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Radiological Protection against Radon Exposure

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Radiological Protection against Radon Exposure

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Abstract- In this report, the Commission provides updated guidance on radiological protection against radon exposure. The report has been developed considering the recently consolidated ICRP general recommendations, the new scientific knowledge about the radon risk and the experience gained by many organisations and countries in the control of radon exposure.

The report describes the characteristics of radon exposure, covering sources and transfer mechanisms, the nature of the risk, the exposure conditions, the similarities with other existing exposure situations and the challenges to manage radon exposure.

To control the main part of radon exposure the Commission recommends an integrated approach focussed as far as possible on the management of the building or location in which radon exposure occurs whatever the purpose of the building and the types of its occupants. This approach is based on the optimisation principle and a graded approach according to the degree of responsibilities at stake, notably in workplaces, and the level of ambition of the national authorities. The report emphasises the importance of preventive actions.

The report also provides recommendations on how to control radon exposure in workplaces when workers' exposure can reasonably be regarded as being the responsibility of the operating management. In such a case workers' exposures are considered as occupational and controlled using the corresponding requirements on the basis of the optimisation principle and the application, as appropriate, of the dose limit.

Keywords: Radon exposure, Prevention, Mitigation, Dwellings, Buildings, Workplaces

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PREFACE

At its meeting in Porto (Portugal) in November 2009, the Main Commission of the International Commission on Radiological Protection (ICRP) approved the formation of a new Task Group, reporting to Committee 4, to develop guidance on radiological protection against radon exposure.

The terms of reference of the Task Group were to prepare a publication that describes and clarifies the application of the new recommendations (Publication 103) for the protection against radon exposure in dwellings, workplaces and other types of locations. The publication should discuss in which cases exposure to radon is either a planned exposure situation or an existing exposure situation with the relevant application of the radiological protection principles, as well as the dosimetric reference and the rationale behind. The publication should also address the setting of reference levels and the way to manage radon risk through a national action plan.

The publication should be developed building on the previous relevant ICRP publications such as *Publication 65* on protection against radon-222 at home and at work, *Publication 101*, part 2, on the optimisation of radiological protection, and *Publication 103* containing the last general recommendations of ICRP. The publication should also take into account the result of the Task Group N°64 on the lung cancer risk from radon and progeny, reporting to Committee 1 and now published as ICRP Publication 115, the Commission's Statement on radon adopted in November 2009 as well as experience from many countries and organisations.

The membership of the Task Group was as follows:

J-F. Lecomte (Chairman)	T. Jung	C. Murith
J. Takala	S. Salomon	S. Kiselev
P. Strand	Weihan Zhuo	

Corresponding members were:

R. Czarwinski	A. Janssens	B. Long
S. Niu	F. Shannoun	

In addition Céline Bataille, acting as secretary of the Task Group, provided a welcomed scientific assistance. Numerous helpful comments were also received from Andre Poffijn. The chairman of the Task Group received also many comments from a French mirror group of about twenty experts from different concerned bodies (authorities, expert bodies, industries). Moreover, Werner Zeller as well as Jane Simmonds (in a first period) and Senlin Liu (in a second period) acted as critical reviewers from Committee 4. The Task Group would like to thank all these persons as well as the CEPN (Fontenay-aux-Roses) for facilities and support during its meetings.

The Task Group worked mainly by correspondence and met twice:

28-30 April 2010, CEPN, Fontenay-aux-Roses, France
19-21 September 2010, CEPN, Fontenay-aux-Roses, France

The membership of Committee 4 during the period of preparation of this report was:

J. Lochard, Chairman	W. Weiss, Vice-Chairman	P. Burns
P. Carboneras	D. A. Cool	M. Kai
J-F. Lecomte, Secretary	H. Liu	S. Liu
A. Mc-Garry	S. Magnusson	G. Massera
K. Mrabit	S. Shinkarev	J. Simmonds
A. Tsela	W. Zeller	

The report was adopted by the Main Commission at its meeting in xxx on xxx. The critical reviewers were John Cooper and Jan Pentreath.

EXECUTIVE SUMMARY

(a) The objective of the present Publication is to describe and clarify the application of the Commission's system to the protection of the members of the public and the workers against radon 222 and radon 220 exposures in dwellings, workplaces and other types of locations.

(b) Radon 222 is a radioactive decay product of uranium 238 which is present in the earth's crust in varying concentrations. Because radon is a gas, it is capable of movement from the soil to indoors. This movement is dependent on the type of building and/or location. Radon 220 is a radioactive decay product of thorium 232 also present in the earth's crust. Both radon 222 and 220 may also come from some building materials. The concentration of radon in a building may vary from several orders of magnitude.

(c) Because radon is inert, nearly all of the gas inhaled is subsequently exhaled. However, when inhaled, the short-lived radon progeny can deposit within the respiratory tract. Depending on the diffusion properties of the particles (size distribution of the aerosols), the decay products present in the air deposit in the nasal cavities, on the walls of the bronchial tubes and in the deep lung. Two of these short-lived progeny, polonium-218 and polonium-214, emit alpha particles and the energy deposited by these alpha particles may lead to health effects, principally lung cancer.

(d) The Commission made recently a thorough review and analysis of the epidemiology of radon for both workers (underground miners) and the general population (ICRP, 2011). There is now compelling evidence that radon and its progeny can cause lung cancer. For solid tumours other than lung cancer, and also for leukaemia, there is currently no convincing or consistent evidence of any excesses associated with radon and radon progeny exposures. For radiological protection purposes the Commission now recommends a detriment-adjusted nominal risk coefficient for a population of all ages of $8x10^{-10}$ per Bq h m^{-3} for exposure to radon-222 gas in equilibrium with its progeny (i.e. $5x10^{-4}$ WLM^{-1}), which is approximately twice the value previously used by the Commission in Publication 65.

(e) Radon exposure situations have the characteristics of existing exposure situations since the source is unmodified concentrations of ubiquitous natural activity in the earth's crust. Human activities may create or modify pathways increasing indoor radon concentration compared to outdoor background. These pathways can be controlled by preventive and corrective actions. The source itself, however, cannot be modified and then already exists when a decision on control has to be taken. Some workplaces, however, may be deemed to be planned exposure situations from the outset by national authorities. Such workplaces may include uranium mines associated with the nuclear fuel cycle.

(f) Radon is not likely to give rise to an emergency exposure situation even though the discovery of very high concentrations in a place may require the prompt implementation of protective actions. The philosophy of *Publication 103* compared to *Publication 60* is to recommend a consistent approach for the management of all types of exposure situations. This approach is based on the application of the optimisation principle implemented below appropriate constraints or reference levels.

(g) Several characteristics of radon exposure in dwellings (and in many other locations) are similar to those of exposures arising from other existing exposure situations such as exposures to NORM or exposures in a long-term contaminated area after a nuclear accident or a radiation emergency. Radon exposure affects nearly all living places of a population. The ubiquity and the variability of radon concentration result in a very heterogeneous distribution of exposures. Day to day life or work inevitably leads to some exposure to radon. The persistence or reduction of the risk is mainly dependant on individual behaviour. Domestic radon exposure management should address several considerations such as environmental, health, economic, architectural, educational, etc. A large spectrum of parties is concerned. The role of self-help protective actions is also crucial.

(h) Control of indoor radon exposure poses many challenges. As a given individual can move from place to place in the same area, the radon policy should provide consistency in the management of the different locations in an integrated approach. As the radon risk is mainly due to domestic exposure, the radon policy should address primarily exposure in dwellings in a public health perspective. As the radon concentration in many buildings is above the level at which the risk has been demonstrated, a real ambition is needed to both reduce the overall risk for the general population and the highest individual exposures. Radon policy should not be in contradiction with the raising role of energy saving policies. It should be as simple as possible, properly scaled with other health hazards, supported and implemented on a long term basis and involving all the concerned parties.

(i) A national radon policy has also to address many challenges in terms of legal responsibilities, notably the responsibility of the individual householder towards her/his family, of the seller of a house or a building towards the buyer, of the landlord towards the tenant, of the employer toward the employee, and generally speaking of the responsible person for any building towards its users. The degree of enforcement of the actions that are warranted is very much related to the degree of legal responsibility for the situation.

(j) The responsibility dimension calls clearly for the need of a graded approach in defining and implementing a radon policy. Such a graded approach should be based on realism, effectiveness and ambition. Any radon policy should thus aim to maintain and/or reduce radon concentration as low as reasonably achievable in an effective way keeping in mind that it is not possible to totally eliminate indoor radon concentration.

(k) The Commission considers that a national radon protection strategy appears to be justified since radon is a significant source of radiation exposure (second cause of lung cancer after smoking), radon exposure can be controlled and a radon policy has positive consequences on other public health policies (indoor air quality or anti-smoking policies). The Commission considers that radon strategies should address together both smokers and non-smokers.

(l) It is the responsibility of the appropriate national authorities, as with other sources, to establish their own national reference levels, taking into account the prevailing economic and societal circumstances and then to apply the process of optimisation of protection in their country. The objective is both to reduce the overall risk of the general population and, for the sake of equity, the individual risk in particular the risk of the most exposed individuals. In both cases the process is implemented through the management of buildings and should result in radon concentrations in ambient indoor air as low as reasonably achievable below the national reference level.

(m) According to the characteristics of radon exposure (control by actions on pathways, benefit for individuals due to the use of buildings, general information provided to enable individuals to reduce their doses), the appropriate reference level should therefore be set corresponding to an annual dose in the range 1 mSv to 20 mSv (see table 5 of Publication 103). Further, the value of 10 mSv, which is the middle of this range, should remain the upper value of the dosimetric reference level for radon exposure as set in Publication 65.

(n) Reference levels for radon are typically set in terms of the mesurable quantity, Bq m^{-3}. The Commission therefore recommends an upper value of the reference level for radon gas in dwellings of 300 Bq m^{-3} (see ICRP Statement from Porto meeting). The measurement should be representative of the annual mean concentration of radon in a building or location. For the sake of simplicity, considering that a given individual going from place to place in the same area along the day should be protected on the same basis whatever the location, the Commission recommends to use *a priori* the same upper value of 300 Bq m^{-3} in mixed-use buildings (with access for both members of the public and workers).

(o) Within a graded approach the radon protection strategy should start with a programme aiming at encouraging relevant decision makers to enter in a process of self-help protective actions such as measurement and, if needed, remediation, with more or less incentive and helping provisions and, if judged necessary, even requirements. Then the degree of enforcement of these various actions would be increasing depending on the degree of legal responsibility for the situation and the ambition of the national radon protection strategy.

(p) A specific graded approach should be implemented in workplaces. Where workers' exposures to radon are not considered as occupational exposures, i.e. when workers exposures to radon cannot reasonably be regarded as being the responsibility of the operating management (typically office buildings), the first step is to reduce concentration of radon-222 as low as reasonably achievable below the same reference level as set for dwellings (even though the corresponding level in dose is below 10 mSv per year because the conditions of exposure in workplace are different than those in dwellings), If difficulties are met in the first step, a more realistic approach is recommended as the second step. It means optimising exposure on the basis of a dose reference level of 10 mSv per year taking into account the actual parameters of the exposure situation.

(q) In workplaces, if despite all reasonable efforts to reduce radon exposure, the exposure remains durably above the dose reference level of 10 mSv per year, and/or where workers' exposure to radon can reasonably be regarded as being the responsibility of the operating management (e.g. some underground workplaces, spas…), the workers should be considered as occupationally exposed. In such cases, the Commission recommends applying the optimisation principle and the relevant requirements for occupational exposure.

(r) The dose limit should apply when the national authorities consider that the radon exposure situation should be managed like a planned exposure situation. In any case, using either the occupational dose limit or a reference level, the upper value of the tolerable risk for occupational exposure (on the order of 20 mSv per year, possibly averaged over 5 years) should not be exceeded.

(s) A national radon action plan should be established by national authorities with the involvement of relevant stakeholders in order to frame the implementation of the national radon protection strategy in dwellings, places open to the public and workplaces. The action plan should establish a framework with a clear infrastructure, determine priorities and responsibilities, describe the steps to deal with radon in the country and in a given location, identify concerned parties (who is exposed, who should take actions, who could provide support), address ethical issues (notably the responsibilities) and provide information, guidance, support as well as conditions for sustainability.

(t) To be efficient, the national radon protection strategy should be established on a long term perspective. The process to reduce the radon risk of the general population significantly is rather a matter of several decades than several years. The national action plan should be periodically reviewed, including the value of the reference level.

(u) The Commission considers now that for the sake of clarification, when dealing with existing exposure situations, the distinction should be made between prevention aiming at maintaining exposure as low as reasonably achievable under the prevailing circumstances and mitigation aiming at reducing exposure as low as reasonably achievable.

(v) As a consequence, a radon protection strategy should include a prevention part. Whatever the indoor location is, the category of individuals inside and the type of exposure situation, it is possible to optimise radon exposure by taking into account the issue of radon exposures during the planning, design and construction phase of a building. Preventive actions mean land-planning and building codes for new buildings and for renovation of old buildings. They also mean the integration of the radon protection strategy consistently with other strategies concerning buildings such as indoor air quality or energy saving in order to develop synergies and avoid contradictions.

(w) The mitigation part of a national radon protection strategy concerns mainly existing buildings or locations. Then the control of exposure should be ensured as far as possible through the management of the building (or location) and the conditions of its use, whatever the category of individuals inside. The main steps are measurement and; when needed, corrective actions. The actions plan should also deal with radon measurement techniques and protocols, national radon surveys to identify radon prone areas, methods for mitigating the radon exposure and their applicability in different situations, support policy including information, training and involvement of concerned parties as well as assessment of effectiveness. The issues of buildings with public access and workplaces, with specific graded approaches, should also be addressed.

MAIN POINTS

- **People are exposed to radon at home, in workplaces and in mixed-use buildings. Only indoor concentration is at stake. The ubiquity and variability of radon concentration result in a very heterogeneous distribution of exposures.**
- **There is now compelling evidence that exposure to radon and its progeny may lead to health effects, principally lung cancer (second cause after smoking).**
- **The detriment-adjusted nominal risk coefficient recommended by the Commission is now approximately twice the value previously used in Pub. 65.**
- **Radon exposure situations are existing exposure situations since the source is unmodified concentrations of ubiquitous natural activity in the earth crust. Only pathways can be controlled.**
- **Radon exposure has key characteristics: it is mainly due to domestic exposure (public health perspective); radon concentration in many buildings is above the level at which the risk has been demonstrated; radon policy may be in contradiction with other policies such as energy saving policy; the persistence or reduction of the risk is mainly dependant on individual behaviour (self-help protective actions); efficiency can only be achieved in a long term perspective; exposure in workplaces may be adventitious (cannot reasonably be regarded as being the responsibility of the operating management) and not occupational.**
- **The justification of launching a national radon strategy (national action plan) is decision by the national authorities.**
- **The radon strategy should be simple and realist (same approach for smokers and non-smokers), integrated (consistent for all buildings), graded (according to the situation and the legal responsibilities) and ambitious (choice of the reference level; addressing both highest exposures and the global risk).**
- **The radon strategy should include both preventive (new buildings) and corrective (existing buildings) actions.**
- **The management of radon exposure is mainly based on the application of the optimisation principle below an appropriate reference level. The Commission recommends 10 mSv per year as an appropriate dosimetric reference level for radon exposure.**
- **The upper value of the reference level (RL) recommended in dwellings is 300 Bq.m^{-3} (annual mean concentration). For the sake of simplicity, the same value is recommended for mixed-use buildings.**
- **A specific graded approach is recommended in workplaces: 1) application of the same RL in concentration as for dwellings (although the corresponding dose is below 10 mSv/y mainly because of the time of exposure); 2) application of the dosimetric RL (10 mSv/y) taking into account the actual conditions of exposure 3) application of the relevant**

requirements for occupational exposure when, despite all reasonable efforts, the exposure remains above 10 mSv/y (quantitative criterion) or when the work activity is in a national positive list of radon prone work activities (qualitative criterion).

- **The dose limits may be applied when the national authorities consider that the radon exposure situation should be managed like a planned exposure situation.**

GLOSSARY

Categories of exposure

The Commission distinguishes between three categories of radiation exposure: occupational, public, and medical exposures of patients.

Employer

An organisation, corporation, partnership, firm, association, trust, estate, public or private institution, group, political or administrative entity, or other persons designated in accordance with national legislation, with recognized responsibility, commitment, and duties towards a worker in her or his employment by virtue of a mutually agreed relationship. A self-employed person is regarded as being both an employer and a worker.

Equilibrium equivalent concentration (EEC)

The activity concentration of radon gas, in equilibrium with its short-lived progeny which would have the same potential alpha energy concentration as the existing non-equilibrium mixture.

Equilibrium factor, F

The ratio of the equilibrium equivalent concentration to the radon gas concentration. In other words it is the ratio of potential alpha energy concentration (PAEC) for the actual mixture of radon decay product to that which would apply at radioactive equilibrium.

Existing exposure situations

A situation resulting from a source that already exists when a decision on control has to be taken, including natural background radiation, long-term contaminated areas after a nuclear accident or a radiological emergency and residues from past practices that were operated outside the Commission's recommendations.

Exposure pathway

A route by which radiation or radionuclides can reach humans and cause exposure.

Graded approach

For a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control.

Medical exposure

Exposure incurred by patients as part of their own medical or dental diagnosis or treatment; by persons, other than those occupationally exposed, knowingly, while voluntarily helping in the support and comfort of patients; and by volunteers in a programme of biomedical research involving their exposure.

Member of the public

Any individual who receives an exposure that is neither occupational nor medical.

National radon survey

A survey carried out to determine the radon concentration distribution, which is representative of the radon exposure to the population within a country.

NORM (naturally occurring radioactive material)

Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides. Material in which the activity concentrations of the naturally occurring radionuclides have been changed by some process are included in NORM.

Occupational exposure

All exposures of workers incurred at work as a result of situations that can reasonably be regarded of being the responsibility of the operating management, with the exception of excluded exposures and exposures from exempt practices or exempt sources.

Operating management

The person or group of persons that directs, controls, and assesses an organization at the highest level. Many different terms are used, including, e.g., chief executive officer (CEO), director general (DG), managing director (MD), and executive group.

Optimisation of protection

The process of determining what level of protection makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account.

Planned exposure situations

Planned exposure situations are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures).

Potential alpha energy concentration (PAEC)

The concentration of short-lived radon-222 or radon-220 progeny in air in terms of the alpha energy emitted during complete decay from radon-222 progeny to lead-210 or from radon-220 progeny to lead-208 of any mixture of short-lived radon-222 or radon-220 in a unit volume of air.

Public exposure

Exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure.

Radon 220 progeny

The decay products of radon-220, used herein in the more limited sense of the short-lived decay products from polonium-216 through polonium-212 or thallium-208.

Radon-222 progeny

The decay products of radon-222, used in this report in the more limited sense of the short-lived decay products from polonium-218 through polonium-214. Radon progeny are sometimes referred to as “radon decay products”.

Radon-prone area

A geographic area or an administrative region defined on the basis of surveys indicating a significantly higher level of radon concentration than in other parts of the country.

Reference level

In existing 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 prevailing circumstances of the exposure under consideration.

Risk

Risk relates to the probability that an outcome (e.g. lung cancer) will occur.

Terms relating to risk are grouped together here:

• Excess relative risk (ERR)

Relative risk – 1.

• Relative risk

The ratio of the incidence rate or the mortality rate from the disease of interest (lung cancer) in an exposed population to that in an unexposed population.

• Risk coefficient

Increase of risk per unit exposure or per unit dose. In general, expressed as ERR per WLM, per J h m^{-3}, per 100 Bq m^{-3} or per Sv.

• Detriment

Detriment is an ICRP concept. It reflects the total harm to health experienced by an exposed group and its descendants as a result of the group's exposure to a radiation source. Detriment is a multi-dimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable non-fatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs.

Worker

Any person who is employed, whether full time, part time or temporarily, by an employer, and who has recognised rights and duties in relation to her/his job.

Working level (WL)

Any combination of the short-lived progeny of radon in one m^3 of air that will result in the emission of 1.300 x 10^8 MeV m^{-3} of potential alpha energy, which is approximately equal to 2.08 x 10^{-5} J m^{-3}.

Working Level Month (WLM)

The cumulative exposure from breathing an atmosphere at a concentration of 1 working level for a working month of 170 hours.

1. INTRODUCTION

1.1. Background

(1) The Commission has previously published recommendations on protection against radon exposure. In *Publication 65* (ICRP, 1993), the Commission reviewed the existing knowledge about the health effects of inhaled radon and its progeny and developed the approach to radon exposure in both dwellings and workplaces in line with the general recommendations published two years before (ICRP, 1991).

(2) In 2006, in *Publication 101 Part 2* (ICRP, 2006), the Commission extended its recommendations on the optimisation of radiological protection. This Publication does not contain specific provisions on radon exposure but reinforces the importance of the optimisation principle in radiological protection as applicable in all exposure situations and recommends broadening the process. At the same time the Commission revised its general recommendations in *Publication 103* (ICRP, 2007). A section of *Publication 103* is devoted to radon in dwellings and workplaces. This section broadly confirms the recommendations of *Publication 65*, except for the replacement of the concept of action level by the concept of reference level.

(3) More recently, the Commission reviewed available scientific information on the risk due to radon. In November 2009 the Commission adopted a Statement on Radon summarising its updated position on radon exposure at home and in workplaces, with revised risk detriment values and reference levels. The ICRP Statement on Radon has been published in Publication 115 related to the lung cancer risk from radon and progeny (ICRP, 2011).

(4) Since the last ICRP recommendations on radon in 1993 (ICRP, 1993), many countries have acquired experience in the implementation of radon strategies and policies to control radon exposure. In addition, international organisations have provided scientific information and guidance on this issue. In particular, the United Nation Scientific Committee on the Effects of Atomic Radiation has published a report on radon exposure and risks (UNSCEAR, 2009) and the World Health Organisation has published a handbook dealing with indoor radon exposure from a public health perspective (WHO, 2009).

(5) The purpose of the present publication is to update and revise the recommendations on controlling exposure to radon, taking into account all these publications and experiences. Summarizing the Commission's approach to dealing with radon exposure, it complements ICRP *Publication 115* (ICRP, 2011), which provides a revised assessment of the risk arising from such exposure. The publication by the Commission of the revised dose coefficients for the inhalation and ingestion of radionuclides, including radon and radon progeny, will complete the updated set of publications on the control of exposure to radon.

1.2. Scope

(6) Radon is a radioactive decay product of uranium-238, uranium-235 and thorium-232. In the case of the uranium 238 series, the resulting isotope is radon-222, direct decay product of radium-226 (Fig. 1). In the case of uranium-235 series,

the resulting isotope is radon-219 (Fig. 2). In the case of the thorium series, the resulting isotope is radon-220, direct decay product of radium-224 (Fig. 3). Human exposure to radon is mainly due to radon-222 or more precisely its progeny. Because of its short half life, exposure to radon-220 in ambient indoor air is generally less significant. The contribution of radon 219 to exposure is insignificant and therefore it is not considered in this publication.

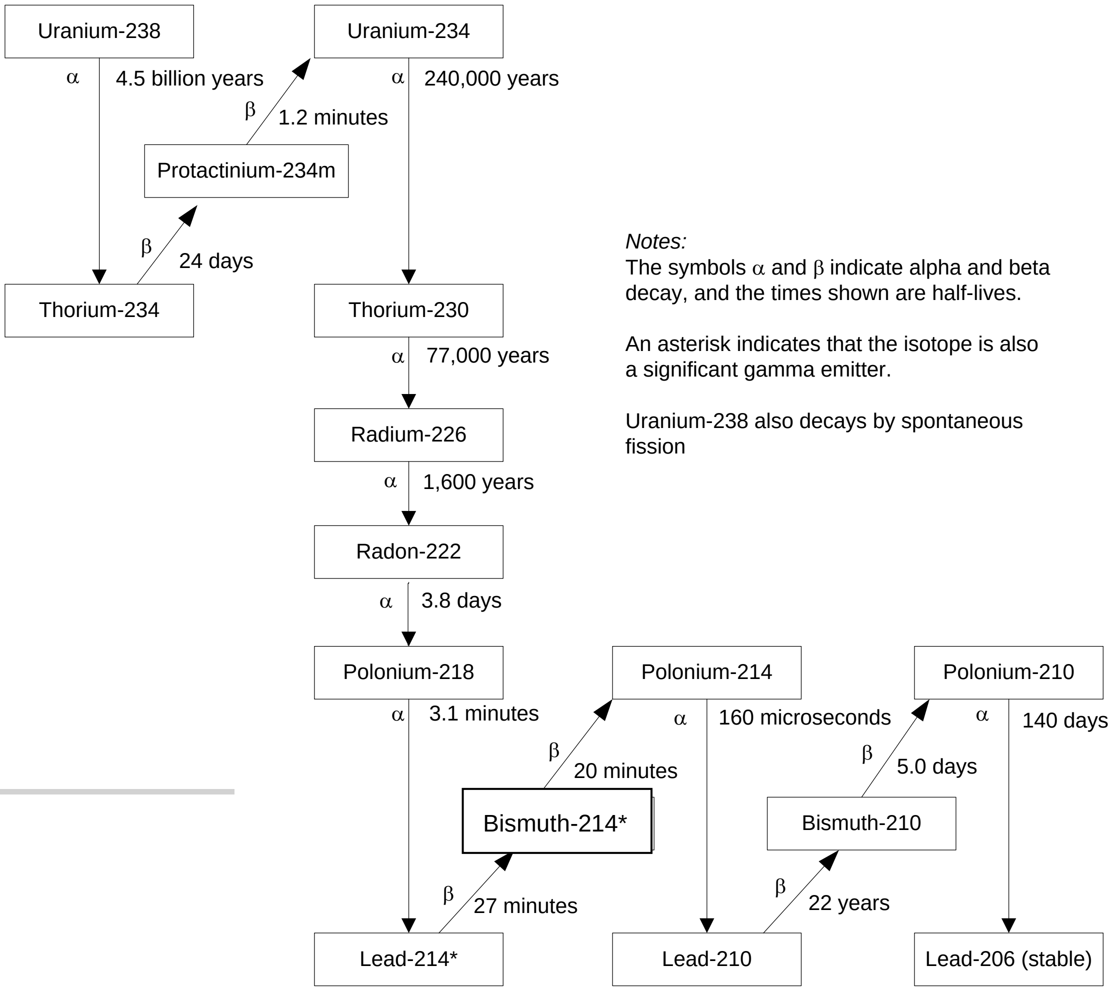

Fig. 1: Uranium-238 decay products

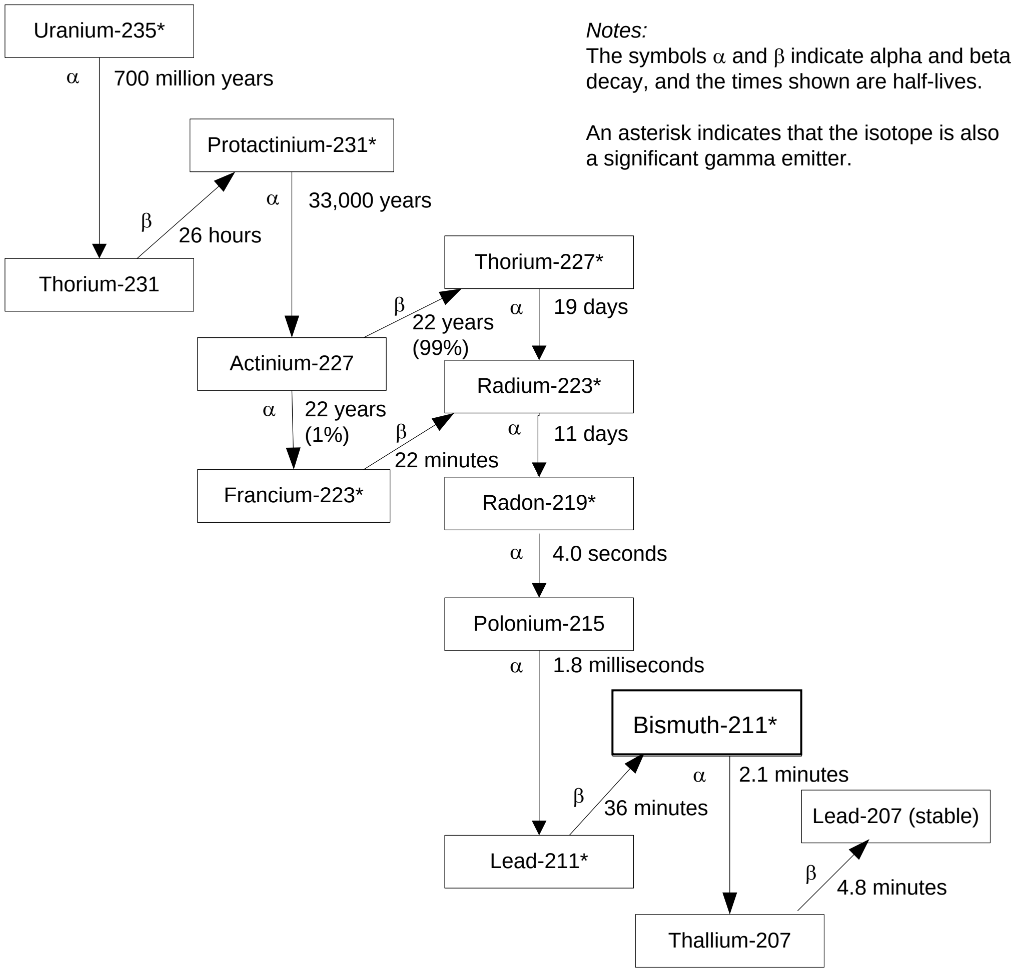

Fig. 2: Uranium-235 decay products

(7) People are exposed to radon-222 and radon-220 as members of the public in dwellings or as workers in workplaces. People also are exposed to radon in public or private places open to the public (such as town halls, post offices, schools, hospitals, housing for the elderly, jails, shops, entertainment buildings…) either as members of the public (e.g. customer, user, visitor, pupil…) as patients (in hospitals) or as workers (e.g. staff, porter, shopkeeper, guide, guard, teacher, nurse, etc., amongst them some may be inhabitant such as a caretaker or a school director). The present Publication is applicable to the control of radon-222 and radon-220 exposures in any location and for all individuals.

(8) In summary, the objective of the present Publication is to describe and clarify the application of the Commission's system to the protection of the members of the public and the workers (including workers in uranium mines and other mines) against radon-222 and radon-220 exposures in dwellings, workplaces and other types of locations.

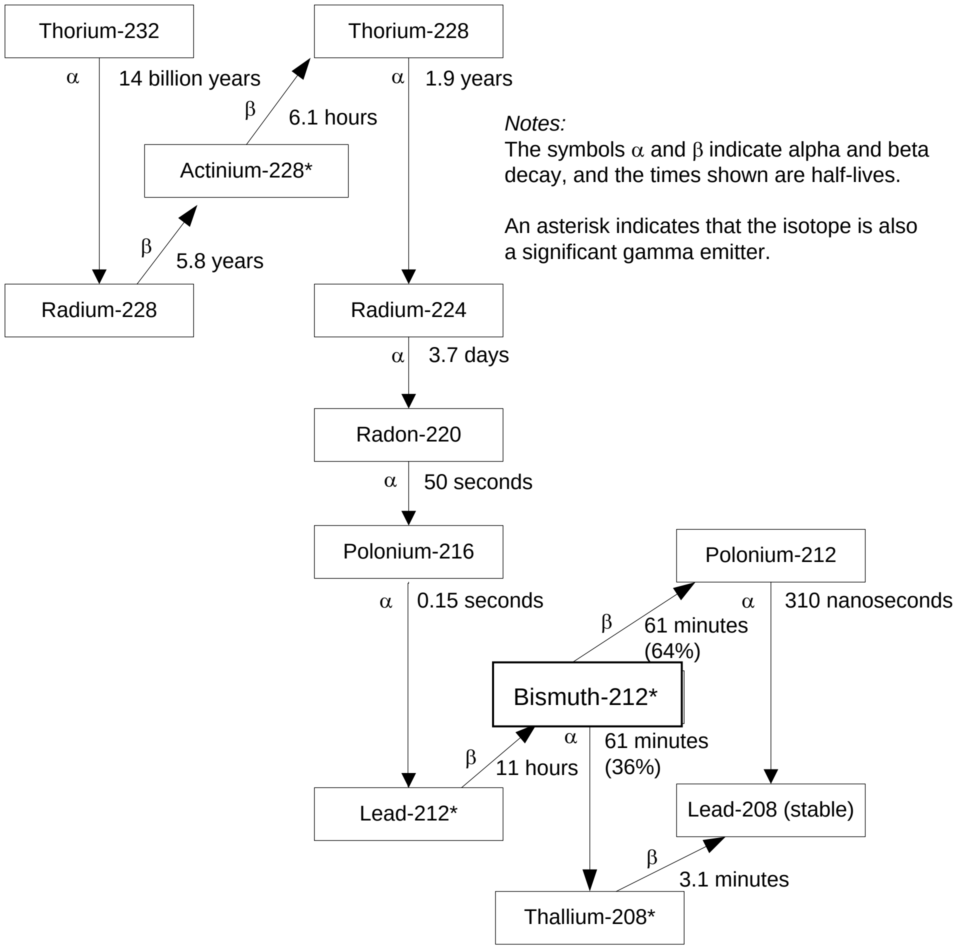

Fig. 3: Thorium-232 decay products

1.3. Structure

(9) Chapter 2 presents the characteristics of radon exposure. It provides a brief history of the control of radon exposure, with a description of the radon sources and exposures, covering production and transfer mechanisms, as well as the nature and the quantification of the health risk associated. The similarities with other existing exposures situations, notably in contaminated territories, are highlighted. Finally, the main challenges in developing a national radon policy are outlined.

(10) Chapter 3 contains the Recommendations of the Commission related to radon exposure. After an explanation on how to deal with the categories of individuals exposed in the different types of situations, three sections are devoted to respectively the justification of protection strategies, the optimisation of the protection and the application of dose limits when relevant.

(11) The last chapter (chapter 4) provides guidance on the implementation of protection strategies for the control of radon exposure, depending on the situation. The first section addresses the control of exposure in buildings through a national action plan covering both prevention and reduction of exposures. The second section deals with the control of occupational exposure in some workplaces. The third one addresses the case of radon protection of workers in the uranium mining industry.

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2. CHARACTERISTICS OF RADON EXPOSURE

2.1. Historical perspective

(12) The existence of a high mortality rate among miners in central Europe was recognised already before the seventeen century, and the main cause of their death was identified as lung cancer in the late nineteen century (Haerting and Hesse, 1879). In 1924 it was suggested that these lung cancers could be attributed to radon exposure (Ludewig and Lorenser, 1924).

(13) Early radon measurements were largely confined to environmental studies of diverse phenomena such as atmospheric electricity, atmospheric transport and exhalation of gases from soil. Monitoring programmes in uranium mines for radon progeny exposure were developed in the 1950's to control worker exposure.

(14) The first indoor radon measurements were made in the 1950's (Hultqvist, 1956), but attracted little attention. However, from the 1970's, there were an increasing number of measurements of elevated radon levels in dwellings in some countries. During the last ten years, significant radon surveys in dwellings and workplaces as well as management strategies have then been implemented in many countries.

(15) This history of radon as a cause of lung cancer was formalised in 1986, with identification of radon by the World Health Organisation as a human lung carcinogen (WHO, 1986; IARC, 1988). At that time, the main source of information on risks of radon-induced lung cancer was epidemiological studies of underground miners (ICRP, 1993).

(16) Since the 1990's, several studies have provided informative data on risks at lower levels of exposure (e.g., Lubin et al., 1997; NRC, 1998; EPA, 1999; 2003, Tomášek et al., 2008). In addition, recent combined analyses of lung cancer data from case-control studies of residential radon exposure have demonstrated raised risks at lower levels of exposure (Darby et al., 2005; 2006; Krewski et al., 2006; Lubin et al., 2004).

(17) A more comprehensive review of the history of the control of radon exposure is given as a separate publication in ICRP *Publication 65* (ICRP, 1993, 2011).

2.2. Radon sources and exposures

2.2.1. Sources and transfer

(18) Radon-222 is a radioactive decay product of uranium-238 which is present in the earth's crust in varying concentrations (at parts per million levels). Radon-222 has a half-life of 3.82 days and is the direct decay product of radium-226.

(19) In the course of decay, the resulting products generally remain in the rock at the place where the atom decays. In the case where the decay product is gaseous, this atom is capable of movement; if it is created in the pore space next to a fracture or to a discontinuity in the rock then it can move from its point of production. The

air in the soil is heavily loaded with radon at concentrations of between 2,000 and 1 million Bq m^{-3}. The radon in the pore spaces is mainly transported by diffusion, with the transport rate depending on the porosity and permeability of the soil or by convection, dependent on the presence of cracks and faults. The movement of dissolved radon via ground water is another significant transport mechanism.

(20) Before it decays, some of the radon can pass from the soil into atmospheric air layers. The quantity of radon emanating from the soil is typically small and the radon is strongly diluted in the air, with the amount of dilution dependent on the atmospheric stability and presence of wind and level of turbulence (related to the vertical temperature gradient). The concentration of radon-222 in atmospheric air is consequently generally low but variable. Measurements over land vary between 1 and 100 Bq m^{-3}. Typical outdoor levels of radon-222 are of the order of 10 Bq m^{-3}, with lower levels near coasts and over small islands (UNSCEAR, 2000, 2009).

(21) Radon-220 is a radioactive decay product of thorium-232 which is present in the earth's crust in varying concentrations. Radon-220 has a much shorter half-life ($T_{1/2}$=55 s) than radon-222 so it does not move significantly from its source. Its behavior in the environment is quite different from that of radon-222. Radon-220 may also come from some building materials. There is considerable variability of radon-220 gas concentrations from place to place. In general the average levels of radon-220 gas indoor in different countries are in the range of 0.2 –12 Bq m^{-3} (UNSCEAR, 2000) with typical value of 0.3 Bq m^{-3}. These typical values do not present radiological protection problems.

(22) While the radon flux from soil to outdoor air is strongly diluted, this is not the case if the flux enters closed premises such as dwellings (Fig. 4). Depending on the ventilation rate of the building, radon gas can concentrate as compared to outdoor air. This feature is not the dominant cause of high radon concentrations however. Depending on meteorological parameters and in particular the temperature difference between outdoor and indoor air, there is a pressure differential between the soil and the foundations of the building. This causes an enhanced flow of radon-rich soil air, depending on the permeability of the floor slab resting on the soil and the ventilation of the sub-slab crawl space if this exists. This flow in general is much more important than transfer of radon by diffusion. In the absence of pressure differences the transfer of radon by diffusion is reduced as a result of the higher density of the basement slab compared to the soil surface

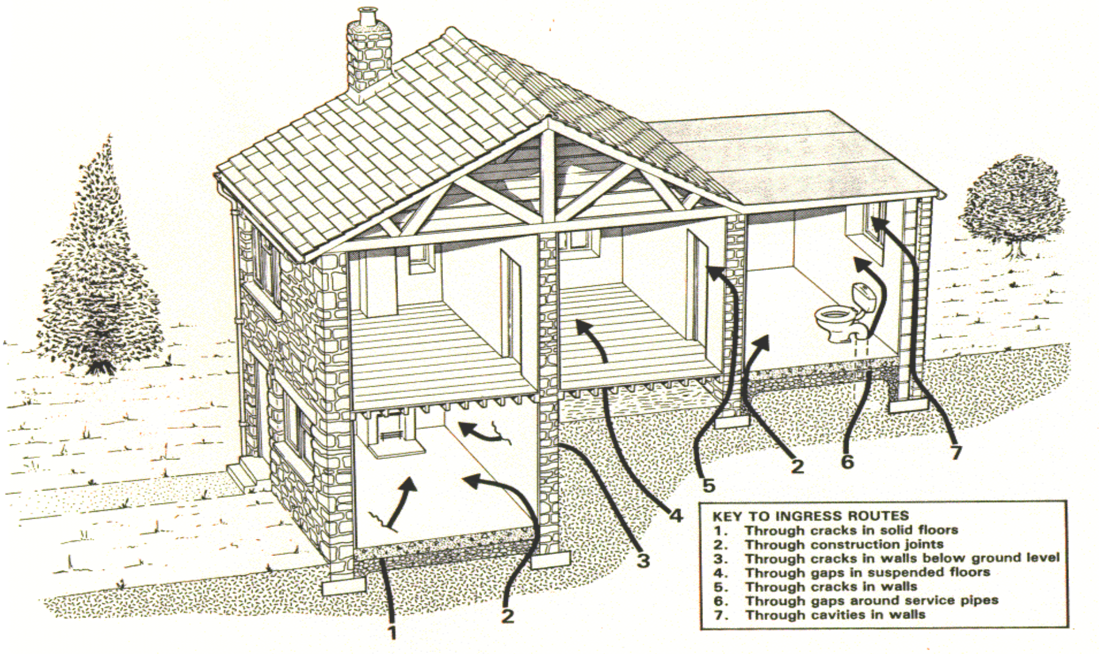

Fig. 4: Sources of indoor radon

(23) The transfer of radon from the soil to a building depends on several parameters:

- The composition of the soil: chemistry, geology, soil moisture, permeability to radon;
- The concentration of radon in the soil;
- The pressure differential between inside and outside, between the soil and atmosphere surrounding the building and between the soil and the lower rooms of the building;
- The area of building in contact with the ground;
- The air tightness of the outer shell of the building (presence of cracks, pipe ducts and cable ducts, etc.), especially in the floors and foundations of the building.

(24) The transfer of radon within the building also depends on several factors:

- The ventilation system in the building;
- The air circulation in the building;
- The meteorological and seasonal parameters, mainly the temperature difference between outside and inside air;
- The floor level and the size of the rooms;
- The life styles and the working habits of the building occupants.

(25) Building materials have variable contents of uranium and thorium. Radon can be released from these materials into the surrounding air. The amount released depends on the rate of radon production and the porosity of the material. For ordinary building materials, the volumetric rate of ingress is between 0.05 and 50 Bq $(m^3.h)^{-1}$ and the corresponding concentration is between 0.03 and 30 Bq m^{-3} (for an average rate of air renewal of 0.7 per hour). Situations do exist, for example in the case of concrete containing high radium concentration, such as that manufactured

using natural “alum shale”, where the concentration of radon can reach 1,000 Bq m^{-3}. However in the majority of cases this source of radon is of secondary importance compared with radon infiltration from the soil (EC, 1999).
Radon concentration in ground water varies considerably and can be relatively high in spite of the poor solubility of radon in water. It depends on the concentration of uranium in the surrounding rock, on the circulation of subterranean water and on the distribution of the aquifer with respect to the surrounding rock. The values range from 1 to 10,000 Bq l^{-1}. For some private wells, boreholes and springs relatively high radon concentrations have been observed. If water containing radon is used for a domestic supply, the radon can degas into indoor air causing elevated levels. Radon levels in most public supplies are in general relatively low due to the decrease in radon by decay or degassing during transfer.

(26) Whatever the source of radon (soil, building materials or water) the concentration in buildings may vary over several orders of magnitude: from 10 Bq m^{-3} to 70,000 Bq m^{-3} according to UNSCEAR (UNSCEAR, 2009) knowing that indoor concentrations of less than 10 Bq m^{-3} and more than 70,000 Bq m^{-3} have been observed in some countries (United Kingdom). The average world value indoors is about 40 Bq m^{-3}.

2.2.2. Nature and quantification of the radon risk

(27) Because radon is an inert gas, nearly all of the radon that is inhaled is subsequently exhaled. Radon-222 decays to form one atom of non-gaseous polonium-218 (half-life: 3.098 minutes). In turn, this atom decays into other radionuclides (see Fig. 1): lead-214 (half-life: 26.8 minutes), bismuth-214 (half-life 19.8 minutes), polonium-214 (0.2 milliseconds), lead-210 (22 years), bismuth-210 (5.0 days), polonium-210 (138.4 days) and finally lead-206 (stable). These radionuclides, called radon progeny or radon decay products, exist either in air as unattached, ultrafine atoms, as atoms attached to airborne submicron particles or they will deposit onto surfaces.

(28) When inhaled the short-lived radon progeny can deposit within the respiratory tract at locations dependent on the diffusion properties of the particles, predominantly the size distribution of the aerosols. The decay products present in the air deposit in the nasal cavities, on the walls of the bronchial tubes and in the deep lung. Because of their relatively short half-lives (less than half an hour), the radon progeny decay mainly in the lung before biological clearance can take place.

(29) Two of these short-lived progeny, polonium-218 and polonium-214, emit alpha particles whose deposited energy dominates the dose to the lung. It is believed that the irradiation of the sensitive basal cells of these organs by the alpha particles emitted by polonium-218 and polonium-214 may lead to health effects, principally lung cancer (see ICRP, 2011). The long-lived lead-210 is transported from the lungs by clearing mechanism and transferred to the blood. It does not contribute significantly to the dose to the lung, but other organs of the body may accumulate this long lived radionuclide. However, the dose to these other organs from lead-210 formed within the body is relatively low.

(30) The radio-toxicity of radon in ambient air is, in principle, not directly proportional to the individual concentration but depends on its potential alpha energy concentration (PAEC), a linear combination of all the energies of the emitted alpha particles associated with the decay of all the radon progeny present in the volume of air under consideration. The SI unit of PAEC is the J m^{-3}. Historical units

of PAEC include the Working Level (WL). One WL corresponds to 2.08 x 10^{-5} J m^{-3}. For a radon concentration C_{Rn}, the equilibrium factor is the ratio of the PAEC to the PAEC for progeny in equilibrium with the radon concentration $C_{Rn.}$ The equilibrium equivalent concentration of radon (EEC) is another measure of PAEC and is the product of the equilibrium factor and the radon concentration. In the case where the decay products are in equilibrium with radon, a concentration of radon-222 (EEC) of 1 Bq m^{-3} corresponds to 5.56 x 10^{-9} J m^{-3}. The equilibrium factor varies with the entry flux of radon, the ventilation rate, the rate of deposition of the decay products onto the surfaces. A typical value for the equilibrium factor in dwellings is 0.4 (UNSCEAR, 2009). Thus, a concentration of radon of 100 Bq m^{-3} corresponds to an EEC of 40 Bq m^{-3}.

(31) The dose received by the lungs will depend on the PAEC, the duration of exposure, the rate of respiration, the aerosols properties, including the size distribution and hygroscopicity, the "unattached fraction" *f*, as well as factors such as the sensitivity of the biological tissues and the depth of the mucosal layer. Dosimetric models based on the ICRP Human Respiratory Tract Model (ICRP, 2006) are used to assess the dose received by the various tissues of the lungs. It should be noted that in the domestic environment or in ordinary workplaces, as opposed for instance to uranium mines, the ventilation rate is often rather low, and the equilibrium factor is determined by the plate-out of the relatively high *f*, for low aerosol concentrations. Hence, using the dosimetric models it was found that the dose correlates better with the radon concentration than with PAEC in these circumstances. (Porstendörfer and Reineking, 1992, Vanmarcke, Berkvens and Poffijn, 1989)

(32) In the past, significant discrepancies (a factor of approximately 2) have been observed between the dose per PAEC exposure from the dosimetric models and the dose per PAEC exposure factor obtained using the risk detriment from the epidemiological studies of miners exposed to radon and risk detriment based on the epidemiological studies of survivors of Hiroshima and Nagasaki. With the revised risk detriment for the uranium miner studies in *Publication 115* (ICRP, 2011; Marsh et al., 2010) this discrepancy has been reduced and both approaches seem now to be more consistent.

(33) In Publication 115 on the lung cancer risk from radon and progeny (ICRP, 2011) the ICRP made a thorough review and analysis of the epidemiology of radon for both workers (underground miners) and the general population. Its main conclusions were the following:

> "• There is compelling evidence from cohort studies of underground miners and from case-control studies of residential radon exposures that radon and its progeny can cause lung cancer. For solid tumours other than lung cancer, and also for leukaemia, there is currently no convincing or consistent evidence of any excesses associated with radon and radon progeny exposures.
>
> • The three pooled residential case-control studies (in Europe, North America and China) gave similar results and showed that the risk of lung cancer increases at least by 8% for an increase of 100 Bq m^{-3} in the radon concentration (Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004).
>
> • After correcting for random uncertainties in the radon activity concentration measurements, the European pooled residential case control study gave an excess relative risk of 16% (5% to 32%) per 100 Bq m^{-3} increase (Darby et al., 2005). This value may be considered as a reasonable estimate for risk

management purposes at relatively low and prolonged radon exposures in homes, considering that this risk is linked to an exposure period of at least 25 years.

• There is evidence from the European pooled residential case-control study that there is a risk of lung cancer even at levels of long-term average radon concentration below 200 Bq m^{-3} (Darby et al., 2005).

• The cumulative risk of lung cancer up to 75 years of age is estimated for lifelong non-smokers as 0.4%, 0.5% and 0.7% for radon activity concentrations of 0, 100 and 400 Bq m^{-3}, respectively. The lifetime cumulative risks of lung cancer by age 75 for lifelong smokers are close to 10%, 12% and 16% for radon activity concentrations of 0, 100 and 400 Bq m^{-3}, respectively (Darby et al., 2005; 2006). Cigarette smoking remains the most important cause of lung cancer.

• Appropriate comparisons of lung cancer risk estimates from miner studies and from indoor studies show good consistency.

• Based upon a review of epidemiological studies of underground miners, including studies with relatively low levels of exposure, a detriment adjusted nominal risk coefficient of 5 10^{-4} per WLM (0.14 per J h m^{-3}) is adopted for the lung detriment per unit radon exposure. This value of 5 10^{-4} WLM^{-1} (0.14 per J h m^{-3}) is derived from recent studies considering exposure during adulthood and is close to twice the value calculated in Publication 65 (ICRP, 1993)."

(34) As a result of this review, for radiological protection purposes, the Commission recommends in its Statement on radon (ICRP, 2011) a detriment-adjusted nominal risk coefficient for a population of all ages of $8x10^{-10}$ per Bq h m^{-3} for exposure to radon-222 gas in equilibrium with its progeny (i.e. $5x10^{-4}$ WLM^{-1}). The Commission's findings are consistent with other comprehensive estimates including that submitted to the United Nations General Assembly by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2009).

(35) In its handbook on indoor radon (WHO, 2009), the WHO listed key messages related to the health effects of radon:

"• Epidemiological studies confirm that radon in homes increases the risk of lung cancer in the general population. Other health effects of radon have not consistently been demonstrated.

• The proportion of all lung cancers linked to radon is estimated to lie between 3% and 14%, depending on the average radon concentration in the country and on the method of calculation.

• Radon is the second most important cause of lung cancer after smoking in many countries. Radon is much more likely to cause lung cancer in people who smoke, or who have smoked in the past, than in lifelong non-smokers. However, it is the primary cause of lung cancer among people who have never smoked.

• There is no known threshold concentration below which radon exposure presents no risk. Even low concentrations of radon can result in a small increase in the risk of lung cancer.

• The majority of radon-induced lung cancers are caused by low and moderate radon concentrations rather than by high radon concentrations, because in general less people are exposed to high indoor radon concentrations."

2.3. Similarities with other existing exposure situations

(36) Several characteristics of radon exposure in dwellings (and in many other locations) are similar to those of exposures arising from other existing exposure situations such as exposures to NORM or exposures in a long-term contaminated area after a nuclear accident or a radiation emergency (see ICRP, 2009).

(37) Radon exposure affects nearly all living places of a population and the exposure is impossible to control directly at the source. The ubiquity and the variability of radon concentration result in a very heterogeneous distribution of exposures. Day to day life or work, especially in a radon prone area, inevitably leads to some exposure to radon. The persistence of the risk or the potential for reduction is mainly dependant on individual behaviour.

(38) As the responsibility for remediation falls on individuals, the role of so-called self-help protective actions implemented with the support of the authorities and complementary to the protective actions implemented by the authorities, is crucial. Typical self-help protective actions are those aiming at the characterisation by the individuals of their own radiological situation and adapting their way of life (including prevention and mitigation of radon exposure) accordingly to reduce their exposure.

(39) Domestic radon exposure cannot be managed with radiological protection considerations alone, and other relevant factors should be addressed. These factors include: environmental considerations such as radon prone areas; the health status of the individuals, smoking habits, economic circumstances; architectural considerations such as the characteristics of the building and the link between radon prevention and energy saving; educational (development of information and awareness), psychological and cultural aspects (in particular for people living in a house for a long time, sometimes several generations) as well as ethical political and other relevant factors.

(40) Similar to a contaminated area, an inhabitant in a dwelling with high radon concentration may adopt a denial or a fatalist attitude. The direct involvement of inhabitants and local professionals in management of the situation is an effective way to improve the remediation process.

(41) The large spectrum of parties concerned with the management of radon exposure is also a feature shared with other types of existing exposure situations. Whereas the decision maker is mainly an individual (as dweller or building manager), the question is who can help him to deal with the radon issue. Several types of professionals are concerned such as in health, building and real-estate fields as well as local civil servants and elected representatives responsible for some types of public buildings, provided that they have been appropriately informed and trained. Other parties, such as experts or associations, may be mobilised at both national and local levels.

(42) It should also be noted that, in some cases, radon exposure in buildings or locations (dwellings, workplaces or mixed-use buildings) may arise in areas contaminated with radium (from past activities).

2.4. Challenges for a national radon policy

(43) Control of indoor radon exposure poses many challenges to be addressed by a national radon policy. These issues include:

2.4.1. Public health perspective

(44) People are exposed to radon as members of the public in dwellings or as workers in workplaces. They also are exposed to radon in public or private places open to the public either as members of the public, as patients or as workers. Since an individual can move between many places during the same day, a radon policy should ideally provide consistency in the management of the different locations in a given area and should also provide an integrated approach even though the time of occupancy varies from a location to another.

(45) People spend much of their time indoors, essentially at home and the remainder in different types of places in diverse capacities. From a public health perspective, since the radon risk is mainly due to domestic exposure, a radon policy should address primarily exposure in dwellings rather than in public spaces and workplaces where regulation is easier to enforce.

(46) From a public health perspective, a prevention policy is recommended to reach long-term objectives of radon reduction. Prevention of radon exposure is indeed critical, especially with new buildings. The implementation of preventive measures in new and renovated buildings provides a good partial solution, the cost-effectiveness increasing with time (STUK, 2008). It also helps developing awareness amongst professionals. Prevention also means to consistently plan to integrate a radon reduction strategy and energy saving strategy before their implementation to achieve the best outcome in building construction.

(47) Remediation in existing buildings is also often cost-effective, in particular in buildings with high radon concentrations. In such situations there may be a primary source of radon ingress, and radon levels can be reduced by more than a factor of ten.

(48) The evidence of a risk of lung cancer exists even at levels of long-term average radon concentration below 200 Bq m^{-3} (ICRP, 2011). An achievable ambition is to reduce the radon exposure and hence risk to the whole population as well as, for the sake of equity, reducing the highest individual exposures as low as reasonable achievable. However, one must keep in mind that the total elimination of radon exposure is not feasible.

(49) Radon exposure is not the only source of risk for the population. The radon policy should be properly scaled taking into account the other health hazards identified in the country. Furthermore, a combination between radon policy and other public health policies such as anti-smoking or indoor air quality policies should be sought in order to both avoid inconsistencies and achieve a better effectiveness.

(50) Taking into account the ubiquity of radon exposure and the multiplicity and diversity of situations and decision makers, a simple radon policy is more effective, which addresses most situations in the same, integrated approach. It must be supported and implemented on a long term basis (several decades), and involve all the parties concerned appropriately.

2.4.2. Responsibilities

(51) A national radon policy has to address many challenges in terms of legal responsibility, notably the responsibility of the householder towards her/his family, of the seller of a house or a building towards the buyer, of the landlord towards the

tenant, of the employer towards the employee, and generally speaking of the responsible person for any building towards its users.

(52) Since radon exposure is mainly a domestic issue, the success of the radon policy greatly depends on the decisions taken by individuals to reduce the risk in their home when relevant. A clear awareness of the general population about the risk associated to radon is required, in particular in radon prone areas, to help individuals in taking on their responsibilities. It has to be recognized that currently, apart from some countries which have developed radon policies for a long time, this awareness is often poor and has to be increased. Ways of improvement should combine the enforcement of regulations as well as the development of a radiation protection culture aiming at raising the awareness and scaling of the risks to develop a questioning and proactive attitude. The provision of a good infrastructure and support for information, measurement and remediation is a prerequisite.

(53) The degree of enforcement of the actions that are warranted is very much related to the degree of legal responsibility for the situation. The owner of a house may have such responsibilities if the house is rented or sold. An employer has a legal responsibility for the health and safety of his employees. The manager of a school (or the local authority) has also a legal responsibility for the health of the pupils as well as of the teachers. The same consideration may apply to other public building and workplaces. A radon policy should ensure that the requirements related to such responsibilities in the radon policy are commensurate with the global public health policy in the country.

(54) The issue of responsibility shows clearly the need for a graded approach in defining and implementing a radon policy. Such a graded approach should be based on both ambition and realism. Any radon policy should also aim to effectiveness (see sections 3.3.3 and 4.1.3).

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3. RECOMMENDATIONS OF THE COMMISSION

(55) The Commission's system of radiological protection of humans is described in *Publication 103*[1] (ICRP, 2007). According to paragraph 44, it "applies to all radiation exposures from any source, regardless of its size and origin." In particular, according to paragraph 45, "the Commission's Recommendations cover exposures to both natural and man-made sources. The Recommendations can apply in their entirety only to situations in which either the source of exposure or the pathways leading to the doses received by individuals can be controlled by some reasonable means. Sources in such situations are called controllable sources."

(56) Indoor radon exposure is controllable since the pathways from the source to the exposed individuals can be controlled. Outdoor radon concentrations at ground level can be high but the radon gas is normally diluted through dispersion into the atmosphere, so that concentrations in the ambient air are in general rather low, a few tens of Bq m^{-3} (UNSCEAR,2009), apart from some areas with very high exhalation of radon. Since neither the source nor the pathways can reasonably be controlled, the Commission considers that human exposure to outdoor radon is reasonably unamenable to control.

3.1. Exposure situations and categories of exposure

(57) The categories of exposure and the types of exposure situations are introduced in *Publication 103* (ICRP, 2007). According to paragraph 169, "everybody is exposed to ionising radiation from natural and man-made sources. It is convenient to think of the processes causing these human exposures as a network of events and situations. Each part of the network starts from a source. Radiation or radioactive material then passes through environmental or other pathways leading to the exposure of individuals. Finally, the exposure of individuals to radiation or radioactive materials leads to doses to these individuals. Protection can be achieved by taking action at the source, or at points in the exposure pathways, and occasionally by modifying the location or characteristics of the exposed individuals. For convenience, the environmental pathway is usually taken to include the link between the source of exposure and the doses received by the individuals. The available points of action have a substantial effect on the system of protection."

(58) As far as radon exposure is concerned, the source is mainly concentrations of natural activity in the earth's crust. Water extracted from wells (whose concentration also depends on the natural activity in the earth's crust) and building materials may constitute other sources of less importance in most circumstances. The pathways are related to the building or location in which radon is accumulated.

3.1.1. Types of exposure situations

(59) According to the paragraph 176 of *Publication 103* (ICRP, 2007), "the Commission intends its Recommendations to be applied to all sources and to individuals exposed to radiation in the following three types of exposure situations which address all conceivable circumstances.

[1] At the time of the issue of the present publication the Commission was revising the glossary enclosed in the Pub 103 because of some imperfections and inconsistencies with the text so that this publication is referring to the text of Pub 103 rather than to its glossary.

• *Planned exposure situations* are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise both to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures).

• *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.(…)"

(60) Radon exposure situations have the characteristics of existing exposure situations since the source is unmodified concentrations of ubiquitous natural activity in the earth's crust. Human activities may create or modify pathways increasing indoor radon concentration compared to outdoor background. These pathways can be modified by preventive and corrective actions. The source itself, however, cannot be modified and already exists when a decision of control has to be taken. Radon in dwellings or workplaces is mentioned as examples of existing exposure situations in paragraph 284 of *Publication 103* (ICRP, 2007). Such a consideration is *a priori* still valid.

(61) Exposure to workers involved in uranium mining is often managed in the same way as a planned exposure situation, because uranium mining is part of the nuclear fuel cycle and also because workers are occupationally exposed to other radiation sources than radon (external exposure to gamma radiation and inhalation or ingestion of dust). It is for national authorities to decide which workplace situations are to be regarded from the outset as planned exposure situations.

(62) Radon is not likely to give rise to an emergency exposure situation even though the discovery of very high concentrations in a place may require the prompt implementation of protective actions, in particular when the exposure affect other occupants for whom the decision maker for a property has a duty of care.

(63) The philosophy of *Publication 103* (ICRP, 2007) compared to *Publication 60* (ICRP, 1991) is to recommend a consistent approach for the management of all types of exposure situations. This approach is based on the application of the optimisation process below appropriate dose constraints or reference levels.

3.1.2. Categories of exposures

(64) The Commission distinguishes between three categories of exposures: occupational exposures, public exposures, and medical exposures of patients. The Commission's approach for the management of radon exposure is also directly related to the type of location (dwellings, workplaces and mixed-use buildings).

(65) *Occupational exposure* is defined by the Commission as all radiation exposure of workers incurred as a result of their work in the paragraph 178 of *Publication 103* (ICRP, 2007). The Commission has noted the conventional definition of occupational exposure to any hazardous agent as including all exposures at work, regardless of their source. However, because of the ubiquity of radiation, the direct application of this definition to radiation would mean that all workers should be subject to a regime of radiological protection. Then the paragraph 178 of *Publication 103* specifies that "the Commission therefore limits its use of 'occupational exposures' to radiation exposures incurred at work as a result of

situations that can reasonably be regarded as being the responsibility of the operating management".

(66) *Publication 65* (ICRP, 1993) indicates in its paragraph 86 that "workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as members of the public". This is still valid, taking into account that the health and safety of the workers continue to be under the responsibility of their employer. In other words, the "common" workplaces (where radon exposure is adventitious) are not managed by controlling individual exposures but, like dwellings, by controlling the building (or location) in order to ensure the collective protection of its occupants.

(67) In the particular case of situations which are already recognised as planned exposure situations for the conduct of a specific practice, if workers' exposures to radon cannot reasonably be regarded as being the responsibility of the operating management, then the Commission recommends a pragmatic approach. This approach is that radon exposures of workers should not be part of the overall occupational exposure taking into account, if relevant, the specific graded approach for workplaces described in sub-section 3.3.6..

(68) The Commission also introduced in the paragraph 298 of *Publication 103* (ICRP, 2007) the concept of entry point which is a level of concentration above which occupational protection requirements apply to radon exposure in workplaces. Now the Commission recommends the use of an integrated and graded approach within the optimisation process to determine in which circumstances the application of occupational protection requirements is appropriate, on the basis of either a reference level or qualitative considerations (see section 3.3.6).

(69) According to the paragraph 180 of *Publication 103* (ICRP, 2007), "*public exposure* encompasses all exposures of the public other than occupational exposures and medical exposures of patients. It is incurred as a result of a range of radiation sources. The component of public exposure due to natural sources is by far the largest, but this provides no justification for reducing the attention paid to smaller, but more readily controllable, exposures to man-made sources. (…)" This definition is appropriate for radon exposure. It means that people exposed to radon in dwellings and in workplaces where radon exposure of the workers cannot reasonably be regarded as being the responsibility of the operating management, should be considered as members of the public.

(70) *Medical exposures* are mainly radiation exposures of patients. Such exposures occur in diagnostic, interventional, and therapeutic procedures. The exposure is intentional and for the direct benefit of the patient. Radon exposure arising from prescribed medical treatment of patients at spas using radon in the care process is considered as medical exposure and should be controlled using the relevant requirement provided notably in *Publication 103* (ICRP, 2007). It is not the purpose of this Publication to consider in more details such type of exposure.

3.2. Justification of protection strategies

(71) In the ICRP system of protection, the principle of justification is one of the two source-related fundamental principles (see ICRP, 2007; paragraph 203). In application of this principle, any decision that alters the radiation exposure situation should do more good than harm. This means that, by introducing a new radiation source, by reducing existing exposure, or by reducing the risk of potential exposure,

one should achieve sufficient individual or societal benefit to offset the detriment it causes.

(72) Radon exposure can be controlled mainly by action modifying the pathways of exposure and normally not by acting directly on the source. In these circumstances, the principle of justification is applied in making the decision as to whether or not to implement a protection strategy against radon exposure. Such a decision, which always will present some disadvantages, should be justified in the sense that it should do more good than harm (see ICRP, 2007; paragraph 207). The responsibility for judging the justification of radon protection strategies to ensure an overall benefit to the society falls on governments or national authorities. The Commission considers that many arguments are globally supporting that the implementation of national radon protection strategies is justified:

- Radon is a significant source of radiation exposure which is the second cause of lung cancer in the general population, after smoking.
- Radon exposure can be controlled. Feasible techniques do exist to prevent and mitigate high indoor radon concentration.
- A radon policy has positive consequences on other public health policies such as indoor air quality (when other pollutants are present) or anti-smoking policy (reducing radon concentration contributes mitigating health effects of tobacco).

(73) Although radon is much more likely to cause lung cancer in people who are smoking, or who have smoked in the past, than in lifelong non-smokers, it seems to be the primary cause of lung cancer among people who have never smoked. The excess relative risk is comparable for smokers and non-smokers. In practice, it would be difficult to address the radon issue separately or differently for smokers, non smokers, passive smokers and/or past smokers. Hence the Commission considers that radon strategies should address together both smokers and non-smokers.

3.3. Optimisation of the protection

(74) Optimisation is the second fundamental principle of radiological protection, and is central to the system of protection. It is source-related like the principle of justification and applies to all three exposure situations: planned exposure situations, emergency exposure situations, and existing exposure situations. According to the principle of optimisation, the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors. This means that the level of protection should be the best under the prevailing circumstances, maximising the margin of benefit over harm. In order to avoid severely inequitable outcomes of this optimisation procedure, there should be restrictions on the doses or risks to individuals from a particular source (dose or risk constraints and reference levels) (see ICRP, 2007; paragraphs 203 and 211).

(75) Implementation of the optimisation principle of protection is a process that is at the heart of a successful radiological protection programme. It must be framed carefully to take into account the relevant attributes of the exposure situation. Furthermore, it should include, as appropriate to the exposure situation, the involvement of the relevant stakeholders. These two elements are considered by the

Commission as important components of the optimisation process (see ICRP, 2006; paragraph 23).

3.3.1. Dose reference level

(76) In *Publication 65* (ICRP, 1993), the Commission considered that some remedial measures against radon in dwellings were almost always justified above a continued annual effective dose of 10 mSv. The Commission also considered that it was logical to adopt an action level for intervention in workplaces at the same level of effective dose as the action level for dwellings. Taking into account that, for simple remedial measures, a somewhat lower figure could be considered, it recommended to use the range of about 3-10 mSv as a basis for adopting action levels for intervention in dwellings or workplaces. An action level was defined as the annual mean concentration of radon at which intervention is recommended to reduce the exposure in a dwelling or a workplace.

(77) In *Publication 103* (ICRP, 2007), the Commission no longer used the concept of action level but instead the concept of reference level. The reference level represents, in emergency or existing controllable exposure situations, the level of dose or risk above which is judged to be inappropriate to plan to allow exposures to occur, and for which therefore protective actions should be planned and optimised. The consequence of using the concept of reference level instead of the concept of action level is that optimisation should be applied as appropriate above and below the reference level and not only above. It must be kept in mind that reference levels do not represent a demarcation between ‘safe’ and ‘dangerous’ or reflect a qualitative change in the associated health risk for individuals.

(78) According to *Publication 103*, the chosen value for a reference level will depend upon the prevailing circumstances of the exposure situation under consideration (ICRP, 2007; paragraph 234). In order to provide guidance for selecting appropriate values, the Commission defined a dose scale (ICRP, 2007; Table 5) reflecting the fact that, within a continuum of risk (linear non-threshold assumption), the risk that everyone is ready to accept depends on the exposure context. This scale is divided into three bands reflecting the more or less important need for action which is depending on the characteristics of the exposure situation: controllability of the source; individual or societal benefit from the situation; requirements with regard to information, training and dosimetric or medical surveillance. Numerically speaking, the three bands are: <1 mSv, 1-20 mSv and 20-100 mSv (in acute or annual doses). They should be seen as indicators.

(79) The second band, greater than 1 mSv but not more than 20 mSv, fits to most radon exposures. It applies when individuals receive direct benefits from the exposure situation and when exposures may be controlled at source or, alternatively, by action in the exposure pathways, so that general information should be, where possible, made available to enable individuals to reduce their doses. Radon exposure cannot normally be controlled at the source (apart from a few exceptions) but through many pathways by preventive and corrective actions which are not disproportionately disruptive. Every person receives an obvious direct benefit from being indoor since life and human activities would be impossible outdoor. For the occupant of a building with high radon concentration there is generally a benefit from continuing to use it rather than moving to another building or even another area, which is strong enough to offset the risks of indoor radon exposure.

(80) In *Publication 103* (ICRP, 2007), for the sake of continuity and practicality, the Commission retained the upper value of 10 mSv adopted in *Publication 65* (ICRP, 1993) for the individual dose reference level, even though the nominal risk per sievert has changed slightly between 1993 and 2007. This value, which is the middle of the band 1-20 mSv, is consistent with the rationale provided in Table 5 of *Publication 103*.

(81) Taking into account these considerations, the Commission considers it appropriate to retain the value in the order of 10 mSv per year as the upper value for the individual dose reference level for radon exposure.

3.3.2. Upper value for Reference level in concentration

(82) According to paragraph 225 of *Publication 103* (ICRP; 2007), "the concepts of dose constraint and reference level are used in conjunction with the optimisation of protection to restrict individual doses. A level of individual dose, either as a dose constraint or a reference level, always needs to be defined. The initial intention would be to not exceed, or to remain at, these levels, and the ambition is to reduce all doses to levels that are as low as reasonably achievable, economic and societal factors being taken into account."

(83) The paragraph 226 of the same publication adds that, "for the sake of continuity with its earlier Recommendations (ICRP, 1991), the Commission retains the term 'dose constraint' for this level of dose in planned exposure situations (with the exception of medical exposure of patients). For emergency exposure situations and existing exposure situations, the Commission proposes the term 'reference level' to describe this level of dose. The difference in terminology between planned and other exposure situations (emergency and existing) has been retained by the Commission to express the fact that, in planned situations, the restriction on individual doses can be applied at the planning stage, and the doses can be forecast so as to ensure that the constraint will not be exceeded. With the other situations a wider range of exposures may exist, and the optimisation process may apply to initial levels of individual doses above the reference level."

(84) In its Statement on Radon (see ICRP, 2011), the Commission revised the upper value for the reference level for radon gas in dwellings from the value published in the 2007 Recommendations (ICRP, 2007) of 600 Bq m^{-3} to 300 Bq m^{-3}. This value of concentration is greater than the level at which a statistically significant risk has been observed in residential epidemiological studies but it would be quite difficult to reduce radon exposures below such a level (around 200 Bq m^{-3}) in some countries. However, the effective doses implied by radon concentrations up to this level are within the Commission's band for existing exposure situations (1 mSv to 20 mSv) and close to the level of 10 mSv per year in the condition of exposure of a dwelling. Then the Commission still recommends 300 Bq m^{-3} as the upper value of the reference level for radon gas in dwellings.

(85) For the sake of simplicity, considering that a given individual going from place to place in the same area along the day should be protected on the same basis whatever the location, the Commission recommends to use *a priori* the same upper value of 300 Bq m^{-3} for the reference level for radon gas in mixed-use buildings (e.g. schools, hospitals, shops, cinemas…) with access for both members of the public and workers, and, by extension, in workplaces without access for public when workers exposures to radon cannot reasonably be regarded as being the responsibility of the operating management (e.g. office buildings or common

workshops). Specific requirements, however, may be applicable in workplaces where such a global approach does not fit (see sub-section 3.3.6).

(86) As said in *Publication 103* (ICRP, 2007; paragraph 295), it is the responsibility of the appropriate national authorities, as with any other controllable radiation sources, to establish their own national reference levels, taking into account the prevailing economic and societal circumstances and then to apply the process of optimisation of protection in their country. It is important to note that reference levels relate to the annual mean concentration of radon in a building or location.

3.3.3. Optimisation process

(87) According to paragraph 22 of *Publication 101* (ICRP, 2006), "to provide the best protection under the prevailing circumstances (in normal, emergency or existing controllable situations), the process of optimisation below a dose restriction must be implemented through an ongoing, cyclical process (called the optimisation process) that involves evaluation of the exposure situation to identify the need for action (framing of the process); identification of the possible protective options to keep the exposure as low as reasonably achievable; selection of the best option under the prevailing circumstances; implementation of the selected option through an effective optimisation programme; and regular review of the exposure situation to evaluate if the prevailing circumstances call for the implementation of corrective protective actions."

(88) The Commission considers now that for the sake of clarification, when dealing with existing exposure situations, the distinction should be made between prevention aiming at maintaining exposure as low as reasonably achievable under the prevailing circumstances and mitigation aiming at reducing exposure as low as reasonably achievable (see Fig. 5).

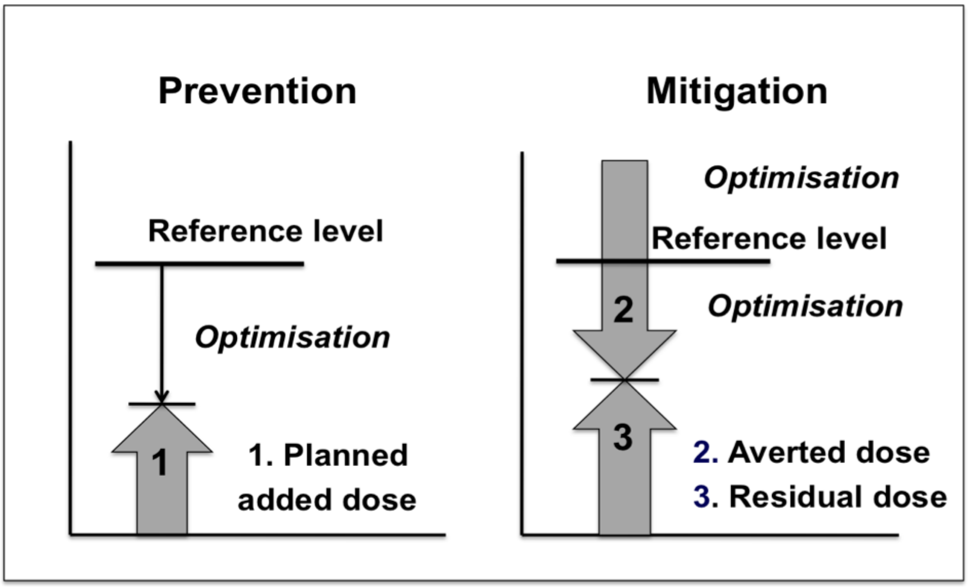

Fig. 5: The implementation of the optimisation principle in existing exposure situations

(89) The optimisation process is implemented for radon exposures through national protection strategies (see chapter 4). The objective is both to reduce the

overall risk of the general population and, for the sake of equity, the individual risk in particular the risk of the most exposed individuals (see Fig. 6). In both cases the process includes the management of buildings and should result in radon concentrations in ambient indoor air as low as reasonably achievable below the national reference levels. In a given building, in general, no further action will be required apart from monitoring radon activity concentration sporadically to ensure that radon levels remain low. However, before starting a major renovation of the building for example to improve the insulation radon exposure should be taken into account during the planning, design and renovating phases.

(90) National authorities should establish their own radiation protection strategy with a long-term perspective. The aim of significantly reduce the radon risk at the level of the general population is rather a matter of several decades than several years.

(91) Optimisation of protection from radon exposures in buildings and locations can be determined using standard cost-benefit analysis techniques. Thus, comparisons can be made between the financial costs associated to the estimated of number of lung cancer cases likely attributable to radon at different levels of exposure, the selection of protective actions for a given population, and the costs of preventive and protective actions to reduce radon exposures (e.g. HPA, WHO, 2009). Such analyses can be used to inform decisions on the cost-effectiveness of measures to reduce radon levels in existing properties and new homes.

(92) In many countries, the national radon protection strategy is sufficiently justified to necessitate the clear expression of a real ambition. Such an ambition does not prevent from the implementation of a graded approach taking into account the more or less need for action (depending on the magnitude of the exposure, the degree of responsibility, the means, etc.).

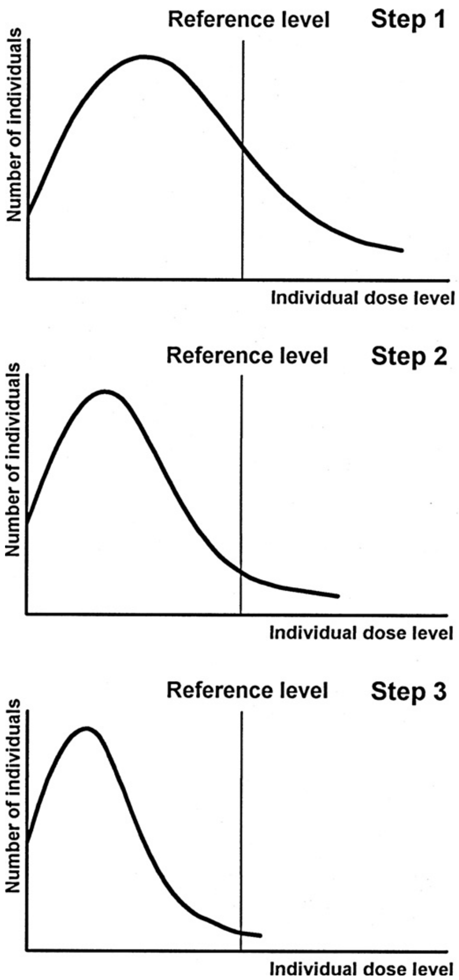

Fig. 6: The use of a reference level in an existing exposure situation and the evolution of the distribution of individual exposures with time as a result of the optimisation process

3.3.4. National Reference level

(93) As stated previously, it is the responsibility of the appropriate national authorities, as with any other controllable radiation sources, to establish their own national reference levels, taking into account the prevailing economic and societal circumstances and then to apply the process of optimisation of protection in their country.

(94) In the Commission's system of radiological protection, a reference level represents the level of dose or risk or radionuclide concentration, above which it is judged to be inappropriate to plan to allow exposures to occur, and for which therefore protective (both preventive and corrective) actions should be planned and optimised. The Commission no longer used the concept of action level but instead the concept of reference level. The consequence of using the concept of reference level instead of the concept of action level is that optimisation should be applied as appropriate above and below the reference level and not only above.

(95) For radon exposure in buildings, the reference level should be given in terms of indoor radon concentration (in Becquerel per cubic meter). It is most easily measurable and it is directly linked to lung cancer risk as shown by the pooled indoor radon studies.

(96) The lower the national reference level, the more the overall population risk from radon exposure would be mitigated. In its handbook on indoor radon (WHO, 2009) WHO considers that, in view of the latest scientific data on health effects of indoor radon, a reference level of 100 Bq m^{-3} is justified from a public health perspective because an effective reduction of radon-associated health hazards for the population is expected. However, WHO added that if this level cannot be implemented under prevailing country - or region - specific geological and house construction conditions, the chosen reference level should not exceed 300 Bq m^{-3}.

(97) The first step is to characterise the exposure situation of individuals and the general population in the considered country, as well as other relevant economic and societal criteria, and the practicability of reducing or preventing the exposure. The appropriate value for the reference level may then be established by a process of generic optimisation that takes into account national or regional attributes and preferences together, where appropriate, with considerations of international guidance and good practice elsewhere. Many factors such as the mean radon level and the radon distribution, the number of existing homes with high radon levels, etc. should be taken into consideration. The prevalence of smoking in a society should be targeted in an overall smoking control policy ideally in a coordinated action with the national radon protection strategy, however, the reference level is applicable to smokers, non-smokers, passive smokers and never-smokers in the same way.

(98) When a national reference level has been established, preventive and corrective actions should be intended to produce substantial reduction in radon exposures. It is not sufficient to adopt marginal improvements aimed only at reducing the radon concentrations to a value just below the national reference level.

(99) Periodically the value of the national reference level for radon exposure should be reviewed to ensure that it remains appropriate.

3.3.5. Graded approach

(100) The radon protection strategy should start with an intensive programme of actions including provision of general information on radon behaviour and risk, campaigns aiming at increasing the awareness of a targeted public, campaigns of concentration measurement as well as, for example, organisation of a technical or financial support for measurement and remediation (see chapter 4). These actions may be implemented preferentially in certain areas such as radon prone areas and in high risk building (e.g. with high occupancy i.e. frequented by many people and/or with a long stay individually). The aim of this starting programme is to encourage relevant decision makers to enter in a process of self-help protective actions such as measurement and, if needed, remediation, with more or less pressure but mainly with incentive and helping provisions.

(101) The degree of enforcement of the actions that are warranted is very much related to the ambition of the national radiation protection strategy and the degree of responsibility for the situation. In situations comprising legal responsibilities (e.g. employer/employee, landlord/tenant, seller/buyer, public building with high occupancy…), some mandatory provisions may be required. Such requirements should be commensurate with the degree and the type of responsibility, and decided after making an assessment showing that mandatory provisions are more effective than incentive ones under the prevailing circumstances. They could be to ensure good traceability and record-keeping or compliance with the reference level.

(102) The consequence of a failure in the compliance with the reference level when required is also dependent upon the situation: it could result in the obligation for the responsible individual or organisation to provide the result of the measurement (e.g. to an authority, to the buyer…), the loss of some advantage (e.g. in the tax system), the obligation to undertake remediation or another type of obligation or penalty. A radon policy should ensure that the requirements related to such responsibilities are commensurate with the means in the hand of the responsible person and that the benefit in terms of risk reduction offsets the disadvantages for example in terms of deterring people from initial measurement or decreasing value of the property or overweighed procedures.

(103) The graded approach may be implemented in a specific way in some workplaces (see below).

3.3.6. Specific graded approach for workplaces

(104) As explained above, because of the ubiquity of radiation, the Commission limits its use of 'occupational exposures' to radiation exposures incurred at work as a result of situations that can reasonably be regarded as being the responsibility of the operating management. It also considers that workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as members of the public. Such a way is without prejudice to the legal responsibility of the employer towards its employees.

(105) Workplaces where radon exposure are incurred as a result of situations that cannot reasonably be regarded as being the responsibility of the operating management are workplaces where radon exposure is adventitious and more related to the location than to the work activity. In fact, many workplaces are in that category which comprises most of the mixed use buildings (school, hospitals, post offices, jails, shops, cinemas, etc.) as well as office buildings and common workshops.

(106) In these workplaces, the first step of the graded approach consists in managing the working location like another building using the same national reference level (300 Bq m^{-3} or less) and implementing the optimisation process above and as necessary below this reference level. Such an integrated approach (for dwellings, mixed use buildings and "common" workplaces) makes sense for individuals daily confronted with radon exposure at home, at work, at school and in all indoor spaces they enter. It makes sense also for the national authorities since a simple common type of management covers all cases except specific cases. The value of 300 Bq m^{-3} should become the appropriate upper reference level for the design of any new building whatever its purpose. The responsibility of the employer may be exercised by applying the regulatory or standardised framework laid down for the control of radon exposure in buildings.

(107) However, the relationship between measured radon concentration and effective dose depends upon factors including attached fraction, that can vary between different locations. Therefore if the reference level is exceeded in a workplace, this does not mean that the dose reference level of 10 mSv per year is also exceeded.

(108) Consequently, if difficulties are met in keeping indoor radon concentration below the reference level in workplaces, the radon protection strategy should provide, as a second step of the graded approach, the possibility to make further investigation using a more realistic approach. It means making an assessment of

radon exposure taking into account the actual parameters of the exposure situation (for example, the actual time of occupancy or the measurements of radon progeny). The dose reference level of 10 mSv per year should be used to size the specific indicators used for the control of radon exposure. Depending on the case, these indicators may be in becquerel per cubic meter, in time of occupancy (of specific rooms), in millisievert per year, etc. At this stage, the aim is to ensure a collective protection rather than to control individual doses.

(109) In workplaces where, despite all reasonable efforts to reduce radon exposure, it remains durably above the dose reference level of 10 mSv per year, then the workers should be considered as occupationally exposed and managed using the relevant radiological protection requirements set for occupational exposure. It is the third step of the graded approach.

(110) Further, national authorities may decide that workers' radon exposures in some types of workplaces should be considered as occupational exposure whether above or below a reference level. A positive list of workplaces or work activities should then be established nationally on the basis of this qualitative criterion (e.g. mines and other underground workplaces, spas…).

(111) Anyway, the decision whether or not workers' exposures to radon are considered as the responsibility of the operating management should be under the control of the national authorities.

(112) In workplaces where the workers are considered as occupationally exposed, the Commission recommends determining the working areas concerned (the whole or a part of a building or a location) and applying the optimisation principle as well as the relevant requirements for occupational exposure such as exposure monitoring (in doses or PAEC), dose recording, training, health surveillance, etc. In any cases, the upper value of the tolerable risk for occupational exposure (on the order of 20 mSv per year, possibly averaged over 5 years) should not be exceeded.

3.4. Application of dose limits

(113) According to *Publication 103* (ICRP, 2007; paragraph 203), the principle of application of dose limits is the third fundamental principle of the ICRP system. It is individual-related and applies in planned exposure situations. It means that the total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the Commission. In the following paragraph (paragraph 204), it is explained that regulatory dose limits are determined by the regulatory authority, taking account of international recommendations, and apply to workers and to members of the public in planned exposure situations.

(114) Dose limits apply only in planned exposure situations. For the sake of consistency, dose limit should apply in radon exposure situations for which national authorities decided that they are regarded from the outset as planned exposure situations, typically when workers are considered as occupationally exposed.

(115) The dose limit recommended by the Commission for occupational exposure is expressed as an effective dose of 20 mSv per year, averaged over defined 5 year periods (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year. (see ICRP, 2007; paragraph 244).

(116) The Figure 7 below shows the general approach now recommended for the management of the different radon exposure situations.

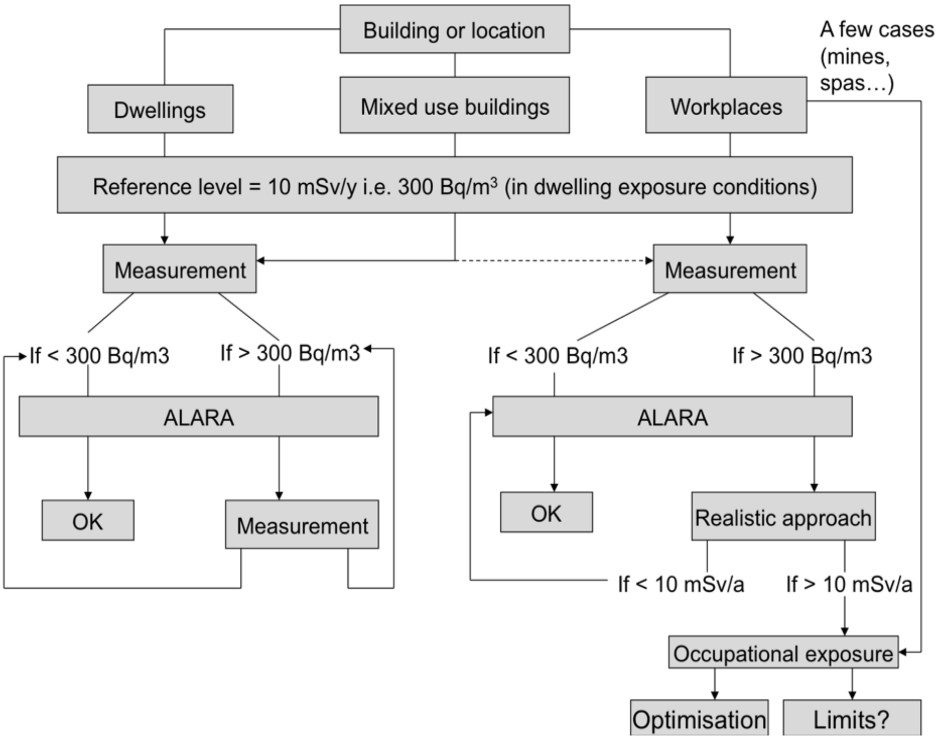

Fig 7: General approach for the management of radon exposure

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4. IMPLEMENTATION OF PROTECTION STRATEGIES

(117) Radon exposure is principally a public health issue. A national radon protection strategy should be as simple as possible and address all radon exposure in a both integrated and graded approach. Nevertheless, the degree of enforcement of the actions that are warranted will be very much related to the degree of responsibility for the situation.

(118) A national action plan should be established to frame the strategy aiming at controlling radon exposure through the management of the building or location. The radon protection strategy in the national action plan should be justified and then based on the application of the principle of optimisation of protection. The main steps are the setting of a reference level and then the application of the optimisation process. The national action plan should provide both preventive and corrective measures.

(119) The national radon protection strategy should also provide a frame to deal with workplaces where workers' exposures to radon are regarded as occupational exposures. Such situations are controlled using the relevant requirements for occupational exposures on the basis of the application of the optimisation principle and, if decided by the national authorities, the principle of individual dose limitation.

4.1. Control of exposure in buildings (dwellings, places open to the public and workplaces)

4.1.1. National radon action plan

(120) A national radon action plan should be established by national authorities with the involvement of relevant stakeholders. The objective is to reduce both the collective risk of the population and the individual risk to indoor radon exposures on the basis of the optimisation principle.

(121) The action plan should address radon exposure in dwellings, places open to the public and workplaces. The result of the optimisation process is indoor radon concentration activities as low as reasonably achievable below an appropriate reference level, taking into account economic and social factors as well as prevailing local circumstances about radon. No predetermined endpoint should be established.

(122) Preventive and corrective actions should indeed be intended to produce substantial reduction in radon exposures. It is not sufficient to adopt marginal improvements aimed only at reducing the radon concentrations to a value just below the national reference level. The World Health Organisation recommends a similar approach (WHO, 2009).

(123) The action plan should establish a framework with a clear infrastructure, determine priorities and responsibilities, describe the steps to deal with radon in the country and in a given location, identify concerned parties (who is exposed, who should take actions, who could provide support), address ethical and legal issues (notably the responsibilities) and provide information, guidance, support as well as conditions for sustainability. The national radon action plan should as far as possible be integrated with other public health policies such as anti-smoking or indoor air quality policies, as well as with energy saving policy.

(124) The implementation of the national radon action plan needs therefore the cooperation between national, regional and local authorities competent in different domains (radiological protection, public health, labour, land planning, housing, building construction, etc.), different professional disciplines (architects and other building professionals, radiation protection professionals, public health inspectors, medical professionals, etc.), different types of supporting organisations (experts, supporting agencies, associations…) and different responsible players (individual and institutional).

(125) The action plan may contain both incentive and mandatory provisions. Considering that responsibility for taking action against radon will often fall on the individuals who cannot be expected to carry out a detailed optimisation exercise, the action plan should provide appropriate support to those individuals to be able to address the radon issue themselves through self-help protective actions (e.g. self measurement, proper use of buildings, simple remediation techniques…).

(126) To be efficient, the national radon protection strategy should be established on a long term perspective, the national action plan should be periodically reviewed, including the value of the reference level.

(127) Many provisions mentioned in this chapter are presented as applicable to private homes. They are also generally applicable to many other buildings or locations. In the framework of the national action plan, national authorities may decide to strengthen the degree of enforcement of some requirements of the optimisation process (see section 3.3).

4.1.2. Prevention

(128) A radon protection strategy should include preventive actions to minimise future radon exposure. Whatever the indoor location is, the category of individuals inside and the type of exposure situation, it is possible to optimise radon exposure by taking into account the issue of radon exposures during the planning, design and construction phases of a building or location. Preventive actions mean land-planning and building codes for new and renovated buildings. It also means the integration of the radon protection strategy consistently with other strategies concerning buildings such as indoor air quality or energy saving in order to develop synergies and avoid inconsistencies.

Regional and local land planning

(129) The potential for any building to have high indoor radon concentrations is highly variable, notably due to the large variation of geological conditions. Therefore potential risks should be taken into account during regional and local land planning processes, at least in radon prone areas. Local radon maps may be established on the basis of geological data, radon measurements in the soil or indoor radon measurements in existing buildings (see section 4.1.3). They should be regularly complemented by data on radon concentration in constructed buildings, in water supplies from drilled wells, etc.

(130) Local radon maps and appropriate data should be made available for relevant local, regional and national authorities, for building professionals and home builders as well as for the general population to help them in planning and constructing or renovating buildings.

(131) Although land-planning may be mandatory a radon map remains indicative. It is not possible to predict the radon concentration in a given building before

construction. Further investigation, such as measurements in soil, may be useful. However, since radon concentration in a building is depending on many factors, only a measurement in the constructed building is able to provide the final result.

Radon protection strategy and energy saving strategy

(132) Radon prevention should be carefully coupled with the national energy saving strategies. When improving the insulation of a building to save energy, indoor air quality measures should be considered. For instance, in case of an increasing insulation and a decreasing air exchange rate in a building, the indoor radon concentration will in most cases increase. Therefore national energy saving programmes, the national radon action plan and other indoor air quality related programmes should be coordinated.

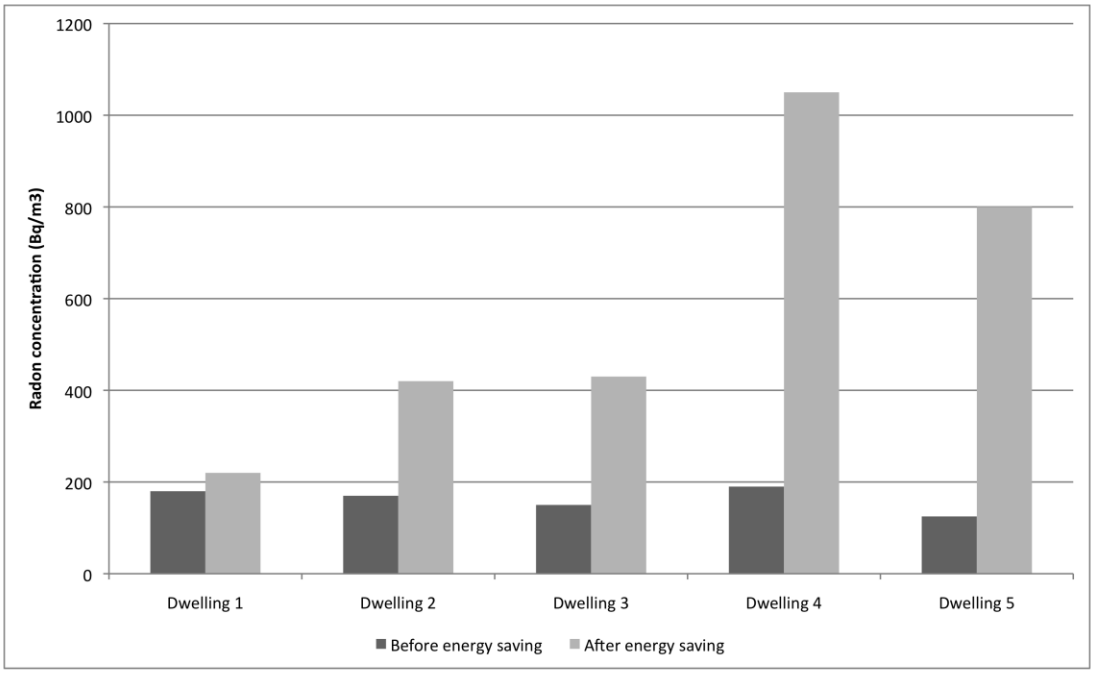

Fig. 8: Radon and energy saving (from Dr. Andreas Guhr, Altrac, in: Architektenkammer Niedersachsen “Radonprobleme durch energetische Gebäudesanierung”)

Building regulations and building codes

(133) Lowering the average radon concentration for the overall population through the implementation of appropriate building regulations and codes is of prime importance from a public health point of view.

(134) National, regional and/or local authorities should consider the implementation of building regulations or building codes that require radon prevention measures for all homes and buildings under construction or major renovations. Implementing radon prevention measures in the design and during the construction period of a building is considered as the most cost-effective way to protect the overall population. If implemented correctly, such measures will reduce, over time, the national average level of radon and decrease the number of new homes with radon concentrations above or close to the national reference level.

(135) Ensuring compliance with these special building regulations and building codes is important. Quality assurance programmes should be implemented at the level of professionals or at a regulatory level as appropriate. It is important to note,

that these building regulations and codes alone cannot guarantee that radon levels in new buildings will be below the reference level. Therefore householders should be made aware that the only way of knowing the radon situation of the building is through a measurement.

Building materials

(136) Construction materials of mineral origin are in general of minor importance for radon exposure, but may be in special cases a radon source which cannot be neglected. As far as radon-220 is concerned the main source of radioactive gas in buildings is the thorium concentration in building materials (concrete, bricks, etc.). Hence the control of thorium concentrations in building materials of surface dressing (plasters, etc) of walls, ceilings and floors can decrease the probability of elevated radon-220 values in buildings. To prevent and optimise the impact from building materials, materials that have low levels of radium-226 and thorium-232 should be chosen. A benchmark system has been established (radioactive concentration index) in order to characterise the risk associated to gamma radiation emitted by specific building materials and to specify the conditions of their use. (EC, 1999). In general, if building materials are controlled with regard to gamma radiation, the radon exhalation is expected to be relatively low.

4.1.3. Mitigation

(137) A national radon protection strategy should also include a mitigation part, especially in existing buildings or locations. Then the control of exposure should be ensured as far as possible through the management of the building (or location) and the conditions of its use, whatever the category of individuals inside. The main steps are measurement and; when needed, protective actions.

Radon measurement techniques and protocols

(138) While the health risk arises primarily from the radon progeny and not from the radon gas itself, the lung cancer risk from indoor radon exposure is often related to and expressed with radon gas concentrations (ICRP, 2011). In most cases radon gas concentration in the indoor air is the indicator and the subject of management even though in some cases the situation may be managed through the radon progeny using the PAEC.

(139) Several measurement methods do exist (WHO, 2009). Radon measurements in a given building or location should be targeted to produce a reliable estimate of the long-term radon exposure of the occupants (taking into account many factors such as the building occupancy and the daily or seasonal variability of the concentration). Radon measurements also allow establishing a data base for information about the radon exposure situation in the country. Consistency and quality assurance among radon measurements are important prerequisites. Therefore radon measurement protocols should be established and regularly updated.

(140) It should be noted that the presence of radon-220 can influence radon-222 measurements, so the radon-222 measuring devices should be tested for their sensitivity to radon-220 before their use in radon survey programs.

(141) Ideally long-term measurements over a whole year to cover all seasons should be preferred to short-term estimates. However, difficulties may arise when the period is too long (dosimeters moved or forgotten). Reliable measurement

should be representative of the annual concentration average. The measurement should be accomplished at low to modest costs. Measurement devices should be easily available with clear instructions about their use. After mitigation a measurement is needed, in the same conditions than for the initial measurement, to test the effectiveness of the mitigation system. Measurements should be repeated periodically to ensure the situation does not deteriorate.

(142) When using radon progeny measurement, conversion to radon concentration is implemented by assuming by default a generic equilibrium factor of 0.4 between indoor radon gas and its progeny, unless evidence shows otherwise.

National radon surveys and radon prone areas

(143) A national radon survey should be conducted, using recognized radon measurement devices and protocols, to determine the radon concentration distribution which is representative of the radon exposure of the population of a country. The two key objectives of a national radon survey should be:

- To estimate the average exposure of the population to indoor radon and the distribution of exposures. This may be best achieved by a population–weighted survey in representative selected homes, in which long-term radon measurements are performed.
- To identify areas where high indoor radon concentrations are more likely to be found (radon-prone areas). Screening for these areas may be best achieved coupled with long-term radon measurements in selected homes.

(144) The radon maps may be used as a tool to optimise the search for homes or other buildings with high radon concentrations and to identify areas for special preventive actions during the planning and the construction of new buildings. However, estimates resulting from these surveys should be verified by long-term measurements in selected buildings in suspected radon-prone areas.

(145) Even in confirmed radon-prone areas the distribution of radon concentrations in homes is often quite wide and values in most buildings may be low. Conversely, even in areas not classified as radon-prone areas, dwellings with high radon concentrations can be found, although with a lower probability. Therefore, as well as identifying radon-prone areas, some efforts should also go into the identification of building characteristics that may be associated with higher radon concentrations, i.e. buildings without a concrete foundation or buildings with double glazing.

(146) Radon-prone areas can be identified indirectly using radon gas concentrations in soil (provided there are established transfer factors correlating radon concentrations in homes to radon gas concentrations in soil beneath the foundation of a building) or directly by using indoor radon measurements. However, various definitions of a radon-prone area exist in different countries. It could be defined using administrative divisions or not and be based on different criteria as for example the average concentration (arithmetic, geometric), the proportion of buildings exceeding the reference level, the probability to exceed that level, etc. The definition of a radon-prone area should be specified in the national radon action plan.

(147) Once radon-prone areas are identified, the national radon action plan should develop special mitigation programmes for these areas, providing that these areas include a large fraction of buildings with estimated high radon concentrations. New and existing buildings should be covered by these programmes. Some preventive

and protective actions may concern the whole territory of the country. However, the radon map should never result in areas where buildings are forbidden.

Methods for mitigating the radon exposure and their applicability in different situations

(148) The main ways to achieve mitigation of radon exposure are both to prevent radon inflow from entering into occupied spaces and to extract radon from indoor air using both passive and active techniques combined.

(149) The primary radon mitigation techniques aim at reducing convection and diffusion radon intake from the soil under the building and focus on the following items:

- Reinforce the air tightness of the shell of the building (e.g. sealing radon entry routes);
- Reverse the air pressure differences between the indoor occupied space and the outdoor soil through different soil depressurization techniques (e.g., reducing the pressure in the soil beneath the building, installing a radon sump system, applying an overpressure in the cellar, etc).

(150) Indoor radon concentration reduction by dilution with more pure (with respect to radon) common air is another mitigation technique used in dwellings. The mitigation is achievable by passive (operating windows or vents manually) or active (fan application) means that allow venting occupied spaces. In heating and/or cooling indoor climatic conditions, balanced ventilation may be used. Balanced exhaust ventilation neither pressurizes nor depressurizes the indoor air condition in relation to the pressure of air in soil and outdoors. This form of ventilation dilutes radon after it has entered the building. Fan-powered ventilation can dilute indoor radon after it enters as well as reduce pressure differences between the soil and the occupied space. Some of these solutions are not suitable for all types of houses, nor are they suitable for all levels of radon. In many cases, a combination of above described techniques provides the highest reduction of radon concentrations.

(151) For buildings where an artesian borehole serves as the water supplying source, this water may be a potential source of radon. When water degasses radon into the room atmosphere (especially during water spraying) significant short time exposures may occur. Techniques for mitigating the entry into ambient air from water principally involve degassing of the water prior to its use or water filtration on beds of active charcoal.

(152) Detailed guides explaining the different mitigation techniques, developed by national or international bodies, are available (WHO, 2009).

Support policy, information, training and involvement of concerned parties

(153) The first step of a support policy is the development of awareness which appears to be very weak in many countries. Easily available information about what is radon, how it can be trapped inside enclosed spaces, what is the related risk (including the link with tobacco) and – overall – how to mitigate high concentrations should be disseminated toward the general population, parents and children (at school), elected representatives, civil servants in administrative divisions, home owners, employers, etc.

(154) Training professionals on radon mitigations (builders, architects, radiation protection professionals, employers, trade unions and workers, etc.) is needed to help to ensure that recommended prevention and remediation measures are correctly designed, planned and installed. Training programmes for professionals should be an

integral part of the national radon action plan so that householders or property owners subjected to radon concentrations above or close to the reference level get access to a radon prevention and mitigation infrastructure. They will then be able to take prompt informed action to reduce radon concentrations. An appropriate information and training should also be provided to other concerned professionals (health, real estate…).

(155) Since the synergy between radon and smoking has been demonstrated in the assessment of the lung cancer risk, a link between public health programmes for radon reduction and anti-smoking strategies is warranted, at least in terms of warning. Doing that, the national authorities should not forget that a radon reduction strategy is also beneficial to reduce lung cancer risk amongst non smokers.

(156) The national radon action plan may comprise mandatory provisions, especially in case of legal responsibilities (employer/employee, landlord/tenant, seller/buyer, some places open to the public). For example, measurements, communication of the results, record keeping, compliance with the reference level may be imposed. However, the national radon action plan should also include incentive and supportive measures such as organisation of measurement campaigns, operations for habitat improvement including radon issue, etc., with financial support or fiscal measures. Such measures should be regularly repeated.

Assessment of effectiveness

(157) The national radon action plan should include provisions about the assessment of the cost and the effectiveness of both preventive and corrective actions. Data should be regularly gathered at different levels (local, regional, national) and made available to the various stakeholders.

Buildings with public access

(158) Consideration should be given to buildings with public access and extended public occupancy such as schools, kindergartens, care institutions, hospitals, jails,.. People present in these buildings often have no choice but to use them and can spend a significant part of their time inside, even though it might be a temporary situation. They may be not aware that they are exposed to radon and they are not in a position to reduce the exposure levels themselves.

(159) For buildings with mixed use by public and workers the appropriate reference level should be the one set for dwellings,. It is not recommended to have different reference levels for the same enclosed location.

(160) Further, preventive and corrective actions should be implemented in order to guarantee the compliance with the reference level. Monitoring, as well as record keeping of radon concentrations, may be required. Relevant information should be provided to members of the public using the building as well as to staff working inside. Appropriate support should be provided to persons responsible for this type of building in order to ensure they are able to fulfil their responsibilities and obligations.

(161) The national action plan could provide a graded approach applicable to buildings with public access like in workplaces (see section 3.3.6), under the control of the national authorities.

Added provisions for workplaces

(162) In workplaces where workers' exposure to radon is not regarded as occupational exposure, workers are usually treated in the same way as members of

the public. This means that, like in dwellings, the control of exposures is exercised through the management of the building (or location) and its use rather than through the management of individuals. The Commission recommends applying the source-related principles of radiological protection for controlling the radon exposure with a central role given to the optimisation principle and the use of reference levels. In general, no further requirements are needed.

(163) However, notably when the workplaces are without access to the public (or when the public access is for a very limited period of time), some specific or complementary provisions may be established within the optimisation process. Such provisions may be:

- Specific measurements protocols (e.g. measurement when and where the workers are working);
- Specific use of the reference level or indicator according to the actual exposure parameters such as time of occupancy or equilibrium factor, keeping the value of 10 mSv per year as the dose reference level;
- Arrangement of working conditions (e.g. by limiting the time of occupancy of some premises);
- Requirements concerning implementation of measurements, communication of the results, record keeping, compliance with the reference level.

(164) An external expertise may be needed to implement such specific provisions, as well as the supervision of the national authorities.

4.2. Control of occupational exposures

(165)This section applies to workplaces where workers' exposure to radon can reasonably be regarded as being the responsibility of the operating management and is therefore considered as occupational exposure. As said in chapter 3, it is when, despite all reasonable efforts to reduce radon exposure, it remains above the reference level and when national authorities decided in advance that workers radon exposures in some types of workplaces are occupational exposure (positive list of workplaces or work activities). Then the control of radon exposure is mainly ensured through the application of the relevant requirements for occupational exposure (notably the control of individual exposures of workers) rather than mainly through the management of the building or location.

(166) The main examples of workplaces where workers' exposure to radon may be regarded as occupational exposures are mines (whatever the mined substance), other underground workplaces such as caves, etc. (which are prone to high radon concentrations), spas (using radon in the care process or not), desalinisation of underground brines and when radon exposure is due to deliberate operation of radon-222 and radon-220 parent radionuclides (uranium and radium chains) such as some operations with naturally occurring radioactive materials (NORM).

(167) Depending on the case the whole or only a part of the requirements for occupational exposure should be requested. The requirements generally relevant for radon exposure are the following:

- Setting of appropriate reference levels (in effective dose, radon concentration or PAEC taking into account the time of occupancy);
- Determination of the working areas concerned (although the classification of controlled or supervised areas does not fit well, it remains important to

properly determine the area in which occupational exposure may occur and to control as appropriate the access in such areas);
• Adequate information, instruction and training of workers;
• Use of personal protective equipments in some exceptional cases;
• Monitoring of exposures (individual monitoring, collective monitoring or, if inappropriate, inadequate or not feasible, on the basis of the results of the monitoring of the workplace);
• Recording of exposures;
• Provision of a health surveillance for workers;
• Promotion of a radiological protection culture;
• Compliance with the reference level. This can involve area workplace monitoring combined with tracking time in specific work locations. Personal radon monitors can also be used either on a group average or on an individual basis. In any cases, the upper value of the tolerable risk for occupational exposure (on the order of 20 mSv per year, possibly averaged over 5 years) should not be exceeded.

4.3. Radiological protection of workers in the uranium mining industry

(168) In circumstances where occupational exposure to radon is clearly part of a practice (a planned exposure situation) eg uranium mining is part of the nuclear fuel cycle, regulatory authorities may chose to apply the system of protection for planned exposure situations from the outset. Factors that influence this choice include the levels of exposure to other sources in the mine including external exposure to gamma radiation and inhalation or ingestion of radioactive dusts. The long-lived radioactive dust can be uranium ore during the mining and initial stages of milling and/or the refined uranium product, often a uranium oxide powder. In addition, there can be potential exposures to other uranium decay series radionuclides, depending upon the details of the processing environment, e.g. radium scale. In uranium mines radon progeny will often be the dominant source of radiation exposure. Protection of workers against exposures to radon in the uranium and thorium mining industries are regarded as being the responsibility of the operating management.

(169) According to the ICRP system for a planned exposure situation, exposures should be controlled by the optimisation process below a dose constraint as well as with the application of dose limits. Ideally the dose constraint should be determined at the design stage of an operation. The nature of uranium deposits is highly variable implying that a variety of mining methods and approaches are needed to successfully extract the resource. As a result, dose constraints and what constitutes an optimised dose will vary between mines and in some cases will vary over time at the same installation as the physical conditions change.

(170) The principles used to control occupational exposures to radon and radon progeny in a uranium mine are similar to those used in other workplaces in planned exposure situations. In some cases the potential for highly variable and/or high radon and radon progeny exposures is elevated in uranium mines because of the relative strength of the source term and other physical constraints (e.g. underground work). In these cases additional attention needs to be paid to the details of the monitoring program to ensure it adequately assesses workplace conditions and worker doses. Strategies such as real-time monitors and personal dosimeters should be considered in situations with high and variable radon concentrations. Conversely

in situations with low and stable radon and radon progeny concentrations periodic workplace monitoring may be sufficient. In general, the active ventilation of workplaces means that the concentration of radon gas together with approximations of equilibrium conditions cannot be relied upon to assess exposures to radon progeny and that measurements of radon progeny concentration (potential alpha energy concentration) should be used.

(171) In a uranium mine environment there will also be potential for exposure to gamma radiation and long-lived radioactive dust although radon progeny will often be the dominant source of radiation exposure. However, this can vary and in the later stages of an uranium processing facility radon is usually less prominent. These other types of radiation exposure must also be monitored and incorporated into the worker's total effective dose.

Converting exposures from radon progeny to doses requires the use of dose conversion factors. In the past (ICRP, 1993) the dose conversion factors for radon progeny have been based on epidemiological studies. The Commission is now recommending the use of reference biokinetic and dosimetric models for all other radionuclides (ICRP, 2011). The current dose conversion values may continue to be used until dose coefficients are available.

4.4. References

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