REPORT

IRSN
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Faire avancer la sûreté nucléaire

New dose coefficients for radon, recommended in ICRP Publication 137

Explanatory note

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Contents

1. INTRODUCTION

In January 2018, the International Commission on Radiological Protection (ICRP) issued Publication 137 entitled “Occupational Intakes of Radionuclides: Part 3” (ICRP, 2017). That document is part of a series of publications that aim to provide basic data and parameters, for the main chemical elements and their radioactive isotopes, to describe the distribution of these elements in the human body in the event of intake. For this, the publications provide a review of available data and biokinetic models and provide factors for calculating the effective doses associated with ingestion or inhalation of the radionuclides in question. Publication 137 covers fourteen elements, including radon (Rn).

The present document aims to present the new dose coefficients adopted by the ICRP for radon inhalation, to specify the assumptions and scientific data on which they are based, and to discuss the associated uncertainties.

Some basic information on radon is given in Chapter 2, then Chapter 3 presents the foundations of the dosimetric approach on which the definition of dose coefficients given in ICRP Publication 137 is based. Chapter 4 examines the consistency of these new values with those derived from the epidemiological approach previously used by the ICRP. The variability and uncertainties associated with determining the dose coefficients are discussed in Chapter 5. A conclusion is given in Chapter 6.

2. BASIC INFORMATION ON RADON

Radon is an inert radioactive gas, produced naturally by the uranium and thorium decay chains. Its most abundant isotopes are radon-222 (^{222}Rn), with a half-life of 3.8 days, radon-220 (^{220}Rn), with a half-life of 55.6 seconds, commonly referred to as thoron, and radon-219 (^{219}Rn), with a half-life of 3.96 seconds, commonly referred to as actinon. Given the respective half-lives of these isotopes, only ^{222}Rn and to a lesser extent ^{220}Rn are likely to produce significant doses in the event of intake. While Publication 137 covers the three isotopes mentioned above, only the case of ^{222}Rn is described in the rest of this report. For simplification, in the remainder of this document, the term radon will be used indiscriminately to refer to the element or its isotope radon-222.

Radon is quickly diluted in outside air and its mean concentration (or activity concentration) generally remains low, most often less than about ten becquerels per cubic meter (Bq m^{-3}) of air. In confined spaces such as underground mines, caves and buildings in general, it can accumulate and reach concentrations as high as several thousand Bq m^{-3}. The radon gas present in the ambient air transforms, by alpha decay, into solid progeny, themselves radioactive with short half-lives (less than 30 minutes). Among these progeny, two – polonium-218 and polonium-214 – are also alpha emitters.

Due to their high mobility, radon's short half-life radioactive progeny fix onto water vapour or gas molecules in trace form in the air (constituting the "unattached fraction" of nanometric size) or onto atmospheric aerosols (forming the "attached fraction" with a size from a few nanometres to a micrometre). Progeny, regardless of whether fixed onto aerosols or not, quickly diffuse in the atmosphere and are ultimately deposited onto the ground or the walls of buildings, such that, regardless of the location, they are never totally in radioactive equilibrium with radon. The equilibrium fractions of radon's short half-life progeny are described by a dimensionless factor called the "equilibrium factor"[1]. This factor ranges from 0 (when radon is present in the air without progeny) to 1 (when radon's short half-life progeny are present in the air at the same concentration as radon).

When a person is exposed to radon and its short half-life progeny, whether attached to dust or not, the inhaled progeny are deposited in the respiratory system and irradiate it. The delivered dose depends on the location of the deposits, which is itself a function of particle size. Finer particles (in particular the unattached fraction) can reach the sensitive cells of the bronchial epithelium and the pulmonary alveoli and thereby deliver larger doses. Radon is a gas and is largely exhaled again so it only weakly irradiates.

Epidemiological studies on uranium miners have shown a risk of excess mortality due to lung cancer associated with radon exposure. More recent studies in the general population have shown that this risk is also significant for continuous domestic exposure to radon at concentrations above approximately 200 Bq m^{-3}. Since 1987, the World Health Organisation has recognised radon as a known cause of human lung cancer. Its action, combined with that of smoking, leads to a relative lung cancer risk somewhere between the sum and the product of the two relative risks.

3. DOSE COEFFICIENTS FROM ICRP PUBLICATION 137 AND THEIR BASIS: THE DOSIMETRIC APPROACH

The dose coefficients given in ICRP Publication 137 were determined based on a dosimetric approach. This consists of taking into account the physical phenomena that determine the distribution of radionuclides in the body to quantify the energy deposited per unit mass in the various regions of the body and to give it a weighting based on the toxicity of the radiation and the radiosensitivity of the tissues. This is the approach that the ICRP has always used to determine dose coefficients for all radionuclides, except for radon for which it previously used an epidemiological approach (see Chapter 4).

[1] The equilibrium factor is $F = (0.105C_1 + 0.516C_2 + 0.379C_3) / C_0$, where C_0 is the concentration of radon in the air, and C_1, C_2 and C_3 that of its three progeny (polonium-218, lead-214 and bismuth-214 respectively).

Dosimetric model adopted

In the case of radon inhalation, the main contribution to the effective dose is from alpha irradiation of radiosensitive lung cells. This irradiation is mainly due to radon progeny deposited in the respiratory system during breathing. The contribution of radon gas itself is estimated to represent only around 2% to 5% of the effective dose.

The human respiratory tract model on which the dosimetric approach adopted in ICRP Publication 137 is based is described in ICRP Publication 66 (ICRP, 1994). This model is used to estimate the fraction of radioactive aerosols deposited in the bronchi and pulmonary alveoli, based on their aerodynamic and thermodynamic properties. After being deposited, radioactive particles are removed from the lung by mechanical transport to the digestive tract and by absorption into the blood. The short radioactive half-life of radon progeny means that no significant proportion of these radionuclides is removed before their decay. The energy deposited in the lung cells is calculated based on their position with respect to the radionuclide deposit sites and the range of the alpha particles emitted. Furthermore, the respiratory tract model used considers that a fraction of the radon gas present in the air in the lung is dissolved into the blood stream which distributes it in the body causing irradiation of other organs. As stated above, this irradiation only marginally contributes to the effective dose.

In the effective dose calculation, a radiation weighting factor $W_R = 20$ is assigned to the dose resulting from alpha radiation with respect to that from gamma radiation and a tissue weighting factor $W_T = 0.12$ is assigned to the pulmonary dose with respect to the whole body dose (ICRP, 2007).

Exposure situations considered

The dose from radon inhalation depends on parameters specific to the environmental conditions and parameters associated with respiratory physiology:

- significant ventilation of the rooms, as in the case of mines, reduces the probability of progeny forming, thereby reducing the equilibrium factor and the dose received.
- dusty air reduces the unattached fraction and, due to the fact that progeny attached to dust have a lower dosimetry weighting than that of unattached progeny, the dose received also reduces;
- more intense physical activity increases the breathing rate and, thus, the inhaled activity of radon and its progeny;
- the size of ambient aerosols to which the progeny are attached influences their deposition in the respiratory tract. Dust size between 1 and 10 nm increases its deposition in the bronchi and bronchioles and the resulting dose.

In practice, the equilibrium factor is used to convert a radon gas exposure measurement in becquerel hours per cubic meter (Bq h m^{-3}) into an exposure to progeny in millijoule hours per cubic meter (mJ h m^{-3}) or in Working Level Month[2] (WLM).

In most buildings, a reduction in the equilibrium factor is associated with an increase in the unattached fraction. As the delivered dose varies in the same way as these two parameters, their influence on the dose assessment based on the radon concentration tends to cancel out. For this reason and for practicality, in ordinary dwellings and workplaces, radon gas is measured. The measurement is thus expressed in becquerels per cubic meter (Bq m^{-3}). In contrast, in highly-ventilated mines this inverse correlation is not observed and monitoring is generally based on measurement of progeny. In this case, the measurement is in millijoules per cubic meter (mJ m^{-3}) or in Working Level[3] (WL).

For practical implementation of its dosimetric approach, the ICRP adopts a limited number of standard exposure situations. This choice aims to overcome the difficulties associated with the numerous influencing parameters listed above and the diversity of possible conditions. It also aims to offer operational aspects applicable to the vast majority of workplaces.

Specifically, ICRP Publication 137 adopts four exposure situations covering three types of location: buildings, underground mines and tourist caves. For these three types of location, exposure is defined in reference to the case of a worker engaged in physical activity two thirds of the time, with a mean breathing rate of 1.2 m^3 h^{-1}. For buildings, the ICRP also considers the case of an individual performing sedentary work, such as office work. This is assumed to involve mild physical activity one third of the time and a mean breathing rate of 0.86 m^3 h^{-1}.

Choice of exposure parameters

To calculate the dose coefficients for each of the four situations adopted, the ICRP has set default values for the following key parameters:

- the unattached fraction of radon progeny, which depends on the aerosol concentration in the air and the size of these aerosols;
- the equilibrium factor which depends on the ventilation rate and the unattached fraction;
- the aerosol size distribution, which affects the location of pulmonary deposits and thus the distribution of received dose among the various regions of the respiratory tract;
- finally, the humidity, which will affect the apparent size of particles at the entrance to the upper airways and therefore their distribution in the lungs.

In the absence of precise, available data for all exposure situations, the ICRP has issued assumptions on the dust level in mines, on the type of aerosols based on the heating method and on their behaviour based on ambient humidity. For tourist caves, it has also made the assumption that the ambient humidity would modify particle size before entry into respiratory airways. It has

[2] 1 WLM corresponds to exposure to a concentration of 3,700 Bq m^{-3} of radon in equilibrium with its short half-life progeny over a period of 170 hours, considered representative of monthly working time.
[3] 1 WL corresponds to the concentration of potential alpha energy associated with 3,700 Bq m^{-3} of radon in equilibrium with its short half-life progeny.

also issued other assumptions on mean dust levels in dwellings.

Table 1 below provides a summary of the exposure parameters ultimately used in ICRP Publication 137 for each of the four situations considered and provides the correspondence between exposure, in one of the three units mentioned earlier (Bq h m^{-3}, WLM and mJ h m^{-3}) and the effective dose in mSv.

Table 1: Correspondence between exposure and effective dose for various work situations

Exposure \ Dose (mSv)	Indoor work activity	Indoor sedentary work activity	Mine work activity	Tourist cave work activity
300 Bq m^{-3} for 2,000 h (1)	7.8	5.6	N/A (2)	9
1 WLM	20	14	12	24
1 mJ h m^{-3}	5.7	4	3.3	6.7
Exposure parameter values used				
Mean breathing rate	1.2 m^3 h^{-1}	0.86 m^3 h^{-1}	1.2 m^3 h^{-1}	1.2 m^3 h^{-1}
Equilibrium factor	0.4	0.4	0.2	0.4
Unattached fraction	8%	8%	1%	15%
Activity median thermodynamic diameter of the unattached fraction	30 nm (for 20 %) and 250 nm (for 80 %)	30 nm (for 20 %) and 250 nm (for 80 %)	250 nm	200 nm

1 A concentration of 300 Bq m^{-3} corresponds to the reference value proposed for radon risk management in ICRP Publication 126 (ICRP, 2014) and 2,000 h is the annual working time used in Publication 137.

2 In mines, radon exposure is monitored via measurement of the alpha potential energy of progeny (mJ h m^{-3})

The reference values given in the table for the various parameters have been adopted by the ICRP to define the representative conditions for normal and mean ambient conditions in the four types of situation chosen. As with what ICRP proposes for other radionuclides, with the fast (F), moderate (M), slow (S), and gases and vapours (V) pulmonary absorption types, the choices made for radon remain conventional and the situations described only represent standard situations. Consequently, the effective dose coefficients given for buildings, mines and tourist caves must be understood as reference coefficients, usable under the proposed conditions and under any other similar environmental conditions (spas or water pumping facilities for example).

In cases where the environmental working conditions are very different from the standard conditions adopted by the ICRP, it provides the aspects needed for calculation of potentially more appropriate dose coefficients. The ICRP thus proposes methods for calculating doses by changing the size of aerosols based on their formation mode or changing the unattached fraction of radon progeny.

It should be noted that the values given in Table 1 are given for information purposes, since in the context of risk management, the ICRP ultimately recommends the dose coefficients given below, which are rounded values taking into account the uncertainties associated with the dosimetric model (see Chapter 5).

Recommended dose coefficients

Based on the aspects described in the previous chapters, ICRP Publication 137 ultimately recommends two dose coefficients, associating each one with a specific exposure context:

- **a dose coefficient of 3 mSv per mJ h m^{-3} applicable to activities performed in underground mines and moderate intensity activities performed in buildings.** ICRP considers that this dose coefficient is applicable, by default, in the majority of situations without the need for adjustment to take into account aerosol characteristics (ICRP, 2017; Marsh *et al.*, 2017). **In terms of the other exposure unit mentioned above, the dose coefficient is 10 mSv per WLM**.
- **a dose coefficient of 6 mSv per mJ h m^{-3} applicable to more intense physical activities performed in buildings and in underground tourist caves. In terms of the other exposure unit mentioned above, the dose coefficient is 20 mSv per WLM.**

Table 2: Correspondences between exposure and effective dose recommended by the ICRP

Exposure \ Dose (mSv)	Indoor work activity	Indoor sedentary work activity	Mine work activity	Tourist cave work activity
1 WLM	20	10	10	20
1 mJ h m^{-3}	6	3	3	6

4. CONSISTENCY OF THE PROPOSED DOSE COEFFICIENTS WITH DATA FROM AN EPIDEMIOLOGICAL APPROACH

Before ICRP Publication 137 was issued, the applicable radon dose coefficients were given in Publication 65 (ICRP, 1993). These coefficients were based on an “epidemiological” approach consisting of making a correspondence between radon exposure leading to a given cumulative lifetime risk of fatal lung cancer (estimated based on epidemiological studies of uranium miners) to the “whole body” dose leading to identical detriment (estimated based on the study of survivors of the Hiroshima and Nagasaki atomic bombings) (ICRP, 1993).

On the basis of the epidemiological studies available in 1993, the lung cancer risk per unit of exposure was estimated at 2.83×10^{-4} per WLM. Given the total detriment (cancer and hereditary effects) given by ICRP Publication 60 (ICRP, 1991), namely 5.6×10^{-2} per Sv for workers and 7.3×10^{-2} per Sv for the public, the dose coefficients derived were as follows (ICRP, 1993):

– 5 mSv per WLM for workers (2.83×10^{-4} per WLM divided by 5.6×10^{-2} per Sv);
– 4 mSv per WLM for the public (2.83×10^{-4} per WLM divided by 7.3×10^{-2} per Sv).

In 2010, ICRP Publication 115 gave an update to the lung cancer risk due to radon and its progeny based on recent epidemiological data from studies of weakly exposed uranium miners and studies in the general public (ICRP, 2010). The recent epidemiological studies, in particular in the general population, led to an upward reassessment of the lung cancer risk after radon inhalation in dwellings, for both smokers and non-smokers. Analysis of all epidemiological data showed that the lifetime risk of fatal lung cancer among adults chronically exposed to low concentrations of radon was 5×10^{-4} per WLM, that is approximately twice as high as the 2.83×10^{-4} per WLM estimated in 1993 on the basis of knowledge available at the time.

On this basis, and taking into account the new values for total detriment given by ICRP Publication 103 (ICRP, 2007), namely 4.2×10^{-2} per Sv for workers and 5.7×10^{-2} per Sv for the public, the dose coefficient estimated by the epidemiological approach was:

– 12 mSv per WLM (or 3.3 mSv for 1 mJ h m^{-3}) for a worker and
– 9 mSv per WLM (or 2.5 mSv for 1 mJ h m^{-3}) for the public (Marsh *et al.*, 2010).

As the values derived from the epidemiological approach were order-of-magnitude consistent with those derived from the dosimetric approach, the ICRP chose to harmonise its approach for determining dose coefficients by using the dosimetric approach for radon inhalation, as for other radionuclides (ICRP, 2010).

5. VARIABILITY AND UNCERTAINTIES ASSOCIATED WITH THE DOSIMETRIC AND EPIDEMIOLOGICAL APPROACHES

The doses delivered by radon and its progeny depend on numerous parameters as listed in Chapter 3. Among the most influential factors, there is a distinction between those from variability of individuals or exposure situations, those from the approximations of the dosimetric system, and those from uncertainties associated with lack of knowledge in certain areas.

Calculation of an effective dose may therefore vary considerably from one situation to another depending on the parameters adopted. The ICRP thus provides reference dose coefficients, applicable in standard work situations and for reference individuals. It considers that the coefficients given are sufficiently robust to be applied in the vast majority of situations. Nonetheless, when the conditions are very different from the reference conditions, the approach defined by the ICRP leaves the possibility of adjusting the dose coefficients with recourse to more realistic values for the parameters.

Some examples are given below to illustrate the variability of situations encountered and the consequences on dose calculation.

Parameters subject to variability of individuals and exposure situations

- The exposure parameters such as breathing rate, fraction of radon progeny attached to aerosols and size distribution of these aerosols significantly affect the deposit of radon progeny in the lung, their distribution between bronchi and alveoli and the resulting dose. Calculations performed using the ICRP respiratory tract model (1994) and reviewed by Marsh *et al.* (2010) lead to dose coefficients of approximately 3 to 6 mSv per mJ h m^{-3} (10 to 20 mSv per WLM) depending on the values chosen for these exposure parameters.
- Individual parameters such as the fraction of air inhaled via the nose, the rates of mechanical transport and absorption of radon progeny deposited in the lung, and the age and sex of the person exposed affect the result of the dosimetric model.
- Smokers have slower mechanical removal, which could increase the proportion of inhaled radon progeny which decay in the lung. Smoking could also promote thickening of the mucus layer and thereby distance target cells from the radiation source. These two effects of smoking that may affect radon dosimetry in opposite ways remain difficult to take into account in the models.

Parameters defined by approximation in the dosimetric models

- The radiation weighting factor of 20 applied to alpha radiation in the effective dose calculation is the nominal value adopted from human and animal data that indicates a relative biological effectiveness of around 10 to 20, depending on the effects studied and the study protocols. The value of this factor directly affects the dose coefficient.
- The tissue weighting factor of 0.12 applied to the lung in the effective dose calculation is the nominal value representing the relative radiological detriment specific to the lung with respect to all the tissues of the human body. For simplicity, this value is chosen as equal to the weighting factors of the bone marrow, colon, stomach and breast. However, in ICRP Publication 103, the contribution of lung cancer to total detriment in adults was close to 29% (ICRP, 2007). As for the radiation weighting factor, the value of this factor directly affects the dose coefficient calculation.
- The non-uniformity of received doses is not taken into account in a detailed way in the ICRP approach which calculates a mean absorbed dose in each target region.

- Other dosimetric models than that of the ICRP are available, which use a different model of the respiratory tract and the deposit of radon progeny in it. Application of these models to various exposure situations leads to dose coefficients of around 1.5 to 3 mSv per mJ h m^{-3} (6 to 12 mSv per WLM.) (Marsh *et al.*, 2010).

Parameters generating uncertainties in the dose calculation

- Identification of the position of radiosensitive target cells in the lungs is very important in the dosimetric calculation. In the bronchial tree, they are considered to be the basal and secretory cells, located at a few tens of microns from the surface of the epithelium. However, this position is known with uncertainties. In the absence of more precise information on the sites of origin and spontaneous incidence of lung cancers, the stochastic risk is assumed to be equally distributed between the various types of target cells and between the three regions of the lung (bronchi, bronchioles, and alveoli). Consequently, the equivalent dose to the lung is the mean of the equivalent doses received by these three regions.

Limits and uncertainties with regard to the epidemiological approach

- All available epidemiological results cover adults, whether for studies of miners or studies in the general population. Furthermore, the proportion of women in these studies is limited. There is therefore a lack of data for the risks associated with radon for women and children (ICRP, 2010).
- The epidemiological approach is based on the assumption that the only proven risk of radon exposure is lung cancer. This assumption is consistent with the fact that over 90% of the received dose following radon exposure (inhalation) is delivered to the lung. It is also in agreement with the current state of knowledge on the effects of radon (ICRP, 2010).
- The estimate of lifetime risk of fatal lung cancer associated with chronic radon exposure shows very good consistency between the results of epidemiological studies of uranium miners and the results of studies performed in the general population (ICRP, 2010). Nevertheless, variations persist between studies and between countries, in particular depending on the baseline for lung cancer mortality (dependant, in particular, on smoking rates). Furthermore, significant uncertainties exist on the estimate of the impact of factors that modify the exposure-risk relationship, such as age when the cancer occurs or time since exposure. All these uncertainties and sources of variation may lead to multiplication or division of the lifetime risk estimate attributable to radon by a factor of about 2.
- The lifetime risk of fatal lung cancer associated with radon estimated by the ICRP corresponds to a population including smokers and non-smokers (ICRP, 2010). This choice of a “global” reference population, is justified by the ICRP objective to supply risk management recommendations applicable to the whole population. Nevertheless, this choice does not take into account the major impact of smoking on lung cancer risk. Estimates of the risk of lung cancer attributable to radon indicate that approximately 75% of these cancers involve smokers and 25% non-smokers.

6. CONCLUSION

The dose coefficients for exposure to radon and its progeny recommended in ICRP Publication 65 (ICRP, 1993) were 1.4 mSv per mJ h m^{-3} for workers and 1.1 mSv per mJ h m^{-3} for the public respectively. These dose coefficients were based on an epidemiological approach, considered more direct than the approach based on internal dosimetry, and were nearly three times lower than the values provided by the latter. The difference obtained between the two approaches was explained by their respective uncertainties and considered acceptable with regard to the uncertainties generally accepted in internal dosimetry.

ICRP Publication 115 (ICRP, 2010) gave an update to the lung cancer risk due to radon and its progeny based on recent epidemiological data from studies of uranium miners and studies in the general population. Analysis of this data showed that the lifetime risk of fatal lung cancer among adults chronically exposed to low concentrations of radon was approximately twice as high as that estimated on the basis of knowledge available in 1993. In Publication 115, the ICRP stated that from now on it intends to apply the same dosimetry-based approach to establish the dose coefficients for radon as it uses for all other radionuclides, as the results obtained for radon using this approach are consistent with those obtained by epidemiology.

Taking the dosimetric approach into account, in Publication 137 (ICRP, 2017), the ICRP recommends using a dose coefficient of 3 mSv per mJ h m^{-3} for workers in underground mines and in buildings in most situations. For specific indoor work situations involving intense physical activity and for tourist caves, it recommends a dose coefficient of 6 mSv per mJ h m^{-3}. The ICRP states that the dose coefficient of 3 mSv per mJ h m^{-3} also applies to public exposure situations in dwellings.

The doses delivered by radon and its progeny depend on numerous parameters, including those from the variability of individuals or exposure situations, those from the approximations of the dosimetric system, and those from uncertainties associated with lack of knowledge in certain areas. The situations adopted by the ICRP are meant to cover the vast majority of common workplaces and be extrapolatable to other situations for which the ambient conditions in terms of dust, ventilation or humidity are comparable (water pumping facilities, spas, etc.).

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