now recommended that any radon exposure should be reduced as low as reasonably achievable below the reference level, whereas previous recommendations only focused on exposures above the action level.

This article reviews ICRP publications dealing with the protection of miners, workers and the public against radon.

2. General overview

In 1928, the International X-ray and Radium Protection Committee already took into account radon progeny and its emanation within its recommendations even if at that time ^{222}Rn was considered as a beta/gamma emitter (International X-ray and Radium Protection Committee 1934). The recommendations published in 1928 and 1934 consequently concerned whole body and extremities exposures: they are not further detailed in this article.

It was only from the 1940s that internal exposure of radon was thought to be a possible cause of occupational diseases. At the end of 1950s, the ICRP started to carefully examine the radon issue, uranium mining was more and more intensive. From 1959 to the beginning of the 1980s, ICRP recommendations were only dedicated to the protection of miners against radon. In 1984, following the UNSCEAR publication on the sources of natural radiation for the general public (UNSCEAR 1982), the first ICRP publication dealing with public exposure to radon was elaborated. In 1993, the Commission dedicated an entire publication to protection against radon and introduced two types of exposure situations: in dwellings and at workplaces. Both situations are still considered in the most recent ICRP publications. Three exposure groups can also be distinguished when dealing with radon: workers considered as occupationally exposed to radon (mines), workers considered as members of the public (workplaces) and members of the public (dwellings).

ICRP has used two approaches to assess the radon risk and the associated dose in its different publications. Both approaches allow linking the radon risk and the radon exposure.

They are also used to relate exposure to radon progeny expressed in Working Level Month[1] or Bq h m^{-3} to effective dose in mSv. Indeed, for practical risk management, this factor, known as the dose conversion factor, is needed. It notably allows deriving occupational limits for intake of radon daughters from limits of effective dose. The epidemiological approach is based on the results of epidemiological studies, that is to say on the results of the direct observation of cohorts of population exposed to radon. Radon risk is assessed from the health effects observed in this cohort, compared to those observed in a population that is not exposed. The dose conversion factor is derived from epidemiological studies using the ratio of the risk of lung cancer in miners to the overall risk of cancer in the atomic bomb survivors. In the dosimetric approach, dosimetric models of the human respiratory tract are used to estimate equivalent dose to the lung and effective dose per unit radon exposure. Numerous parameters intervene in the calculations: size distribution of radon progeny, unattached fraction, breathing rate, clearance rate, etc. Once the effective dose is obtained, the concept of total detriment (expressed in Sv^{-1}) is used to assess the associated radon risk.

3. From 1958 to 1993: assessment of radon risk based on the dosimetric approach

3.1. Protection of miners

Three ICRP publications covered the 1958–1984 period: ICRP Publication 2 on permissible dose for internal contamination (ICRP 1959), ICRP Publication 24 on radiation protection in uranium and other mines (ICRP 1977a, 1977b) and ICRP Publication 32 on limits for inhalation of radon daughters by workers (ICRP 1981).

3.1.1. The critical tissue approach. ICRP Publication 2 was dedicated to the calculations of 'Permissible dose for internal contamination' for different radionuclides. It was issued to consider new data and methods for estimating internal dose and to revise permissible exposure values accordingly. The results were primarily made for occupational exposures. In this document, calculations were based on the critical tissue approach: it was considered that dose limitation for an individual could be determined by the dose-equivalent limit for a critical tissue.

In ICRP Publication 2, this approach was applied to radon. It was regarded that the critical tissue for radon was the epithelium of the lung. Consequently, a maximum permissible radon concentration in air was derived from a maximum permissible dose equivalent of 0.15 Sv to the epithelium of the lung (large bronchi). The calculation used a simplified lung model (which paid attention principally to the dose from inhaled daughter atoms attached to airborne particulates) to convert this dose in radon concentration: based on 40 working hours per week and a weighting factor for alpha particles of 10, it was then recommended not to exceed an annual average concentration of radon-222 of 30 pCi L^{-1} (or 1110 Bq m^{-3}). This limit referred to radon-222 in equilibrium with its short-lived daughters.

In 1977, ICRP Publication 24 was the first recommendation dedicated to radiation protection in uranium and other mines. This report was issued to bring advice on the practical application of the general recommendations from ICRP Publication 9 (ICRP 1966) to radiation protection in mines. It focused on monitoring principles, control measures, protective equipment and medical surveillance of miners. This publication endorsed the approach proposed in ICRP Publication 2 and kept recommending not exceeding a secular equilibrium

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[1] The Working Level (WL) is the historical unit of exposure to radon progeny applied to the uranium-mining environment. One Working Level Month (WLM) is defined as the cumulative exposure from breathing an atmosphere of 1 WL for a working month of 170 h.

equivalent radon concentration of 1100 Bq m^{-3} in mines. From ICRP Publication 24, miners have also been submitted to a regime of dose limitation, based on the critical tissue approach.

ICRP Publication 24 appears to be the first publication to refer to the equilibrium factor: 'Expressing any measured concentration of radon in the atmosphere in units of pCi L^{-1} as (Rn) and the measured concentration of the daughters in Working Level units as (WL), a quantity F called the equilibrium factor can be calculated: $F = 100\,(\text{WL})/(\text{Rn})$. For any given co-existing concentrations of radon and short-lived daughters in the atmosphere, F is the ratio of the total potential alpha energy of the actual daughter concentrations to the total potential alpha energy that the daughters would have if they were in equilibrium with the radon'.

F is also entering into ICRP publications with the practical aspects of radon exposure management. This value is specific to radon. It allows us, on the one hand, to describe the equilibrium between radon and its daughters and, on the other hand, to link the two units used in the measurement of radon concentration: WL and Bq m^{-3}.

Since ICRP Publication 24, the equilibrium factor F has always been used. It is a fundamental quantity in the evaluation of risk associated with radon. An F-factor of 1 means equal activities of radon and its progeny. In practice, F varies with the entry flux of radon, the ventilation rate and the rate of deposition of the decay products onto the surface. Generally, a value of 0.4 is used by default for the equilibrium factor in living areas. Thus, a concentration of radon gas of 100 Bq m^{-3} corresponds to an equilibrium equivalent radon concentration of 40 Bq m^{-3}. It is important to note that the choice of F can largely influence the considered concentrations of radon.

3.1.2. Development of a new dosimetric approach. ICRP Publication 32 dealing with limits for inhalation of radon daughters by workers, updated the previous recommendations and limits proposed by ICRP Publications 2 and 24 (ICRP 1981). It was published four years after the general recommendations from ICRP Publication 26 (ICRP 1977a, 1977b).

One of the main outcomes of ICRP Publication 26 was the development of the concept of effective dose: 'in its former recommendations the Commission stated that, when more than one organ of the body is exposed, the irradiation of one particular organ or tissue is likely to be of greatest importance because of the dose it receives, its sensitivity to radiation or the importance to health of any damage that results. This tissue or organ was referred to as the critical one under the circumstances and dose limitation for the individual was determined by the dose-equivalent limit for that tissue or organ. The concept of the critical organ used in this way did not permit the summation of detriment according to the relative radiosensitivities of the irradiated tissues. The Commission now recommends a procedure which takes account of the total risk attributable to the exposure of all tissues irradiated'. In this context, ICRP also defined the weighting factors (w_T) representing the proportion of the risk resulting from tissue (T) to the total risk, for a uniform whole body irradiation. The values of w_T recommended by the Commission in 1977 are outlined in table 1. For lung, a weighting factor of 0.12 was retained.

ICRP Publication 26 defined exposure limits expressed in terms of effective dose: for workers, the Commission recommended a whole body dose-equivalent limit of 50 mSv in a year; for members of the public, it recommended a whole body dose-equivalent limit of 5 mSv in a year. Finally, ICRP Publication 26 reviewed the weighting factor for alpha particles and doubled the value. The w_R factor was evaluated at 20 (replacing the former value of 10). This figure was regarded as an envelope value taking into account new biological effects of all alpha particles, non-specifically related to radon. This had an impact on the dosimetric models used to calculate dose to the lung.

ICRP publication 32 stated that 'this concept of the effective dose equivalent, which replaces the previous concept of the critical tissue,... can also be used for radon and

Table 1. Weighting factors recommended by ICRP Publication 26 (1977).

Organ	Risk factor to develop a pathology (Sv^{-1})	Total risk (Sv^{-1})	Ratio	Weighting factor
Red bone marrow	2×10^{-3} (leukaemia)		0.12	0.12
Bone	5×10^{-4} (bone cancer)		0.03	0.03
Lung	2×10^{-3} (lung cancer)		0.12	0.12
Thyroid	5×10^{-4} (thyroid cancer)	1.65×10^{-2}	0.03	0.03
Breast	2.5×10^{-3} (breast cancer)		0.15	0.15
Gonads	4×10^{-3} (hereditary effects)		0.25	0.25
Other tissues	5×10^{-3} (cancer)		0.3	0.3

radon daughters'. It also considered miners as occupationally exposed workers and thus recommended an annual dose limit of 50 mSv for their protection.

ICRP Publication 32 mainly focused on the way to derive occupational limits for intake of radon daughters from the limit of effective dose of 50 mSv. Several chapters are devoted to the description of the advantages and drawbacks of both dosimetric and epidemiological approaches. Actually, ICRP Publication 32 was the first ICRP publication on radon to take into account epidemiological data on miners. However, in 1981, data only came from two cohorts of miners: one in the USA and another one in the former Czechoslovakia. The Commission considered that they were not reliable enough to be used (small size of the population, lack of knowledge on confounding factors, low reliability of the exposure data, youth of the cohort, etc) and decided to rely on the dosimetric approach to assess the radon risk and to derive a dose conversion factor.

In 1981, new models for estimating the dose distribution in the respiratory tract from inhaled radon daughters were available, notably those developed in ICRP Publication 30 (ICRP 1979). As far as the modelling of the lung was concerned, two approaches were then possible: using either the mean lung dose concept or the regional lung dose concept. Arguing that the irradiation of the lung was not uniform, the Commission decided to use the regional lung dose concept.

On the basis of this dosimetric model, ICRP Publication 32 finally recommended to protect miners by applying an annual exposure limit of 4.8 WLM corresponding to an annual limit of 50 mSv. Assuming an annual working period of 2000 h, this gave a maximum equilibrium equivalent radon concentration of 1500 Bq m^{-3}. This value was recommended until 1993 and was notably endorsed by ICRP Publication 47 (ICRP 1986).

3.2. Publications dedicated to the protection of members of the public

In 1982, the annual effective dose attributable to radon was assessed to increase from 1 to 2 mSv for members of the public (UNSCEAR 1982). This increase was mainly linked by the consideration of the effective dose from the decay products of radon. On the basis of these new findings, ICRP decided to address recommendations on the possibility to control and limit exposures to natural sources. The Commission thus published its first recommendations on natural exposures (ICRP 1984).

ICRP Publication 39 introduced two situations of radon exposure: existing and new exposure situations, and recommended the use of an action level to manage them. It did not provide details on this concept, but it may be considered that an action level is a point from which it is necessary and justified to implement protective measures. Below this level, it is considered that it is not relevant to act.

Table 2. Weighting factors recommended by ICRP Publication 60.

Organ	Weighting factor
Gonads	0.20
Liver	0.05
Breast	0.05
Oesophagus	0.05
Bone marrow	0.12
Colon	0.12
Thyroid	0.05
Skin	0.01
Lung	0.12
Stomach	0.12
Bones	0.01
Bladder	0.05
Other tissues	0.05

For existing situations, the Commission recommended the use of an action level specific to the type of remedial action being considered. For radon, it was thus mentioned 'if the remedial action considered is fairly simple, an action level for equilibrium equivalent radon concentration in the region of 200 Bq m^{-3} (annual effective dose equivalent of 20 mSv) might be considered. For severe and disrupting remedial action, a value several times larger might be appropriate'. The publication did not provide any explanation on why a value of 20 mSv per year was considered to derive this action level while the recommended exposure limit for the public was 5 mSv per year at that time.

For future exposure situations, the Commission recommended that the exposure of the most highly exposed individuals should be limited by the application of an upper bound of individual dose. It was of course expected that the upper bound for a new situation would be lower than the action level for a similar existing situation. The Commission also indicated that a reasonable upper bound for the equilibrium equivalent radon concentration was in the order of 100 Bq m^{-3} (equivalent to 10 mSv per year).

4. From 1993 to 2007: assessment of radon risk based on an epidemiological approach

In 1993, ICRP published full recommendations on the protection against radon-222 (ICRP 1993). It was the first publication covering both workers (including miners) and members of the public and replaced previous publications.

4.1. Elements from ICRP Publication 60

In its 1990 recommendations, the Commission introduced two exposure situations: practices (where human activities introduce new sources or modes of exposure and thus increase the overall exposure) and interventions (where human activities decrease the exposure to existing sources) (ICRP 1991). Management of exposure to radon in dwellings was classified in the regime of interventions 'radon in dwellings and in the open air are examples of situations that can be influenced only by intervention'.

In ICRP Publication 60, new organs are considered in the calculation of the total detriment and a distinction between the whole population and workers is introduced in the calculations (see table 2). However, it did not change the weighting factor used for the lung: the value of 0.12 is maintained.

Table 3. Dose conversion factors proposed by ICRP Publication 65.

Population	Lifetime lung cancer risk (WLM^{-1})	Total detriment (Sv^{-1})	Dose conversion factor (mSv WLM^{-1})
Workers	2.8×10^{-4} (ICRP 65)	5.6×10^{-2} (ICRP 60)	5
Public	2.8×10^{-4} (ICRP 65)	7.3×10^{-2} (ICRP 60)	4

Finally, the publication revised the annual exposure limits: a limit on effective dose of 20 mSv per year, averaged over 5 years (100 mSv in 5 years) for workers, and a limit of 1 mSv per year for members of the public.

4.2. The approach proposed by ICRP Publication 65

ICRP Publication 65 completely reviewed the ICRP approach regarding the assessment of the radiological risk associated with radon exposure: it abandoned the dosimetric approach and adopted the epidemiological approach: 'although there are uncertainties in both the above approaches, they do not lead to widely different results. The Commission has concluded that the use of the epidemiology of radon in mines is more direct, and therefore involves less uncertainty and is more appropriate for the purpose of this report than the indirect use of the epidemiology of low linear energy transfer (LET) radiation from the Japanese data. The Commission therefore recommends that the dosimetric model should not be used for the assessment and control of radon exposures'.

At that time, epidemiological studies were mainly focused on miners while results of studies on dwellings were lacking in statistical power to be taken into account. ICRP thus estimated the risk of lung cancer death from radon exposure on the basis of studies of seven cohorts of miners. The Commission used a multiplicative projection model to derive results obtained with adult males in mines for the general population. The lifetime lung cancer risk was estimated at 2.8×10^{-4} WLM^{-1}.

The dose conversion factors (from radon exposure quantities to effective dose) were then obtained by a direct comparison between the detriment per unit radon exposure (risk of lung cancer) and the total detriment associated with a unit of effective dose (ICRP 1991) (see table 3).

These dose conversion factors were then used to derive radon concentrations from the effective dose limits. The meaning of these concentrations was determined with the classification of radon exposures either in practice or in interventions. According to ICRP: 'in existing dwellings, the exposures can be reduced only by some form of intervention. In workplaces, it is necessary to consider both the need for intervention (as in dwellings) and the continued control of radon exposures as part of the practice carried out in the workplace' (ICRP 1993).

Consequently, for dwellings, ICRP Publication 65 also went on to recommend the use of action levels for initiating intervention: this was consistent with ICRP Publication 39. Here, it can be pointed out that an action level is defined as 'the concentration of radon at which intervention is recommended to reduce the exposure in a dwelling or workplace'. There was no more distinction between existing and new dwellings.

For workplaces, ICRP Publication 65 distinguished, on the one hand, workers who were not regarded as being occupationally exposed to radiation and, on the other hand, miners. For the first case, ICRP Publication 65 decided to consider them in the same way as members of the public and to define an action level to manage their exposure to radon. Miners were considered as occupationally exposed workers and submitted to the occupational annual limit recommended by ICRP Publication 60 (effective dose of 20 mSv per year, averaged over 5 years).

For members of the public and workers who were not regarded as being occupationally exposed to radiation, the Commission then mentioned the following arguments.

- 'It seems clear that some remedial measures against radon in dwellings are almost always justified above a continued annual effective dose of 10 mSv. For simple remedial measures, a somewhat lower figure could be considered, but a reduction by a factor of 5 or 10 would reduce the action level to a value below the dose from natural background sources. The choice of an action level for annual effective dose is thus limited to the range of about 3–10 mSv . . . . The corresponding rounded value of radon concentration is about 200–600 Bq m^{-3}, with an annual occupancy of 7000 h and an equilibrium factor of 0.4.' These values were recommended for both existing and new dwellings.
- 'Workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as members of the public. It is then logical to adopt an action level for intervention in workplaces at the same level of effective dose as the action level for dwellings.' The action level was also derived not to exceed an annual dose of 3–10 mSv. The corresponding rounded value of radon concentration in workplaces was about 500–1500 Bq m^{-3} (assuming an annual occupancy of 2000 h and equilibrium factor of 0.4).

5. ICRP current position on radon exposures

In the new ICRP recommendations (ICRP 2007), the Commission recognised three types of exposure situations, which replaced the previous categorisation into practices and interventions. They are defined as follows.

- 'Planned exposure situations are situations involving the deliberate introduction and operation of sources.
- Emergency exposure situations are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences.
- Existing exposure situations are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations after emergencies.'

According to these definitions, ICRP classified indoor radon in dwellings and workplaces as an existing exposure situation. As a consequence, ICRP recommended that reference levels, set in terms of individual dose, should be used in conjunction with the implementation of the optimisation process for the management of radon exposures. The reference level is defined in the following manner: 'in emergency or existing exposure situations, this (stands) for the restriction on 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'. ICRP underlined that 'for the sake of continuity and practicability, the Commission retains the upper value of 10 mSv for the individual dose reference level'. Reference levels in terms of activity concentrations of radon derived from this effective dose are also endorsed: 600 Bq m^{-3} for dwellings and 1500 Bq m^{-3} for workplaces.

In 2007, in the light of new scientific data coming from both epidemiological studies and dosimetric calculations, ICRP decided to create a specific task group to review the risk related to radon. The task group came to the conclusion that the absolute risk of lung cancer due to radon should be multiplied by 2. Based on these results, the Main Commission published a statement in November 2009 (ICRP 2009). This statement, which is the most recent ICRP position on radon exposure management, acknowledges the latest data on health effects attributable to exposure to radon and its decay products: it recommends a lifetime lung cancer risk of 5×10^{-4} WLM^{-1} (to be compared with the coefficient used in ICRP Publication 65, estimated at 2.8×10^{-4} WLM^{-1}). The statement renews again the ICRP approach to determine dose conversion factors. Indeed, it indicates that ICRP has moved back

Table 4. Summary of the ICRP publications dealing with the protection of miners.

ICRP Publication	Dose limit (mSv)		Radon risk approach	Dose conversion factor	Maximum level of radon
	Dose to the lung	Effective dose			
Pub. 2 and 24 (1959–81)	150	—	Dosimetric	—	2800 Bq m^{-3}
Pub. 32 (1984–93)	—	50	Dosimetric	10 mSv WLM^{-1}	3775 Bq m^{-3}
Pub. 65 (1993–2007)	—	20	Epidemiological	5 mSv WLM^{-1}	3150 Bq m^{-3}
Statement 2009	—	20	Dosimetric	NA	NA

to the dosimetric approach: 'the Commission now proposes that the same approach be applied to intake of radon and progeny as that applied to other radionuclides, using reference biokinetic and dosimetric models. Dose coefficients for radon and progeny will replace the Publication 65 dose conversion convention which is based on nominal values of radiation detriment derived from epidemiological studies comparing risks from radon and external radiation'. It announces also that this change is likely to result in an increase of around a factor of two for the dose coefficients.

As far as the management of radon exposures is concerned, ICRP continues to recommend an annual reference level of 10 mSv and revises the upper values for radon gas in dwellings and workplaces according to the new assessment of the radon risk. Workers exposed to radon incurred as a result of their work are still considered as occupationally exposed and are under the regime of dose limits (20 mSv yr^{-1}).

6. Discussion

Since 1958, ICRP has reviewed several times its approach dealing with radon risk assessment: from 1958 to 1993, it adopted a dosimetric approach to assess the radon risk and to derive dose conversion factors; from 1993 to 2009, it relied on an epidemiological approach and in 2009, the Commission announced its decision to move back to a dosimetric approach. These choices have been based on the best scientific knowledge available at the time of the publications. However, in spite of these changes, it is interesting to note that ICRP recommended levels of radon concentration have not evolved a lot.

Table 4 summarises the evolution of the ICRP publications dealing with the protection of miners. ICRP has always considered miners as exposed workers. They were consequently submitted to occupational dose limits. These limits, expressed in mSv, were then used to derive maximum levels of radon concentration in mines, mainly expressed in WLM. As just said, in spite of changes in the approaches to assess the radon risk and the decrease of the annual dose limit from 50 to 20 mSv for exposed workers, the maximum level of radon concentration remained around 3000 Bq m^{-3}. In practice, this level has not been often used in the daily operation in mines. As miners are exposed to several sources of ionizing radiations, the dose limit has been a better tool to manage their exposure (the notion of additivity of exposures has been introduced by ICRP Publication 65: 'In mines, there will often be exposures to radioactive ore dusts and gamma radiation. In such circumstances, it will be necessary to aggregate the doses for comparison with the dose limit'). It has to be noted that in the last ICRP publication, miners are not explicitly mentioned: they are integrated in the workers 'exposed to radon incurred as a result of their work'.

Table 5 summarises the evolution of the ICRP publications dealing with the protection against radon in dwellings. It shows that three main steps can be distinguished.

Table 5. Summary of the ICRP publications dealing with the protection against radon in dwellings.

ICRP Publication	Protection level	Radon risk approach	Dose conversion factor	Level of radon concentration
Pub. 39 (1984–1993)	Action level: 10 mSv yr^{-1}	Dosimetric	10 mSv WLM^{-1}	500 Bq m^{-3}
Pub. 65 (1993–2007)	Action level: 10 mSv yr^{-1}	Epidemiological	4 mSv WLM^{-1}	600 Bq m^{-3}
Pub. 103 (2007–2009)	Reference level: 10 mSv yr^{-1}	Epidemiological	4 mSv WLM^{-1}	600 Bq m^{-3}
Statement 2009	Reference level: 10 mSv yr^{-1}	Dosimetric	In course of evaluation	300 Bq m^{-3}

- From 1984 to 2007: during this period, in spite of a change in the methods to assess the radon risk, the management approach remained the same. Radon exposures were managed through the use of an action level of 10 mSv, corresponding to a radon concentration close to 600 Bq m^{-3}.
- From 2007 to 2009: this period was marked by the publication of ICRP Publication 103 and the decision to apply the optimisation principle to any exposure situation. In the case of radon, this has implied a fundamental change: any radon exposure should now be reduced as low as reasonably achievable below a reference level. The value of 10 mSv has been retained for the choice of the reference level. The radon concentration of 600 Bq m^{-3} was also endorsed as a reference level expressed in radon gas concentration.
- From 2009: this period is characterised by the publication of the ICRP Statement on Radon. This statement acknowledges the re-assessment of the radon risk and recommends doubling the risk coefficient. Thus, as the Commission keeps its value of 10 mSv as a reference level, ICRP proposes to revise the value of the reference level expressed in radon gas concentration: the value of 300 Bq m^{-3} is now recommended.

As far as radon in dwellings is concerned, major evolutions also occurred in the last three years. One can note that the value of 10 mSv was always retained as a good benchmark value in the various recommendations. Nevertheless, very few rationales were provided to explain these choices. One can also question the relevance of this dose criterion. Indeed, it may be considered that this dose level is quite high compared to the annual average dose due to radon (around 2 mSv) and does not offer a good incentive to reduce radon exposures.

Table 6 summarises the evolution of the ICRP publications covering the protection against radon at workplaces. ICRP introduced the notion of exposure to radon at workplaces in its Publication 65. From that time, it created a distinction between people in workplaces considered as members of the public (non-occupationally exposed workers) and people in workplaces where radiation protection requirements apply (occupationally exposed workers). Since this publication, the difficulty has been in the definition of criteria to distinguish both situations.

In ICRP Publication 65, non-occupationally exposed workers were managed as members of the public: an action level of 1500 Bq m^{-3} (based on an action level of 10 mSv) was recommended to assess their exposures. In addition, it was indicated that 'when simple countermeasures do not reduce the radon concentrations below the action level, the Commission's system of protection should be applied to the practice'. Workers were also considered as occupationally exposed when it was not easy to reduce the radon concentration below 1500 Bq m^{-3}: in that case, they were treated as exposed workers and submitted to an annual dose limit of 20 mSv.

Table 6. Summary of the ICRP publications dealing with the protection against radon at workplaces.

ICRP publication	Protection level	Level of radon concentration
Pub. 65 (1993–2007)	Action level: 10 mSv yr^{-1}	1500 Bq m^{-3}
		If simple countermeasures do not reduce the radon concentration below 1500 Bq m^{-3}: application of occupational protection requirements
Pub. 103 (2007–9)	Reference level: 10 mSv yr^{-1}	1500 Bq m^{-3}
		Entry level to apply occupational protection requirements: 1000 Bq m^{-3}
Statement 2009	No mention	Entry level to apply occupational protection requirements: 1000 Bq m^{-3}

In ICRP Publication 103, radon exposure at workplaces was classified as an existing exposure situation. The value of 10 mSv was maintained as a reference level: the corresponding value of radon concentration of 1500 Bq m^{-3} was also endorsed. Besides, it was written that 'radon exposure at work at levels above the national reference level should be considered part of occupational exposure whereas exposure at levels below should not'. It was then added that a level of 1000 Bq m^{-3} should be used to define the entry point for applying occupational protection requirements. ICRP Publication 103 also proposed two different values and concepts to manage radon exposures at workplaces: on the one hand, it was recommended that radon exposure should be reduced as low as reasonably achievable below the reference level of 1500 Bq m^{-3} and, on the other hand, if the optimisation process does not result in concentration below 1000 Bq m^{-3}, it was recommended to apply occupational protection requirements. The zone between 1000 and 1500 Bq m^{-3} could also be managed through different dispositions.

Finally, in its 2009 statement, one can consider that ICRP simplified these recommendations. Only an entry point of 1000 Bq m^{-3} was defined for applying occupational protection requirements at workplaces. Nevertheless, the statement did not provide any information for the general management of radon exposure at workplaces and did not explicitly mention a reference level either in dose or in radon concentration. In this context, the meaning of the entry point considered above may be interpreted as a reference level to drive the optimisation process for workers with the requirement to treat them as occupationally exposed workers in the case where the levels of exposures can hardly be reduced below 1000 Bq m^{-3}. The statement also outlined that the Commission, within its future publications on radon exposure management, will rely on the dosimetric approach and that 'Dose coefficients will be given for different reference conditions of domestic and occupational exposure, taking into account factors including inhaled aerosol characteristics and disequilibrium between radon and its progeny. Sufficient information will be given to allow specific calculations to be performed in a range of situations'. This approach will provide dose coefficients that should be more appropriate to specific exposure situations and thus appears as an improvement of radon exposure management, even if uncertainties remain in the calculation of such coefficients. It remains important to keep in mind that the radiation protection system does not aim to provide individual but general guidance for the management of exposure to ionizing radiation. Uncertainties have to be managed in a cautious way.

7. Conclusions

ICRP publications on the assessment and management of radon risk have been quite numerous during the last 50 years. The very recent re-evaluation of the radon risk has led ICRP to

decrease the reference levels expressed in radon concentration: in dwellings, a reference level of 300 Bq m^{-3} is now recommended.

Combined with the fact that radon exposure situations should now be managed through the optimisation principle, these modifications are questioning the practical management of the radon risk in numerous countries. While a number of national authorities began to review their regulations, ICRP has created a specific Task Group whose aim is to provide recommendations on the application of ICRP Publication 103 to radon exposures in the light of the 2009 statement. One can expect that this forthcoming ICRP publication will bring clear information to help to further reduce radon exposures both in dwellings and workplaces.

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