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Radiation Protection against Radon in Workplaces other than Mines

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RADIATION PROTECTION AGAINST RADON IN WORKPLACES OTHER THAN MINES

SAFETY REPORTS SERIES No. 33

RADIATION PROTECTION AGAINST RADON IN WORKPLACES OTHER THAN MINES

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FOREWORD

The radioactive gases radon and thoron and their decay products are ubiquitous in the open atmosphere. They are found in higher concentrations in the confined atmospheres of buildings and underground workplaces where workers are exposed to these radionuclides. Exposures to radon and thoron and their decay products may be extremely variable. The main radon source in most above ground workplaces with high radon concentrations is the soil, but there can also be significant contributions from building materials, groundwater, and the storage and processing of large amounts of materials with elevated concentrations of radium. Underground workplaces can accumulate high radon levels, as can natural caves and abandoned mines. In some instances, members of the public may be exposed to radon and thoron and their decay products at workplaces.

The establishment of safety requirements and the provision of guidance on occupational radiation protection form a major part of the IAEA's support for radiation safety in Member States. The objective of the IAEA's occupational radiation protection programme is to promote an internationally harmonized approach to the optimization of occupational radiation protection through the development and application of guidelines for restricting radiation exposures and applying current radiation protection techniques in the workplace. Guidance on conducting dose assessments and recommendations concerning dose limitation are given in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, issued as IAEA Safety Series No. 115 in 1996. Recommendations on the fulfilment of requirements are also given in three interrelated Safety Guides, Occupational Radiation Protection (IAEA Safety Standards Series No. RS-G-1.1), Assessment of Occupational Exposure due to Intakes of Radionuclides (No. RS-G-1.2), and Assessment of Occupational Exposure due to External Sources of Radiation (No. RS-G-1.3), which are jointly sponsored by the IAEA and the International Labour Office.

This report, which is also co-sponsored by the International Labour Office, deals with radon and thoron and their decay products in workplaces other than mines. It is intended for use in the application of radiation protection principles in those workplaces where employers may not have an extensive background in radiation protection. It provides practical information on action levels for workplaces, on monitoring techniques and on actions aimed at reducing exposures to radon and thoron and their decay products when necessary. It is also intended to assist regulatory bodies in establishing their own national policies in controlling high radon and thoron exposures of non-mining workforces.

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EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Until the 1970s radon[1] and its progeny were regarded as radiation health hazards encountered only in the mining and processing of uranium ore. This notion has changed markedly as a result of increasing efforts made in many States to measure radon in dwellings, mines other than uranium mines, and workplaces suspected of having high atmospheric radon levels. In temperate and cold regions, energy conservation measures have been taken in buildings that have resulted in reduced ventilation rates and increased radon concentrations, particularly in winter months. This rise in the indoor air concentration of radon was recognized as a radiation health hazard, potentially causing an increase in the incidence of lung cancer. Radon thus became a concern not only in underground mines but also in buildings in areas with elevated levels of radon in soil gas or in buildings constructed with materials containing significant levels of radium. According to an assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1], environmental radon accounts for half the human exposure to radiation from natural sources.

The IAEA and the International Labour Office acknowledged the importance of controlling radon exposure in workplaces other than mines. These workplaces are varied in nature, such as waterworks, caves and closed-out mines open to visitors, underground stores and shopping centres, spas, kindergartens, schools, factories, shops, public buildings and offices. For this reason, the two organizations considered it necessary to prepare a joint Safety Report on radiation protection in workplaces other than mines.

This report addresses all relevant issues in this subject area, including practical information to assist in compliance with the radiation protection standards established in the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, published in 1996 as IAEA Safety Series No. 115 [2]. Comprehensive recommendations on occupational radiation protection in general are provided in three Safety Guides on occupational radiation protection [3–5].

[1] In this publication, 'radon' refers to ^{222}Rn and 'thoron' to ^{220}Rn.

1.2. OBJECTIVE

The objective of this report is to provide practical guidance to employers whose workplaces may be affected by radon concentrations in excess of the action levels specified in Ref. [2]. This report is intended for use by people who do not necessarily have an extensive background in radiation protection. It is also expected to be useful to regulatory bodies for establishing their own national policies for controlling high radon exposures of the non-mining workforce.

A wide variety of workplaces both above and below ground may be affected by high radon concentrations. It is important that employers and employees are aware of the fact that there may be high radon levels at the workplace. Regulatory bodies can assist in ensuring this awareness by encouraging and supporting surveys of occupational exposure to radon.

1.3. SCOPE

The approach presented in this report is intended for use in protecting employees against radon exposure at workplaces for which radiation protection is not generally considered. This approach is based on a broad consensus and its aim is to achieve a positive net benefit. It also represents an optimized approach for a wide range of exposure scenarios commonly encountered in industrialized and developing countries.

The level of protection effected will ensure that workers will not be subject to undue risk provided that management applies the protective measures properly. However, this report is generic in nature and does not address, for example, unusual site specific exposure conditions. Under special circumstances, regulatory bodies may consider modified approaches in relation to the choice of action levels or countermeasures. Nevertheless, levels different from those presented in this report are to be adopted only after careful consideration of the possible socioeconomic consequences.

The action level and dosimetric quantities used in this report are consistent with Refs [2–5]. Furthermore, the approach is in compliance with the World Health Organization's recommendations on indoor air quality [6].

The scope of this report does not include occupational exposure to radon in facilities for the processing (including storage) of raw materials with elevated levels of naturally occurring radioactivity — this is covered by the Safety Guide on Occupational Radiation Protection in the Mining and Processing of Raw Materials [7].

1.4. STRUCTURE

Section 2 outlines the risks of radon exposure, provides cross-references to sections describing the special quantities and units and concludes with some information on radon concentrations that have been found in workplaces. Section 3 outlines the scheme for the control of radon in workplaces. In essence, radon measurements need to be made in selected workplaces. If levels are found to exceed the national action level, steps need to be taken to reduce radon concentrations to below the action level. If this cannot be achieved then the requirements of Ref. [2] for practices apply; however, it is expected that this will rarely be necessary. Section 4 gives practical advice on how radon levels can be measured and Section 5 describes the remedial measures that can be undertaken if elevated levels of radon are found. Section 6 outlines the steps to be taken if radon concentrations cannot be reduced to below the action level.

Appendices I and II present a summary of the uranium and thorium decay schemes and relevant data on conversion coefficients for the special quantities and units used in calculations relating to radon. Annex I explains how the information on radon control can be adapted to its shorter lived isotope thoron and its progeny. Annex II gives background on the risks arising from radon and discusses the survey data in workplaces other than mines. Other annexes give selected examples of monitoring of radon in workplaces and discuss particular cases for which the control of radon at workplaces necessitates special considerations.

2. WORKPLACES AT WHICH RADON MAY PRESENT A RISK

2.1. RISKS OF RADON EXPOSURE

The radioactive noble gas radon is produced by decay of the naturally occurring radionuclide ^{226}Ra, which in turn is a decay product of ^{238}U. A summary of this decay scheme is given in Appendix I. Since radon is a gas, it may escape into the air from the material in which it is formed, and since uranium and radium occur widely in soil, rocks and water, radon gas is ubiquitous — outdoors as well as indoors, the air that we inhale contains radon.

Radon decays to a number of short lived decay products (‘progeny’) that are themselves radioactive. These may attach to available aerosol particles in the atmosphere, thereby forming what are termed ‘attached’ radon progeny whose size will reflect the size distribution of the ambient aerosol. Those radon progeny that do not attach to aerosols remain in what is termed the ‘unattached’ state, and these unattached particles are usually found to be in the approximate size range of 0.5–5 nm. If inhaled, both unattached and attached radon progeny may deposit in the lungs and irradiate lung tissue as they decay. In lung dosimetry models, in which deposition sites of radioactive material and locations of target cells are taken into account, the risk per unit of inhaled radioactive material is considered to be much greater for radioactive material in the unattached state than for radioactive material in the attached state [8]. While it is the radon progeny rather than radon gas itself that presents the greater risk, the word ‘radon’ is also used generally as a convenient shorthand for both the gas and its progeny.

Radon has been recognized as a radiation hazard causing excess lung cancer among underground miners [9]. Consequently radon has been classified as a human carcinogen [10]. Since the 1970s evidence has been increasing that radon can also represent a health hazard in non-mining environments [6, 11]. Since environmental radon on average accounts for about half of all human exposure to radiation from natural sources [1], increasing attention has been paid to exposure to radon and its associated health risks in both industrialized and developing countries.

Special quantities and units are used in radon work and their conversion coefficients are discussed in Appendix II. One particularly important factor is the radioactive equilibrium between radon and its progeny. This is expressed as the ratio of the total alpha particle energy that the particular mixture of radon and its progeny will emit to the total energy emitted by the same concentration of radon gas in perfect equilibrium with its progeny. For most indoor environments of interest, the state of equilibrium between radon and its progeny is fairly constant, and this ratio is usually taken to be 40–50%. However, depending on conditions (especially ventilation conditions), some workplaces may exhibit values of this ratio down to 20% or up to 80%. For these more extreme cases it may be desirable to modify some of the information in this report relating to radon concentrations. Much of the discussion in the scientific literature on indoor radon is expressed in terms of radon concentrations rather than concentrations of radon decay products, for two principal reasons. Firstly it is much easier to measure concentrations of radon gas than concentrations of its progeny, especially for long term measurements. The second reason is that, owing to the higher dose conversion factor of the unattached fraction of radon progeny in lung dosimetry models and the inverse relationship between the unattached fraction and the equilibrium factor in indoor air, the effective dose relates more to the radon gas concentration than to the equilibrium equivalent radon concentration [12].

Although this publication mainly concerns radon, many of the same considerations apply to thoron, which has a much shorter half-life than radon (about 1 min). In most circumstances, the presence of thoron is of lesser concern than that of radon. Some matters specific to thoron are discussed in Annex I.

2.2. RADON IN WORKPLACES

Radon can present a hazard in a wide range of workplaces other than mines. While this includes below ground workplaces such as subways, tunnels, stores, show caves, closed-out mines open to visitors, and radon spas, the majority of such workplaces will be above ground. Some proportion of normal above ground workplaces such as factories, shops, schools and offices will be affected.

In buildings with high radon levels, the main mechanism for the entry of radon is the pressure driven flow of gas from soil through cracks in the floor. This flow arises because buildings are normally at a slight underpressure with respect to their surroundings. This underpressure is a consequence of the air inside buildings being warmer than that outside, especially in temperate and cold regions, and also of the drawing effect of the wind blowing over chimneys and other openings. However, various other mechanisms can affect the concentrations of radon in dwellings.

Most building materials produce some radon but building materials of certain types can act as significant sources of indoor radon. Such building materials have a combination of elevated levels of ^{226}Ra and a high porosity that allows the radon gas to escape. Examples are lightweight concrete made with alum shale, phosphogypsum and Italian tuff.

Levels of radon can be high in groundwater, particularly in areas of granite rock. Radon levels may be high in workplaces such as laundries and restaurant kitchens as a result of the use of such water. Since many municipal water supplies are provided from surface reservoirs filled by rain catchment, radon levels in public water supplies are not normally high. In Germany some treatment and distribution stations for water supplies drawn from groundwater have been found to have radon concentrations in air of up to several hundred thousand Bq/m^3 [13]. Generally, the annual exposure time of workers in these workplaces is low, but several such water treatment plants are subject to monitoring. Some countries have issued recommendations on radon concentrations in drinking water [14].

Underground workplaces can accumulate high levels of radon in the same way as occurs in caves or abandoned mines. It cannot be assumed that high radon levels in underground workplaces will be limited to those parts of the country where elevated radon levels have been found in above ground workplaces. The possibility of high radon levels exists in any underground workplace.

Elevated levels of radon have been found in workplaces in various countries. A summary is given in Tables I and II and further details can be found in Annexes II and III. It can be seen that radon levels are rather variable. Some countries, but not all, have identified certain workplaces with radon concentrations exceeding 1000 Bq/m^3. However, some of the surveys were small and — even if the mean concentration is low — most distributions are skewed, so there could be a minority of workplaces in which radon concentrations are significantly above the average.

TABLE I. RADON CONCENTRATIONS IN UNDERGROUND WORKPLACES (NON-MINING)

Workplace type	Country	Radon concentration range (Bq/m^3)	Reference
Tourist caves	Germany	400–11 180	[15]
	Hungary	130–21 100	[16]
	Ireland	260–19 060	[17]
	Slovenia	20–10 000	[18, 19]
	USA	48–1 850	[20, 21]
Mines open to visitors	Germany	400–20 280	[15]
Tunnels	Czech Republic	229–3 312	[22]
	Finland	500–7 000	[23]
	Norway	250 (mean)	[24]
Power stations	Norway	20–4 000	[24]
Underground railways	Finland	45–200 (stations); 20–790 (workplaces)	[23]
	Greece	9–22 (stations)	[25]

TABLE II. RADON CONCENTRATIONS IN ABOVE GROUND WORKPLACES

Workplace type	Location	Number surveyed	Radon concentration (Bq/m^3)	Reference
Public buildings	Belgium (Luxembourg province)	36	10% > 200, 3% > 400	[26]
	Finland	155	Mean 505, 37% > 300	[27]
		400	Mean 284, 17% > 300	
	USA	3901	22% > 150, 0.2% > 1000	[28]
Schools	Belgium (Luxembourg province)	421	12% > 200, 2% > 400	[26]
	Islamic Republic of Iran	16	Mean 256, 55% < 100, 100 < 30% < 400, 400 < 15% < 1400	[29]
	Ireland	1762	23% > 200, max. 2688	[30]
	Italy (3 of 21 regions)	486	Range 13–1450, geometric mean 78–129, 4–17% > 400	[31]
	USA	927	2.7% > 150, 0.1% > 1000, max. 2500	[32]
Kindergartens	Italy (5 of 21 regions)	1687	Range 6–1400, geometric mean 38–118, 0.1–15% > 400	
	Norway	3600	Range 5–2800, mean 88, Geometric mean 44	[33]
	Slovenia	730	Range 7–5750, Geometric mean 58	[34]
			Range 10–4700, Geometric mean 58	[35]
Various workplaces[a]	Finland	3050	Mean 255, 37% > 300	[27]
		993	Mean 171, 12% > 300	
	Germany		~60 000 workers exposed to >1000 Bq/m^3	[13]
	Germany (Saxony)	36	Range 25–7000, 10% > 1000, 20% > 800	[36]
	Sweden	150	10% > 400	[37]
	United Kingdom	8000	Mean ~100, max. 7500	[38]

[a] This includes industries using large volumes of groundwater and workplaces in which large quantities of materials with elevated concentrations of radium are stored or processed.

3. SCHEME FOR THE CONTROL OF EXPOSURE TO RADON

3.1. OVERVIEW

Radon is ubiquitous — it is detectable everywhere in workplaces and dwellings — but levels vary from place to place and over time. The scheme for the control of occupational exposure to radon is necessarily somewhat different from that for exposure to artificial sources. This section begins with an overview of the scheme and then provides further details.

Regulatory bodies will need to arrange for surveys to obtain an overview of occupational and domestic exposures to radon in the territory under their authority (Section 4.1). Then a radon programme, adapted to national conditions, needs to be formulated so as to include a manageable proportion of the buildings most affected by high radon levels. In this way regulatory bodies can specify those workplaces that are to be subject to control.

Employers who are responsible for workplaces that are subject to control need to make arrangements for making measurements to determine radon levels in the workplaces. If radon concentrations are found to be above the action level (Section 3.5), the employer will need to take remedial measures aimed at reducing radon levels to below the action level.

If the remedial measures are successful no further action other than periodic retesting will be required. However, if all reasonable measures fail to reduce radon concentrations to below the action level, then the appropriate scheme of radiation protection measures will apply. This is essentially described in Ref. [2]. However, some refinements may be necessary owing to the particular features of radon exposure.

The radon exposure control scheme is outlined in Fig. 1. In the remainder of this section, this scheme is considered in more detail. An example of the control of radon in above ground workplaces is given in Annex IV.

3.2. PUBLIC INFORMATION AND AWARENESS

Experience indicates the need to conduct information campaigns aimed at the public as well as employers and workers to increase understanding of radon, the potential risks it poses to health, and the simple measures that are commonly used to reduce these risks. For occupational exposure, such campaigns are particularly aimed at employers and their organizations, but the targets could also include the appropriate professional societies.

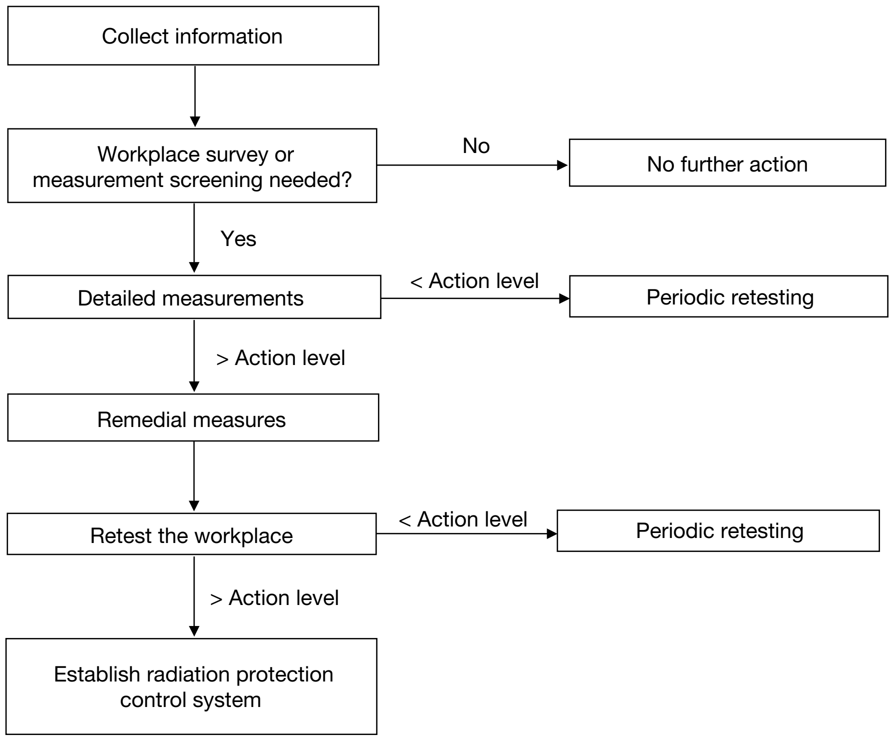

FIG. 1. A suitable scheme for the control of radon levels. If radon levels are very high and their reduction is inexpensive and easy, remedial measures are indicated.

Regulatory bodies need to ensure that adequate information is available to the public as well as to employers and workers on geographical variations in radon levels and on programmes for limiting radon exposures. Carefully designed information and education programmes will facilitate radon programmes.

3.3. PRACTICES, INTERVENTIONS AND ACTION LEVELS

One basic concept of radiation protection is to divide activities into practices and interventions. A ‘practice’ is “Any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed.” An ‘intervention’ is “Any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.” (Ref. [2], Glossary).

There are some difficulties in distinguishing between radon exposures that are to be treated as being due to a practice and those that are to be regarded as being due to an existing situation and thus may require intervention. The use of action levels is helpful to clarify the basis for this distinction. The action level to which this report refers is the radon concentration at which remedial or protective actions will need to be undertaken to reduce excessive exposures to radon in workplaces. The action level may also be regarded as the level at which the system of protection for practices becomes applicable to the continuing control of radon exposures in the workplace.

In its glossary, Ref. [2] defines ‘action level’ as “The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations.” Under the requirements of Ref. [2], it is the responsibility of regulatory bodies to decide under which circumstances radon exposures are subject to the requirements of Ref. [2] for occupational exposures. This may be the case for defined work activities or in defined geographical areas, for example wherever the action level for radon is exceeded in a set proportion of buildings.

The following text from para. 2.5 of Ref. [2] specifies the basis for a protection policy for natural sources of radiation and for radon in particular:

....

> “Exposure to natural sources shall normally be considered as a chronic exposure situation and, if necessary, shall be subject to the requirements for intervention, except that:[3]
>
> ....
>
> (b) occupational exposure of workers to natural sources shall be subject to the requirements for practices given in this section if these sources lead to:
>
> ....

[3] At the time of the endorsement of the Standards, the available quantitative recommendations of the ICRP for protection against exposure to natural sources were confined to radon. It was therefore decided that the General Obligations for practices concerning protection against natural sources will be that exposure to natural sources, which is normally a chronic exposure situation, should be subject to intervention and that the requirements for practices should be generally limited to exposure to radon, the exposure to other natural sources being expected to be dealt with by exclusion or exemption of the source or otherwise at the discretion of the Regulatory Authority.

(ii) exposure to radon incidental to their work, but the exposure is higher than the action level for remedial action relating to chronic exposure situations involving radon in workplaces[4]; unless the exposure is excluded or the practice or the source is exempted...

---

[4] See Schedule VI, Guidelines for Action Levels in Chronic Exposure Situations, para. VI–3."

3.4. SURVEYS

It is likely that surveys will be necessary to assess the geographical variation of radon exposure in buildings and the variations in radon levels between different types of work activity.

Geological considerations will often be a good general guide to identifying areas in which radon levels are likely to be above average. However, there is a complex relationship between geological parameters, such as soil porosity and concentrations of uranium and radium, and levels of radon in buildings.

A systematic and unbiased survey of radon concentrations in buildings is necessary to obtain an understanding of the variations of radon concentrations in workplaces. Geological considerations can be used to interpolate the results of such measurements and may be useful in refining the identification of the relevant areas. At this time, although many workplaces have been surveyed in a number of countries (Tables I and II, Annexes II and III), no systematic and unbiased survey for radon in workplaces has been carried out in any country.

3.5. ESTABLISHING ACTION LEVELS

The radon concentration at which measures would need to be undertaken to reduce radon exposures is known as the action level. The action level for radon in the workplace is given in Ref. [2] as a yearly average concentration of 1000 Bq/m^3 which would, for an assumed occupancy of 2000 hours per year, equate to an effective dose of about 6 mSv. This value of 1000 Bq/m^3 is at the midpoint of the range 500–1500 Bq/m^3 recommended by the International Commission on Radiological Protection (ICRP) [11], and some regulatory bodies may wish to adopt a lower level than was specified in Ref. [2]. It should be noted that the range of values given by the ICRP was based on an assumed equilibrium factor between radon and its progeny of 0.4.

There is a practical advantage to adopting a single value for the action level which may be applied in all situations irrespective of the equilibrium factor. Nevertheless, although not explicitly stated in Ref. [2], other action levels may be appropriate if the equilibrium factor is significantly different from 0.4. For example, if the actual equilibrium factor is 0.8, then in theory at least a value for the action level of 500 Bq/m^3 might be appropriate.

Nevertheless, this action level for radon in workplaces does not mark a boundary between 'safe' and 'unsafe' exposures. Unless the exposure is excluded or the practice or the source is exempted, regulatory bodies are free to establish an occupational action level below 1000 Bq/m^3 if national circumstances make this practicable.

There are some workplaces designated as being subject to radon control where members of the public spend considerable periods of time, such as schools, hospitals and residential care centres. For such workplaces, adopting the action level for dwellings may be considered in the interests of controlling exposures to the public. Action levels for dwellings in many countries are set in the range of 200–600 Bq/m^3 as recommended by the ICRP [11] and specified in Schedule VI of Ref. [2]. Workplaces designated as being subject to radon control but having a relatively low occupancy rate by the public, such as theatres or show caves, are not normally subject to special treatment in relation to exposures to members of the public due to radon. For these buildings the action level for workplaces will apply. An overview of legislation and national guidelines in relation to radon may be found in Ref. [14].

3.6. DETERMINATION OF RADON PRONE AREAS

In order to pursue a focused and manageable programme for radon, regulatory bodies may find it helpful to determine radon prone areas.[2] The results of systematic and unbiased surveys of radon levels in above ground workplaces are an important factor in defining radon prone areas. Radon levels in residential buildings will generally provide a useful indication of areas in which elevated occupational exposures to radon might be expected since it is likely that the radon prone areas for above ground workplaces will coincide with the radon prone areas for domestic exposures.

[2] A radon prone area is one in which, because of the characteristics of the ground and/or building design and usage, the percentage of dwellings with radon concentrations above the action or reference level for radon exceeds a threshold percentage set by the national regulatory bodies.

The country-wide distribution of radon concentrations and the value of the action level are important factors in defining radon prone areas. It may be appropriate, for example, to define a radon prone area as one in which more than 1% of dwellings have an annual mean radon concentration exceeding ten times the national average value. Other ways of defining a radon prone area may also be devised. Even within a radon prone area there is likely to be inhomogeneity in radon concentrations. Special attention will need to be given to the areas with the highest radon concentrations. Caution needs to be exercised, however, to avoid an overreliance on the concept of radon prone areas as a tool for radiation protection. In some countries radon prone areas are relatively underpopulated and in absolute terms may contain very few workplaces. For such situations, limited regulatory resources may be more efficiently and properly used to identify and control the greater number of workplaces with radon levels above the action level that may be found in areas not classified as radon prone but which contain large numbers of workplaces. The decision on the strategy to be adopted in this matter has to be made by regulatory bodies in the light of local circumstances.

Underground workplaces and workplaces such as spas are not included in the concept of a radon prone area. Such workplaces will need to be considered priorities for action unless surveys of these workplaces indicate that action is unnecessary.

3.7. MEASUREMENT OF RADON LEVELS IN WORKPLACES

Regulatory bodies will need to define the types of workplace in which radon levels have to be measured. Employers are responsible for commissioning the necessary measurements and, consequently, need to have access to laboratories from which they can commission measurements of radon levels in their workplaces. These measurements will need to be subject to adequate quality assurance (Section 4.3).

Concentrations of radon in a building vary with time both diurnally and seasonally. These variations are primarily due to the effect of meteorological changes on radon levels in soil gas and also to weather-related changes in practices for ventilating buildings. Consequently, long term measurements over a period of several months are preferable to short term measurements. Various measurement techniques are available (Section 4).

In the detailed measurement phase (Fig. 1), matters other than the technical aspects of these measurement techniques may have to be considered. Many non-industrial type workplaces are unoccupied during the night hours, when radon levels are generally higher than during the daytime when the actual occupational exposure takes place. Many types of offices are likely to be in this category. The question therefore arises whether the assessment of a workplace exceeding the action level ought to be based on a long term, 24 hour average radon concentration or only on the radon concentration during working hours.

With some detectors it is possible to measure radon only during working hours. A similar question arises in the case of well ventilated workplaces with relatively low radon concentrations during daytime hours when staff numbers are high, while few people are present at night when ventilation rates are low and radon levels are higher. This is not an uncommon situation in large modern office blocks.

These and other similar situations need to be considered and addressed by regulatory bodies, but in the majority of cases it is likely that assessments based on the long term 24 hour average radon level will ensure that, in the first instance, the majority of workers receive appropriate radiation protection. Regulatory bodies usually recommend the use of the long term 24 hour average radon level as the basis for the assessment of radon exposures, but recently the five Scandinavian regulatory bodies have recommended that the action level for underground workplaces be in terms of the long term or annual mean radon concentration during working hours [39].

For large workplaces with many rooms or work areas, it is important that more detailed measurements of radon concentrations are made in a sufficient number of these locations in order to make an appropriate assessment of worker exposures to radon in relation to the action level. Individual monitoring may be useful in certain situations. Such situations may arise in working environments in which significant spatial and temporal variations in radon concentrations are evident in tandem with significant differences in staff working patterns. Another possible situation is one in which passive area monitoring has already indicated elevated radon levels, and the work patterns of the staff make a dose assessment based on area monitoring difficult to conduct.

3.8. WORKPLACES IN WHICH RADON LEVELS ARE FOUND TO BE BELOW THE ACTION LEVEL

If radon levels are found to be below the action level, no measures to reduce them are necessary but the regulatory body may specify the intervals at which the buildings are to be retested. Retesting may be necessary if substantial changes are made to a building or to the way in which it is used, especially if the radon levels measured were just below the action level. For workplaces in radon prone areas, retesting every few years may be appropriate, depending on an assessment of the possibility of the action level being exceeded.

3.9. WORKPLACES IN WHICH RADON LEVELS ARE FOUND TO BE ABOVE THE ACTION LEVEL

If radon levels are found to be above the action level the employer will need to arrange for remedial measures to reduce radon concentrations to below the action level. This will preferably be a decisive action aimed at a substantial reduction in radon levels, not simply a stopgap measure to edge concentrations below the action level. It is important for employers to have access to expert advice on remedial measures. It may be appropriate for regulatory bodies to codify expert advice in the form of written guidance in accordance with national building practices.

It is expected that remedial measures will normally be successful in reducing radon concentrations to below the action level. Where this is the case, it is advisable that the building be retested at intervals determined by the regulatory body in order to ensure that the remedial measures continue to be effective. The employer needs to perform regular operational checks of the remedial systems to ensure that fans and other equipment have not failed or been switched off.

In cases where the radon concentration still exceeds the action level after all practicable remedial measures have been taken, the authorities and/or the employer are required to implement an appropriate scheme for radiation protection (Section 6). For those workers whose exposures to radon are monitored the authorities will keep records of individual doses. Regulatory bodies are expected to keep appropriate records of such employers and their workplaces so that they can maintain proper scrutiny of their activities. Regulatory bodies are also expected to provide written guidance on suitable control measures.

3.10. PREVENTION OF ELEVATED RADON LEVELS IN FUTURE WORKPLACES

In addition to remedial action in existing workplaces, regulatory bodies need to consider adopting a cost effective preventive approach to the control of radon in future workplaces as part of a long term strategy aimed at reducing exposures to radon. Some Member States have adopted various preventive measures for the control of radon in dwellings, including specifying the use of particular building technologies for radon proofing in future dwellings in identified regions of high radon levels. Similar preventive measures could be successful in future workplaces in such regions where the major source of radon is soil gas. The limitation or control of certain building materials could also be considered as a possible preventive action.

4. PRACTICAL TECHNIQUES FOR MEASURING RADON CONCENTRATIONS

4.1. GENERAL CONSIDERATIONS

This section describes the performance and limitations of widely used devices for measuring radon. Details of instrumentation and methods for the assessment of radon are given in Refs [40, 41]. The overall goal in relation to radon will determine the choice of monitoring strategy and equipment.

The reasons for performing concentration measurements of radon or radon progeny include:

— Identification of workplaces with high radon levels,
— Measurements in conjunction with remedial actions,
— Measurements for assessing workers' exposures to radon in order to comply with regulatory requirements.

Surveys designed to identify the variation of radon levels in workplaces necessitate the deployment of large numbers of detectors. The cost and the ease of placement of the detectors are important factors to consider. The investigator will need to decide whether short or long term measurements are the more appropriate. However, in view of potential seasonal influences (such as heating, ventilation, air conditioning) on the radon concentration, long term measurements over a period of some months will usually be given preference. Alternatively, repeated measurements over shorter periods (of some days) may be satisfactory if adequate accuracy can be ensured.

If measurements are made during remedial work on a building to identify the source of elevated radon concentrations, short term or grab sample measurements may be necessary. After completion of the remediation process long term measurement is necessary to confirm that the average radon level is below the action level.

If radon levels remain above the action level and individual doses must be assessed to demonstrate regulatory compliance, collection of appropriate data on doses will be necessary. This can be done either by monitoring the work area or by means of personal monitors worn by workers. Decisions on the frequency and duration of measurements, as well as on the choice of instrumentation, need to be acceptable to the regulatory body.

4.2. MEASUREMENT TECHNIQUES

Many techniques are available for measuring radon, thoron and their progeny [40, 42–47]. Although radon progeny are responsible for most of the radiation exposure of the respiratory tract, the parent radon governs the airborne concentrations of the progeny. Instantaneous air samples may be collected and counted in a scintillation cell. Instantaneous samples are of limited use, however, because usually only time averaged values are of interest owing to the known variability of atmospheric radon concentrations. In active techniques (i.e. those that require power for operation), such as those based on the use of well established and robust ZnS (Ag) Lucas scintillation cells, a sample of air is drawn into the cell. Scintillations caused by alpha radiation inside the cell are counted [48]. Flow-through versions of these cells can be connected to appropriate counting and recording devices to create a continuous monitor. Continuous monitors are useful when it is necessary to monitor the time dependence of concentrations of radon or radon progeny. Radon progeny can be measured by analysing the airborne radioactive material collected on a filter or with continuous decay product monitors.

For rapid surveys, canisters containing activated charcoal can be exposed to air for a few days. These devices collect, in a reproducible manner, a fraction of the radon that enters the canister. The amount of radioactive material collected in the activated charcoal is evaluated by gamma spectroscopy or by liquid scintillation counting. This evaluation is normally done in a central laboratory. Sensitive ‘electret’ ion chamber (EIC) devices can also be used for short term measurements [49–51]. These are small ion chambers in which the collecting voltage is supplied by an electret (electrically charged insulator).

Because of temporal variations in radon concentrations (Section 3.7) it is good practice for measurements of indoor radon or its progeny to be averaged over as long a period as practicable. Although determination of the long term average radon concentration in a workplace is preferable, in some instances when time is critical it may be necessary to utilize instantaneous or short term techniques. Methods and devices are available that can be used for measurement periods from as short as a few seconds up to a year or longer. Longer term measurements of average radon concentrations, which can range from three months up to more than one year, can be made easily and accurately with passive radon detectors (requiring no power for operation). The two most commonly used of these passive devices are alpha track detectors and EICs [50, 52–54].

The alpha track detector is the most widely used type of radon detector for long term measurements. It consists of a small plastic container inside which is mounted a small piece of solid state nuclear track detector (SSNTD) material. The SSNTD material behaves as an alpha particle detector. The most commonly used SSNTD materials in passive radon detectors are plastics known as CR-39 and LR-115, and polycarbonate [55]. The opening to the detection volume within the plastic container may be fitted with a filter to prevent the entry of radon progeny and to retard the entry of thoron. In some widely used radon detectors of this type the container — made using high precision plastic moulding technology — has a very narrow entrance slit that acts as a diffusion barrier, thus obviating the need for a filter [56].

A fraction of the alpha particles from radon and its short lived progeny decaying within the sensitive volume of the device strike the SSNTD material and produce submicroscopic damage tracks. After the exposure period the devices are returned to a laboratory where the SSNTD material is etched either chemically or electrochemically in a strong caustic solution. The etching process transforms the submicroscopic damage tracks into tracks that are readily visible under optical magnification. The number of tracks can be counted either visually or with an automated device. The number of tracks is related to the product of average radon concentration and exposure time by a calibration factor which must be determined empirically [56]. Where thoron also is to be measured special detectors, using SSNTD material within two interconnected detecting volumes, have been designed to measure both radon and thoron levels [46, 57].

The other widely used type of passive detector for long term measurement of radon is that for which the sensor is an EIC. The electrical charge of the electret decreases as ions created by radiation are collected. The charge difference in the electret before and after radon exposure is related to the product of average radon concentration and exposure time by a calibration factor. A correction term for ambient gamma radiation is necessary. For this purpose a second electret measuring only the gamma background is often used. The response of electrets can be affected in conditions of high humidity but the electret detector has the following advantages:

(a) Evaluation of the EIC sensor is a simple voltage measurement that may be made in the field;

(b) EICs can be read at any time without disturbing the integrating radon measurement itself;
(c) In many cases the EIC detector can be reused for subsequent measurements at other sites, provided that there is sufficient electrical charge left in the detector.

The principal features of the different measurement techniques are summarized in Tables III and IV.

4.3. QUALITY ASSURANCE AND QUALITY CONTROL

An effective programme for quality assurance and quality control is essential to any activity for monitoring levels of radon and thoron. All methods (including the instruments or detectors themselves) involve calibration traceable to a national or international standard and periodic quality assurance testing to maintain this traceability. A small fraction (5–10%) of the measurements performed by each laboratory needs to be dedicated either to background determination (unexposed blanks) or to estimates of accuracy and precision (in comparison with traceable standards and duplicate measurements). Quality control charts that identify the stability of the measurement systems need to be prepared routinely for each instrument. These charts are prepared by routine measurements of a blank or background sample and of a reliable test source. The results of these routine measurements need to fall within acceptable limits [58]. Companies employed to make radon measurements will provide copies of their quality assurance plans and may be certified, licensed or otherwise approved by an appropriate government entity.

Of considerable help to this quality assurance in Europe has been the series of intercomparisons of passive and active radon detectors that have taken place in recent years in the framework of the Fission Safety Programme of the European Commission at the radon exposure facilities of the National Radiological Protection Board in the United Kingdom [56]. For a number of years the US Environmental Protection Agency (EPA) operated a radon measurement proficiency programme in which the reliability of the measurement techniques used by radon testing companies was tested. This service has now been terminated but similar programmes for proficiency in the measurement of radon operated by commercial laboratories are available in the USA.

TABLE III. OPERATIONAL CHARACTERISTICS OF SOME COMMON MEASUREMENT PROCEDURES FOR RADON GAS AND POTENTIAL ALPHA ENERGY CONCENTRATION (PAEC) OF RADON PROGENY IN AIR

Substance measured	Duration	Common example of method	Operational characteristics		
			Sampling process	Typical delay after sampling	Measurement
Radon gas	Long	SSNTDs	Diffusion	Laboratory analysis necessary	—
		EICs	Diffusion	1 h to establish constant diffusion conditions	5 min with special voltmeter
	Long or short	Lucas cell, flow-through	Pump	2½ h to allow equilibration of radon progeny	At necessary intervals in alpha counter
		Diffusion cell	Diffusion	2½ h to establish constant diffusion conditions	60 min in alpha counter
	Short	Lucas cell	Pump	2½ h to allow equilibration of radon progeny	60 min in alpha counter
		Charcoal canister	Diffusion and adsorption	Laboratory analysis required	—
		Atmos 12 DPX	Pump	1 h to allow progeny ratios to stabilize	At necessary intervals
		Alpha guard PQ 2000	Diffusion or pump	1 h to allow progeny ratios to stabilize	At necessary intervals
		Two filter method	Pump	A few minutes to place the filter in the counter	60 min in alpha counter

TABLE III. (cont.)

Substance measured	Duration	Common example of method	Operational characteristics		
			Sampling process	Typical delay after sampling	Measurement
PAEC	Long or short	CEA and ALGADE dosimeter	Pump	Laboratory analysis necessary	—
		Thomson & Nielson radon WL meter	Pump	1 h to allow progeny ratios to stabilize	60 min in alpha counter
	Short	GAMP [a]	Pump	A few minutes to place the filter in the counter	5–60 min in alpha counter

[a] GAMP: gross alpha measurement procedure which can be single, such as Rolle or Kusnetz, or multiple, such as Tsivoglou. Spectroscopic alpha measurement procedures such as the Nazaroff procedure are also available.

TABLE IV. OPERATIONAL RANGES OF EXPOSURE AND DURATION OF MEASUREMENT FOR PASSIVE RADON DETECTORS

Type	Exposure range ($kBq{\cdot}h/m^3$)		Range of concentrations that can be determined for different measurement periods (Bq/m^3)				Maximum duration of measurement (d)
	Minimum	Maximum	30 d		90 d		
			Minimum	Maximum	Minimum	Maximum	
Plastic	20	10 000	30	14 000	9	4 600	1 000
Electret							
High	6	140	8	180	3	46	14
Low	420	9 600	500	13 000	200	4 400	940

5. REMEDIAL ACTION TO REDUCE RADON LEVELS

If measurements indicate that radon concentrations exceed the action level established by the relevant national authority, the employer will undertake remedial action. The aim is to reduce radon levels by making permanent mitigatory changes to the building or to the way in which it is used. If mitigation is ineffective or not reasonably practicable, the employer will have to adopt an appropriate system of radiation protection for the workplace in accordance with the requirements for practices [2].

Mitigation will take different forms depending on the circumstances. By far the most common cause of elevated radon levels in above ground workplaces is the pressure driven entry of radon through cracks or other openings in the floor. Other mechanisms are by diffusion from soil in contact with the building foundations, by diffusion from construction materials or, rarely, as a result of radon in the water supply. In all these cases remedial measures developed for dwellings may be applicable [55, 59–63]. The special cases of radon spas, caves and show mines are discussed in Annex V and an example of remedial guidance is given in Annex VI.

5.1. SUB-FLOOR DEPRESSURIZATION

For foundations and basements in contact with soil, the most effective mitigatory measure is to reduce the pressure of the soil gas in the vicinity of the foundation relative to the pressure in the structure. This reverses the normal situation in which the indoor air of buildings is generally found to be at an underpressure with respect to the subjacent soil gas. This pressure reversal may be accomplished by installing a system of pipes leading from the soil or aggregate under the foundation to a fan that maintains a negative pressure gradient between the soil and the foundation. The approach effectively reduces the amount of radon entering the structure by reducing the amount of soil gas entering. The soil gas containing radon can then be vented harmlessly to the atmosphere. Where possible, it is desirable to install a small and simple cavity or sump within the foundations to which the system of pipes may be attached. For buildings with extensive and complex foundations a number of such depressurization systems may be needed for effective radon control.

5.2. SUB-FLOOR VENTILATION

If the ground floor is not in contact with soil, an effective mitigatory measure is to ventilate the space beneath the floor. This may be accomplished by increasing natural ventilation or by installing a fan that removes the radon laden air from under the floor and replaces it with outdoor air. The approach effectively reduces the amount of radon entering the structure by reducing the concentration of radon in the air beneath the floor.

5.3. FLOOR SEALING AND MEMBRANES

The cracks and other openings through which radon enters the structure may be sealed. This method is considered less effective than sub-floor depressurization because it is difficult to seal all entry routes adequately and because seals tend to deteriorate over time. This method is likely to be ineffective unless all the cracks are sealed. It can be used as a supplementary measure to increase the effectiveness of sub-floor depressurization or sub-floor ventilation. At the construction stage of a building, heavy duty plastic membranes incorporated into the foundations may act as effective radon barriers provided that they are properly sealed at jointing and are not punctured during installation.

5.4. INCREASED VENTILATION

Radon in indoor air may be diluted by increased ventilation of the indoor spaces with outdoor air. This method can be costly in terms of energy loss, particularly in cooler climates. Energy loss can be reduced by using heat exchangers but these have significant purchase, operating and maintenance costs. In some structures, increased ventilation can actually result in an increase in indoor air radon levels by causing an increase in the underpressure of the indoor air with respect to the subjacent soil gas. For these reasons, ventilation as a method of reducing indoor radon levels is to be used with caution.

5.5. REMOVAL OF SUBSOIL

Elevated levels of radium in the soil underneath or surrounding a building can be the cause of increased radon levels in the indoor air. Removal of the subsoil and replacement with uncontaminated soil has been shown to be effective in lowering radon levels indoors. Since this method represents a major undertaking, it is only used in exceptional circumstances.

5.6. WATER TREATMENT

If the water used in a workplace is a significant source of radon, treatment of the water by aeration or other methods (such as filtration with activated charcoal) to reduce the radon levels prior to use can be effective. In municipal water treatment plants where groundwater with high concentrations of radon is processed, aeration of the water may give rise to very high air concentrations of radon within the plant. In this case strong ventilation of the air spaces of the water treatment plant, coupled with restrictions on working hours for staff, can be effective. In practice staff usually make only periodic brief inspections in the high radon areas of such treatment plants.

5.7. COST AND EFFECTIVENESS OF RADON REDUCTION METHODS

The relative cost and effectiveness of the various remedial measures for radon reduction in buildings are summarized in Table V [11]. Further information on the effectiveness of remedial measures for radon reduction is given in Annex VI.

TABLE V. COST AND EFFECTIVENESS OF REMEDIAL MEASURES FOR RADON REDUCTION IN BUILDINGS

Method	Cost	Effectiveness
Sub-floor depressurization	Moderate	High
Sub-floor ventilation	Moderate/low	Variable
Floor sealing	Moderate	Moderate
Increased ventilation	Moderate	Low
Subsoil removal	High	High
Water treatment	Moderate	High

6. CONTROL OF RADON EXPOSURES WHEN REMEDIAL MEASURES ARE INEFFECTIVE

If radon concentrations in a workplace exceed the action level even after remedial measures have been taken, the system of radiation protection for practices established in Ref. [2] applies. This means that dose limits are required to be observed and exposure reduction is required to be optimized. The estimation of individual exposures will be necessary to meet these requirements, so programmes of individual or workplace monitoring will need to be established. Any legal person intending to carry out such work would need to notify the regulatory body unless the exposure from such activities or the source itself is excluded, or the practice or source is exempted from regulatory requirements. A notification form for the work would need to be submitted to the regulatory body, which may require the legal person to apply for an authorization, depending on national policy. The workers involved will need to be given appropriate training and health surveillance.

6.1. AUTHORIZATION

Reference [2] provides the basis on which to build a protection policy for natural sources of radiation by controlling the levels of radon and its progeny. They require that practices, including those in workplaces where radon concentrations exceed (and cannot be brought to below) the action level, be authorized unless otherwise specified by the regulatory body (Ref. [2], paras 2.1–2.11). Authorization can take the form of licensing or registration. Both forms require a safety assessment to be made by or on behalf of the employer. An authorization by registration is likely to be less onerous than one by licensing. The authorization will include conditions with which the employer must comply. For both registration and licensing the regulatory body may wish to determine the authorization on the basis of a level of activity at which the action level is exceeded.

6.2. CLASSIFICATION OF AREAS

Reference [2] discusses the classification of areas where work involving radiation is carried out. There are two categories, controlled areas and supervised areas [2, 3]. The distinction between them is based on the degree to which special operational procedures are required. Where radon is the only source of exposure for which measures need to be taken, the less stringent approach based on supervised areas will normally be adequate. Normally, the review of the radiological conditions would comprise a programme of regular monitoring of the area and, in some cases, of the individuals working in it. Radiation warning notices are usually required to delineate classified areas. However, for work involving only incidental exposure to radon this may, under appropriate conditions, be relaxed. For example, in parts of workplaces designated as supervised areas to which members of the public may have access, the presence of prominent radiation warning notices may cause unnecessary concern.

6.3. DOSE ASSESSMENT

Paragraphs I.33–I.34 of Ref. [2] state that:

> "For any worker who is normally employed in a controlled area, or who occasionally works in a controlled area and may receive significant occupational exposure, individual monitoring shall be undertaken where appropriate, adequate and feasible. In cases where individual monitoring is inappropriate, inadequate or not feasible, the occupational exposure of the worker shall be assessed on the basis of the results of monitoring of the workplace and…information on the locations and durations of exposure of the worker.
>
> "For any worker who is regularly employed in a supervised area or who enters a controlled area only occasionally, individual monitoring shall not be required but the occupational exposure of the worker shall be assessed. This assessment shall be on the basis of the results of monitoring of the workplace or individual monitoring."

The employer is required to take responsibility for arranging for assessment of the occupational exposure of the workers and for ensuring that adequate arrangements are made with an appropriate dosimetry service under a satisfactory quality assurance programme (Ref. [2], para. I.32). Examples of situations where individual monitoring may be inappropriate or not feasible are presented in Refs [4, 5].

6.4. DOSE LIMITS

A dose limit is defined as “The value of the effective dose or the equivalent dose to individuals from controlled practices that shall not be exceeded” (Ref. [2], Glossary). The limits on effective dose for occupational exposure apply to the sum of effective doses due to external sources and the committed effective doses due to intakes over the same period. Paragraph II-5, Schedule II of Ref. [2] specifies limits on occupational exposures as follows:

“(a) an effective dose of 20 mSv per year averaged over five consecutive years[38];
(b) an effective dose of 50 mSv in any single year;

[38] The start of the averaging period shall be coincident with the first day of the relevant annual period after the date of entry into force of the Standards, with no retroactive averaging.”

For exposures to progeny of radon and thoron, the occupational dose limits may be interpreted as follows:[3]

Radon progeny

(a) 20 mSv corresponds to 14 mJ·h/m^3 (4 WLM, or 2.5×10^6 Bq·h/m^3 radon equilibrium equivalent exposure);
(b) 50 mSv corresponds to 35 mJ·h/m^3 (10 WLM or 6.3×10^6 Bq·h/m^3 radon equilibrium equivalent exposure).

[3] An occupational exposure to radon progeny of 1 Bq/m^3 (equilibrium equivalent concentration (EEC) radon) for 1 h corresponds to a committed effective dose of 8 nSv. An occupational exposure to thoron progeny of 1 Bq/m^3 (EEC thoron) for 1 h corresponds to a committed effective dose of 36 nSv.

Thoron progeny

(a) 20 mSv corresponds to 42 mJ·h/m^3 (12 WLM or 5.6×10^5 Bq·h/m^3 thoron equilibrium equivalent exposure);
(b) 50 mSv corresponds to 105 mJ·h/m^3 (30 WLM or 1.4×10^6 Bq·h/m^3 thoron equilibrium equivalent exposure).

For most workplaces it is likely that initial surveys would be made of the concentrations of radon gas rather than of the progeny. In these situations the occupational dose limits may be more conveniently interpreted in terms of the radon gas concentration in the workplace. An exposure of 1 h to a radon gas concentration of 1 Bq/m^3 at an equilibrium factor of 0.4 corresponds to an effective dose of 3.2 nSv. For a 2000 hour working year, this leads to the following (rounded) derived air concentrations corresponding to the dose limits:

(a) 20 mSv corresponds to a radon gas concentration of 3000 Bq/m^3,
(b) 50 mSv corresponds to a radon gas concentration of 8000 Bq/m^3.

Paragraph II.6 of Ref. [2] specifies a limit on effective dose of 6 mSv in a year for apprentices of age 16–18 who are training for employment involving exposure to radiation or students of age 16–18 who are required to use sources in the course of their studies. It follows that this limit should also apply to apprentices and students of the same age group who are occupationally exposed to radon, even where such exposure is incidental to the work, as will be the case in workplaces within the scope of this publication.

6.5. TRAINING

In order to prevent human errors which might result in undue exposures, all personnel on whom protection and safety depend need to be trained appropriately. The curriculum of this training needs to be in line with the underlying concepts of Ref. [2]. The topics of such a curriculum are given in para. 5.95 of Ref. [3]. This will enable the personnel to understand their responsibilities and to perform their duties with appropriate judgement in accordance with defined procedures.

In Ref. [2] one of the main points emphasized as being central to a strong safety culture is that the responsibilities of each individual, including those at senior management levels, should be clearly identified, and each individual should be suitably trained and qualified (Ref. [2], para. 2.38(c)). In the case of protection against radon in workplaces other than mines, only very basic training will be necessary in the majority of cases.

Since the radon exposures will be incidental to the work, it is unlikely that there will be a familiarity with radiation protection matters in these workplaces, even if they are large enough to have a health and safety officer. Where there are health and safety officers, a very basic training course, perhaps as short as half a day, will in most cases be sufficient to inform workers of the basic principles of radiation protection and the particular problem of dealing with radon levels in the workplace that are found to exceed the action level set by the relevant national authority. Because only basic training will be given to such workplace staff, the regulatory body staff will be expected to possess a thorough knowledge in this area. A course of a few days duration would suffice for this purpose. Such training of regulatory staff will be useful, in particular, in communicating and dealing with employers in small workplaces with no health and safety officer.

6.6. HEALTH SURVEILLANCE

The known attributable public health effect of radon exposure, which will not be detectable if exposure is properly controlled, is an increased risk of lung cancer. This is not a prompt effect following exposure but has a latency period of many years. While employers will make arrangements for appropriate health surveillance according to the rules established by the regulatory bodies, it is unlikely that such a programme will differ from that based on the general principles of occupational health practice.

6.7. OTHER DUTIES OF EMPLOYERS AND EMPLOYEES

Reference [2] places other duties on employers and employees in order to ensure the protection of workers and comply with other requirements. Employees are required to co-operate with employers on matters relating to health and safety. Experts need to be available to advise on the execution of these duties and on the observance of the national regulatory framework. The experts' opinion needs to be taken into account in the establishment of local rules and the inculcation of a safety culture.

6.8. WORKPLACES VISITED BY MEMBERS OF THE PUBLIC

It is possible that some workplaces where radon concentrations cannot be reduced to below the action level will be workplaces that are visited by members of the public. This situation is expected to be rare but might arise in, for example, shops and offices in areas with particularly high radon levels or in caves and closed-out underground mines visited by tourists. It may be necessary in such situations to consider control of doses to members of the public in order to comply with the appropriate dose limit. To that end, it is necessary to estimate the dose likely to be received by the most exposed members of the public.

Occupational doses would not normally exceed the dose limits specified in Section 6.4 and it is expected that the maximum dose to members of the public would normally be much lower. If it is found that the dose to the most exposed members of the public would exceed 1 mSv per year, which is the dose limit for members of the public, then public access to the workplace would need to be limited.

Conversely, if the dose to the most exposed members of the public is less than 1 mSv per year, controls generally will be unnecessary unless a significant fraction of the public visiting the workplace receives a dose close to 1 mSv. It will also be necessary to periodically review the public dose levels.

6.9. WORKPLACES WHERE SPECIAL CONSIDERATIONS APPLY

Some special cases do not precisely follow the scheme outlined here. An example of these is radon spas where members of the public undergo radon exposure as a treatment, which are therefore outside the scheme of control for practices; however, the exposure of the workers has to be controlled on the basis set out here. Another special situation is radon exposure in show caves, where the potential for causing damage to the caves may limit the remedial measures that are possible (such as forced ventilation). This aspect has to be taken into consideration in the optimization process. These two cases are discussed in more detail in Annex V.

Appendix I

SUMMARY OF DECAY SCHEMES

The decay schemes for radionuclides in the ^{238}U and ^{232}Th decay series[4] are summarized in Tables VI and VII.

TABLE VI. RADIONUCLIDES IN THE URANIUM SERIES

Radionuclide (historical name in parentheses)	Half-life	Energy (MeV)		
		Alpha[a]	Beta (max.)[b]	Gamma photons[b] (transition probability in parentheses)
$^{238}_{92}U$	4.47×10^9 a	4.20	—	—
$^{234}_{90}Th$	24.10 d	—	0.20, 0.11	0.093 (0.06), 0.063 (0.05)
$^{234m}_{91}Pa$	1.17 min	—	2.27 (99.84%)[c]	1.001 (0.008), 0.766 (0.003) Internal transition (0.16%)[c]
$^{234}_{92}U$	2.46×10^5 a	4.77	—	—
$^{230}_{90}Th$	7.54×10^4 a	4.69	—	0.068 (0.004)
$^{226}_{88}Ra$	1600 a	4.78	—	0.186 (0.036)
$^{222}_{86}Rn$	3.824 d	5.49	—	—
$^{218}_{84}Po$ (RaA)	3.05 min	6.00 (99.98%) [c]	Energy not known (0.02%)[c]	—
$^{214}_{82}Pb$ (RaB)	26.8 min	—	0.67, 0.73	0.352 (0.38), 0.295 (0.19), 0.242 (0.074)
$^{214}_{83}Bi$ (RaC)	19.9 min	5.5 (0.02%)[c]	3.27, 1.54, 1.51 (99.98%)[c]	0.609 (0.46), 1.764 (0.15) 1.120 (0.15)
$^{214}_{84}Po$ (RaC′)	1.64×10^{-4} s	7.69	—	—
$^{210}_{82}Pb$ (RaD)	22.3 a	—	0.017, 0.064	0.047 (0.043)
$^{210}_{83}Bi$ (RaE)	5.01 d	—	1.16	—
$^{210}_{84}Po$ (RaF)	138.4 d	5.30	—	—
$^{206}_{82}Pb$ (RaG)	Stable	—	—	—

[a] Only the energy of the most intense alpha is listed.
[b] Only the most prominent gammas or betas are listed.
[c] Indicates branching — the percentage in parentheses is the proportional decay by the indicated mode.

[4] Source: Lund/LBNL (Lawrence Berkeley National Laboratory, Berkeley, CA), Nuclear Data Search, version 2.0, February 1999.

TABLE VII. RADIONUCLIDES IN THE THORIUM SERIES

Radionuclide (historical name in parentheses)	Half-life	Energy (MeV)		
		Alpha[a]	Beta (max.)[b]	Gamma photons[b] (transition probability in parentheses)
$^{232}_{90}Th$	1.405×10^{10} a	4.01	—	0.064 (0.0026)
$^{228}_{88}Ra$	5.75 a	—	0.039	0.013 (0.02)
$^{228}_{89}Ac$	6.15 h	—	1.16, 1.73	0.911 (0.26), 0.969 (0.16)
$^{228}_{90}Th$	1.91 a	5.42	—	0.084 (0.012)
$^{224}_{88}Ra$	3.66 d	5.69	—	0.241 (0.041)
$^{220}_{86}Rn$ (Tn)	55.6 s	6.29	—	—
$^{216}_{84}Po$ (ThA)	0.145 s	6.78	—	—
$^{212}_{82}Pb$ (ThB)	10.64 h	—	0.34, 0.57	0.239 (0.43)
$^{212}_{83}Bi$ (ThC)	60.55 min	6.05 (36%)[c]	2.25 (64%)[c]	0.727 (0.066)
$^{212}_{84}Po$ (ThC′)	2.99×10^{-7} s	8.78	—	—
$^{208}_{81}Tl$ (ThC″)	3.05 min	—	1.80, 1.29, 1.53	2.615 (0.36), 0.583 (0.30)
$^{208}_{82}Pb$ (ThD)	Stable	—	—	—

[a] Only the energy of the most intense alpha is listed.
[b] Only the most prominent gammas or betas are listed.
[c] Indicates branching — the percentage in parentheses is the proportional decay by the indicated mode.

Appendix II

CONVERSION COEFFICIENTS

TABLE VIII. SUMMARY OF CONVERSION COEFFICIENTS FOR THE SPECIAL QUANTITIES AND UNITS USED IN RADON WORK (Values are from Ref. [2], Table II–II)

Quantity	Unit	Value
Exposure and radon gas	(mJ·h/m^3) per WLM[a]	3.54
conversions (equilibrium factor 0.4)	(mJ·h/m^3) per (Bq·h/m^3)	2.22×10^{-6}
	WLM[a] per (Bq·h/m^3)	6.28×10^{-7}
Annual exposure per unit radon concentration [b]		
at home	(mJ·h/m^3) per (Bq/m^3)	1.56×10^{-2}
at work	(mJ·h/m^3) per (Bq/m^3)	4.45×10^{-3}
at home	WLM[a] per (Bq/m^3)	4.40×10^{-3}
at work	WLM[a] per (Bq/m^3)	1.26×10^{-3}

[a] WLM (working level month): a unit of exposure to radon or thoron progeny. One WLM is 3.54 mJ·h/m^3 or 170 WL·h, where one working level (WL) is any combination of radon or thoron progeny in one litre of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy. In SI units, the WL is equivalent to 2.1×10^{-5} J/m^3.

[b] Assuming 7000 hours per year indoors or 2000 hours per year at work and an equilibrium factor of 0.4. Where other exposure times or equilibrium factors apply, the conversion coefficient will require adjustment.

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Annex I

CONTROL OF EXPOSURE TO THORON

I–1. INTRODUCTION

Under typical indoor conditions, the dose associated with thoron is an order of magnitude lower than that associated with radon [I–1, I–2]. An exception to this general rule was reported in Japan where mud construction dwellings were found to have concentrations of thoron progeny much higher than those reported for other locations [I–3]. Recently an area with high thoron levels was found in the territory of the former Yugoslavia [I–4].

For most workplaces it is reasonable to expect that the dose from thoron progeny will be much less than the dose from radon progeny. An exception may occur in industries where thorium and its progeny are processed or stored. For example, thoron levels of up to 3000 Bq/m^3 have been measured in the gas mantle industries in India [I–5].

I–2. TECHNIQUES FOR MEASURING THORON AND DIFFERENCES FROM RADON MEASURING TECHNIQUES

It is usually more convenient and less costly to monitor for radon than for radon progeny. For thoron, however, it is easier and more appropriate to measure the progeny rather than the parent gas. Measurements of radon or thoron progeny may be necessary if there is reason to suspect that the equilibrium factor for radon progeny is significantly different than the normal 0.4–0.5, or that thoron may be present. For radon, severe disequilibrium may occur under circumstances of very high ventilation rates where the radon progeny will not have sufficient time to reach the normal fraction of equilibrium or, conversely, where ventilation and air movement are so restricted and aerosol concentrations are so high that equilibrium values well above normal are possible. For thoron, severe disequilibrium is the rule rather than the exception. Significant thoron is likely to be present in ordinary buildings only if there are elevated concentrations of its parent radionuclide in the construction materials which come into contact with the interior air space. In general the short half-life of thoron (<1 min) precludes its transport or diffusion to interior spaces from soil through a masonry foundation. In addition, owing primarily to the short half-life of thoron compared with that of some of its progeny, there is often a considerable difference between the spatial distribution of the gas and its progeny in indoor air, making an assessment of the thoron equilibrium more difficult than for radon.

Various measuring techniques are available for the measurement of thoron and its progeny. For thoron gas a passive alpha track detector technique has been developed which measures both radon and thoron [I–3]. The technique, based on the electret ion chamber generally used to measure radon, has been modified to measure thoron [I–6]. Because of the different half-lives in the radon and thoron decay chains, as shown in Appendix I, techniques have been developed in which time differences between the pulses from these series in detectors can be used to distinguish between them and measure their activities separately [I–7, I–8]. The CEA-ALGADE personal alpha dosimeter records alpha emissions from ^{212}Po separately, which allows direct measurement of exposures to thoron progeny [I–9].

I–3. THE ACTION LEVEL

Owing to the short half-life of thoron (55.6 s), the equilibrium between thoron and its progeny can be extremely variable. It is therefore more meaningful to base the action level on the thoron progeny concentration rather than the thoron gas concentration. The action level for thoron progeny corresponding to an annual occupational effective dose of 6 mSv is 0.3 working level (WL) (80 Bq/m^3 EEC thoron).

I–4. DOSE LIMITS

For exposure to thoron progeny, using a conversion coefficient of 0.48 mSv per mJ·h/m^3 (1.7 mSv per WLM, or 36 nSv per Bq·h/m^3 thoron equilibrium equivalent exposure), the dose limits may be interpreted as given in Section 6.4.

The values given above are essentially those of Ref. [I–10] and are also in close agreement with the EU Basic Safety Standards dose conversion factor of 0.5 mSv per mJ·h/m^3 assumed for exposure to thoron progeny in workplaces [I–11]. With rounding errors, both of these are in agreement with Ref. [I–12]. Recent reviews of the thoron progeny dose conversion factor determined using both comparative and direct dosimetry have produced values ranging from 0.3 to 1.1 mSv per m J·h/m^3 [I–13].

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Annex II

REVIEW OF THE RISK DUE TO RADON AND OVERVIEW OF RADON MEASUREMENTS IN WORKPLACES OTHER THAN MINES

II–1. RISK DUE TO RADON

Exposure to the radioactive progeny of radon in air has been linked to lung cancer in underground miners by several epidemiological studies [II–1]. The generally lower exposure levels to radon in dwellings have been assumed to carry a proportionately lower risk of lung cancer. Direct epidemiological evidence of increased lung cancer due to radon exposures in dwellings is equivocal but numerous studies are under way. Conversely, some human and animal studies with internally deposited alpha emitters seem to indicate the existence of thresholds in dose–effect relationships.

A meta-analysis of eight epidemiological studies, involving 4263 cases and 6612 control subjects, of the lung cancer risk from residential radon was completed [II–2]. The combined trend in the confounder adjusted relative risk (RR) differed significantly from zero (two sided P = 0.03), and an estimated RR of 1.14 (95% confidence interval = 1.0–1.3) at 150 Bq/m^3 was found. The results of this meta-analysis suggested that the risk from indoor exposure is not likely to be markedly greater than that predicted from studies of underground miners.

In 1998 the Committee on the Biological Effects of Ionizing Radiation (BEIR-VI) of the United States National Academy of Sciences evaluated the health effects of exposure to radon [II–3]. The committee examined data from eleven major studies of underground miners exposed to radon, involving 68 000 miners and 2700 deaths from lung cancer. They also examined eight case-control studies of indoor radon and lung cancer and found an agreement between the pooled risk estimate from the studies of underground miners and the pooled risk estimate from the residential studies. The BEIR-VI lung cancer risk estimate is somewhat higher than the 1988 BEIR-IV value [II–4] which the ICRP has used in Publication No. 65 to derive the dose conversion convention [II–1].

II–2. GENERAL CONSIDERATIONS FOR WORKPLACES OTHER THAN MINES

Concern has been raised about radon in workplaces other than mines [II–5 to II–8]. Indoor workplaces may have radon levels higher than the outdoor background levels and the range of levels is likely to be large. Large office buildings and factories are often equipped with forced ventilation and, unless a large fraction of the air is recycled, most can be expected to have low radon concentrations. Atmospheric radon concentrations will generally be lower on the upper floors of buildings than on the ground floor or basement, except for buildings where the radon is due to elevated radium in the construction materials. Small workplaces of similar construction to dwellings are likely to have radon concentrations comparable to those in dwellings [II–5].

II–3. WORKPLACES EXPECTED TO HAVE EXCEPTIONALLY HIGH LEVELS OF RADON

A small fraction of workplaces can have exceptionally large influxes of radon, poor ventilation or both, and can have very high radon concentrations. Examples of such workplaces are underground works and tunnels [II–6 to II–8], facilities which refine or process radium containing ores [II–9], spas in which radon is transferred from water to air or emanates from fissures in rock walls [II–10 to II–12], and caves in which guided tours are provided for visitors [II–13 to II–15]. Groundwater treatment and storage works, especially those which use aeration, may have above background radon levels because radon in the water transfers freely to air [II–16]. Water treatment plants with radon concentrations in the air of up to some hundreds of thousands of Bq/m^3 have been found [II–17]. Other workplaces that may be expected to have elevated radon concentrations include underground facilities such as subway and utility tunnels, highway tunnels, restaurants, shopping malls, power stations and military installations. Buildings constructed of material containing radium in excess of normal levels may also be expected to have elevated atmospheric radon concentrations. Nevertheless, for by far the largest number of workplaces with high radon levels, the cause is almost entirely the high natural levels of radon in the soil gas below the building. The radon levels reported for buildings are reviewed below.

II–4. RADON IN COMMERCIAL AND INDUSTRIAL BUILDINGS

The first published survey of radon in workplaces was conducted in Innsbruck, Austria [II–18]. Ten locations (offices, schools, warehouses) were surveyed and the mean concentrations ranged from 13–58 Bq/m^3. The geometric mean of the 10 sites was 36 Bq/m^3.

In the northwestern USA, a survey was conducted at 163 sites in 40 commercial buildings [II–19]. The levels of radon in the occupied spaces of 39 of the 40 buildings were below the US action level for dwellings of 150 Bq/m^3. The geometric mean was 30 Bq/m^3 and the geometric standard deviation was 2.1. One of the buildings had concentrations ranging from 122 to 340 Bq/m^3. A survey of public and commercial buildings in the vicinity of the University of Pittsburgh, Pennsylvania, indicated that levels in these buildings were near outdoor background levels, lower by a factor of nearly 10 than the levels in single family residences in the same area [II–20]. Geometric means were generally less than 20 Bq/m^3 for the various classes of buildings and the geometric standard deviations ranged from 1.5 to 2.6.

Federal Government buildings in the USA were surveyed for radon by the individual government agencies and a report was compiled for the US Congress [II–21]. More than 50 000 measurements were made. The surveys were not conducted using a single measurement protocol so the results may not be directly comparable. Different instruments and integration times were used by the various agencies. Nevertheless, the results give a general idea of the levels to be found. Excluding government living quarters, 4.3% of the measurements exceeded the US action level for dwellings of 150 Bq/m^3 but only about 0.1% of the measurements exceeded 1000 Bq/m^3.

As an example of the Federal Government building surveys, the US Department of Energy (DOE) surveyed 5700 locations in 3091 buildings at 74 DOE facilities [II–22 to II–23]. The measurements were integrated over time for approximately 3 months and identified 86 buildings at 7 sites that may exceed the US action level for dwellings of 150 Bq/m^3. Fewer than 0.2% of the measurements exceeded 1000 Bq/m^3. The geometric mean was 23 Bq/m^3 and the geometric standard deviation was 1.89. None of the US surveys mentioned were conducted in a radon prone area.

In the United Kingdom, the counties of Cornwall and Devon have been identified as areas of highest radon concentrations and the radon measurement programme for workplaces has been concentrated in those areas. A total of about 8000 above ground workplaces have been measured so far [II–24]. The mean radon concentration corrected to an annual average is about 100 Bq/m^3 with a maximum annual average level of 7500 Bq/m^3 found in one building (see Annex IV for a more detailed discussion). The mean is larger than the means from the US surveys to date. The difference may be due to the fact that the UK measurements were conducted in radon prone areas whereas the US studies were not. Ventilation and construction practices may also play a role.

In the radon prone province of Luxembourg in Belgium, a survey of 36 public buildings showed a mean of 110 Bq/m^3 and a median of 72 Bq/m^3 [II–25]. Ten per cent of the buildings exceeded 200 Bq/m^3 and 3% exceeded

400 Bq/m^3. The arithmetic means for hotel rooms in Ramsar, Islamic Republic of Iran, were 90 Bq/m^3 for old hotels and 50 Bq/m^3 for new hotels [II–26]. Six hospitals surveyed in Madrid, Spain, had values ranging from 10 to 260 Bq/m^3 with a mean of about 50 Bq/m^3 [II–27]. Four other public buildings in Madrid had values ranging from 18 to 350 Bq/m^3 with a mean of 88 Bq/m^3.

In Ireland, radon levels have been measured in a total of 320 workplaces other than schools. The maximum radon concentration measured was 2900 Bq/m^3 [II–28]. Because of the diversity of the workplaces surveyed, their wide geographical distribution and the non-random nature of their selection, a calculated mean value is considered to have almost no meaning from a practical perspective.

In Finland, about 7000 radon measurements have been made in above ground workplaces in the areas where the highest radon concentrations had been previously found in dwellings [II–29]. About 740 work sites have been issued injunctions to begin measures aimed at reducing radon concentrations. In areas where over 25% of dwelling measurements exceeded 400 Bq/m^3, a total of 3050 workplace measurements yielded a mean concentration of 255 Bq/m^3, with 19% of the measurements exceeding 300 Bq/m^3. In areas where 10–25% of measurements in dwellings exceeded 400 Bq/m^3, a total of 993 workplace measurements yielded a mean concentration of 171 Bq/m^3, with 12% of the measurements exceeding 300 Bq/m^3.

In Germany it is estimated that there are 60 000 workers in workplaces in buildings with radon concentrations exceeding 1000 Bq/m^3 [II–17]. An estimated 2300 workers in the water supply and distribution industry in Germany are exposed to radon concentrations above 1000 Bq/m^3 in the workplace. In a recent small study of 36 workplaces in Saxony, indoor radon levels were found to range from 25 to 7000 Bq/m^3, with 90% $<$ 1000 Bq/m^3 and 80% $<$ 500 Bq/m^3 [II–30].

In Greece, recent monitoring of radon in a limited number of types of workplaces has commenced [II–31]. Apart from underground mines these include radon spas, a coal power plant and the Athens metro (underground railway), which is currently under construction. In the radon spas the equivalent equilibrium concentration of radon ranged from 50 to 18 000 Bq/m^3 while in two main metro stations radon concentrations were quite low, ranging from about 9 to 22 Bq/m^3. At the coal power plant investigated, radon concentrations were found to range from 15 to 181 Bq/m^3.

In Italy, no statistically representative survey was conducted in workplaces, except for schools as described in Section 5 and in Table II [II–32]. In some workplaces not in buildings, research surveys have shown very high concentrations, for example in thermal baths (up to several thousands of Bq/m^3). Other workplaces in Italy such as geothermal plants are also expected to give rise to radiation protection concerns due to high radon levels. Radon concentrations of several thousands of Bq/m^3 have been measured in the catacombs of Rome, which are workplaces for guides.

Although radon in dwellings has been studied extensively in Sweden, no representative survey of radon in ordinary above ground workplaces has been conducted [II–33]. The Board of Occupational Safety and Health investigated about 150 selected Swedish workplaces in 1996. About 10% of the investigated workplaces had radon levels exceeding 400 Bq/m^3. Radon air concentrations as high as 18 000 Bq/m^3 have been found in Swedish waterworks using groundwater, and a pilot study of such workplaces has commenced.

II–5. RADON IN SCHOOLS, KINDERGARTENS AND PLAYSCHOOLS

Educational buildings have attracted special interest, not only as workplaces for teachers and staff but as locations of high occupancy times for children [II–34]. Short term measurements were made in 460 kindergartens in the former Yugoslavia. Ventilation was restricted for 12 h prior to measurement. Most measurements ranged from 10 to 180 Bq/m^3, with a mean of about 100 Bq/m^3. The geometric mean was not provided. Follow-up surveys of kindergartens with higher radon levels were made with integrating detectors over three months, which showed values 1.5–2 times lower than the instantaneous measurements.

Vaupotič et al. [II–35] made measurements in Polish kindergartens and playschools where they found the geometric mean to be 23 Bq/m^3 and the geometric standard deviation to be 1.4 [II–36]. They also surveyed all 730 kindergartens and 900 schools in Slovenia. The radon in the air of kindergartens ranged from 7 to 5750 Bq/m^3 with a geometric mean of 58 Bq/m^3. The radon in the air of schools ranged from 10 to 4700 Bq/m^3 with a geometric mean of 68 Bq/m^3.

Radon levels were determined for three rooms in each of 16 schools in Ramsar, Islamic Republic of Iran, and its areas of high natural radioactivity [II–26] where the values ranged from 15 to 1400 Bq/m^3. The arithmetic means for each school ranged from 19 to 560 Bq/m^3. The approximate geometric mean and standard deviation of the measurements are 60 Bq/m^3 and 3 respectively and are heavily influenced by a few high measurements.

The province of Luxembourg in Belgium is recognized as having very high indoor radon concentrations based upon surveys of dwellings [II–25]. A survey of the 421 schools in Luxembourg province resulted in an arithmetic mean of 120 Bq/m^3 and a median of 90 Bq/m^3. Twelve per cent of the schools had levels exceeding 200 Bq/m^3 and in 2% they exceeded 400 Bq/m^3.

In the USA, a survey of 927 schools selected randomly from a population of approximately 101 000 was carried out by the Environmental Protection Agency [II–37]. Short term screening measurements (7 d) were made in all rooms in contact with the ground. In 19.3% of the school buildings, at least one room had a radon level above the US action level of 150 Bq/m^3. Of schoolrooms, 2.7% exceeded 150 Bq/m^3. Approximately 0.1% of the schoolrooms exceeded 1000 Bq/m^3 and the highest value measured was about 2500 Bq/m^3.

In Ireland radon has been measured in 1762 schools using long term alpha track radon detectors [II–38]. Twenty-three per cent of schools had one or more classrooms or offices with average radon concentrations exceeding the 200 Bq/m^3 national reference level for schools. The highest radon concentration measured in any school was 2688 Bq/m^3.

In Norway radon has been measured in 3600 kindergartens out of a total of about 6000, using alpha track radon detectors [II–39]. The range was 5–2800 Bq/m^3 with an arithmetic mean of 88 Bq/m^3 and a geometric mean of 44 Bq/m^3. Continuous measurements in kindergartens with some of the higher radon levels showed that the radon exposure during the daytime is much lower than the average obtained using alpha track radon detectors.

In Italy, radon concentrations were measured in 2173 schools in six regions [II–40]. Regional arithmetic, and geometric means and standard deviations were found to range from 49 to 222 Bq/m^3, from 38 to 129 Bq/m^3 and from 1.9 to 2.7, respectively. Radon concentrations in these schools ranged from less than 10 Bq/m^3 to as high as 1450 Bq/m^3. A significant proportion of schools showed radon concentrations above the reference values, from 150 to 1000 Bq/m^3, which operate in a number of countries.

In Finland, in schools and day care centres in areas where measurements for over 25% of dwellings were over 400 Bq/m^3, a total of 271 measurements were made, yielding a mean radon concentration of 531 Bq/m^3 with 34% of measurements exceeding 300 Bq/m^3 [II–29]. In areas of Finland where 10–25% of measurements for dwellings were over 400 Bq/m^3, a total of 595 measurements in schools and day care centres yielded a mean radon concentration of 294 Bq/m^3 with 19% of measurements exceeding 300 Bq/m^3.

In Sweden most municipalities have made extensive measurements in schools and day care centres and, for most premises of these types with levels exceeding 400 Bq/m^3, levels have been reduced [II–33].

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Annex III

EXAMPLE OF RADON MEASUREMENT IN SCHOOLS

As an example of controlling radon levels in schools, the US Environmental Protection Agency (EPA) procedure is presented here [III–1]. The EPA identifies short term tests as those lasting for two to ninety days and long term tests as those lasting more than ninety days. Short term tests are often made with activated charcoal devices, 'electret' ion chambers (EICs), solid state nuclear track detectors (SSNTDs) or continuous monitors. Long term tests are most often made with SSNTDs or EICs. All measurements include quality assurance efforts including unexposed detectors (blanks), duplicate detectors and detectors that have been exposed by a reference laboratory to a known level (blind spikes). The EPA recommends that tests of 48 hours or longer be used and suggests 90 days. School authorities are free to choose either short term or long term tests. The EPA action level for schools is 150 Bq/m^3 but the principles of the procedure can be applied to any action level adopted by a national authority. The EPA procedure is summarized below.

STEP 1: INITIAL MEASUREMENTS

Make short term measurements in all frequently occupied rooms in contact with the ground.

All rooms are to be tested simultaneously, preferably during the coldest months when the heating system is operating and when windows and doors are closed except for normal exit and entry. For short term tests of two to five days the tests are to be conducted on weekdays with heating, ventilation and cooling systems operating normally.

Make a follow-up test in every room with a radon concentration above the action level.

The EPA does not recommend making a decision on whether action needs to be taken on the basis of a single short term test result. If the initial short term test shows a radon level greater than the action level, schools are to conduct a second short term test or a long term test to confirm an elevated radon level.

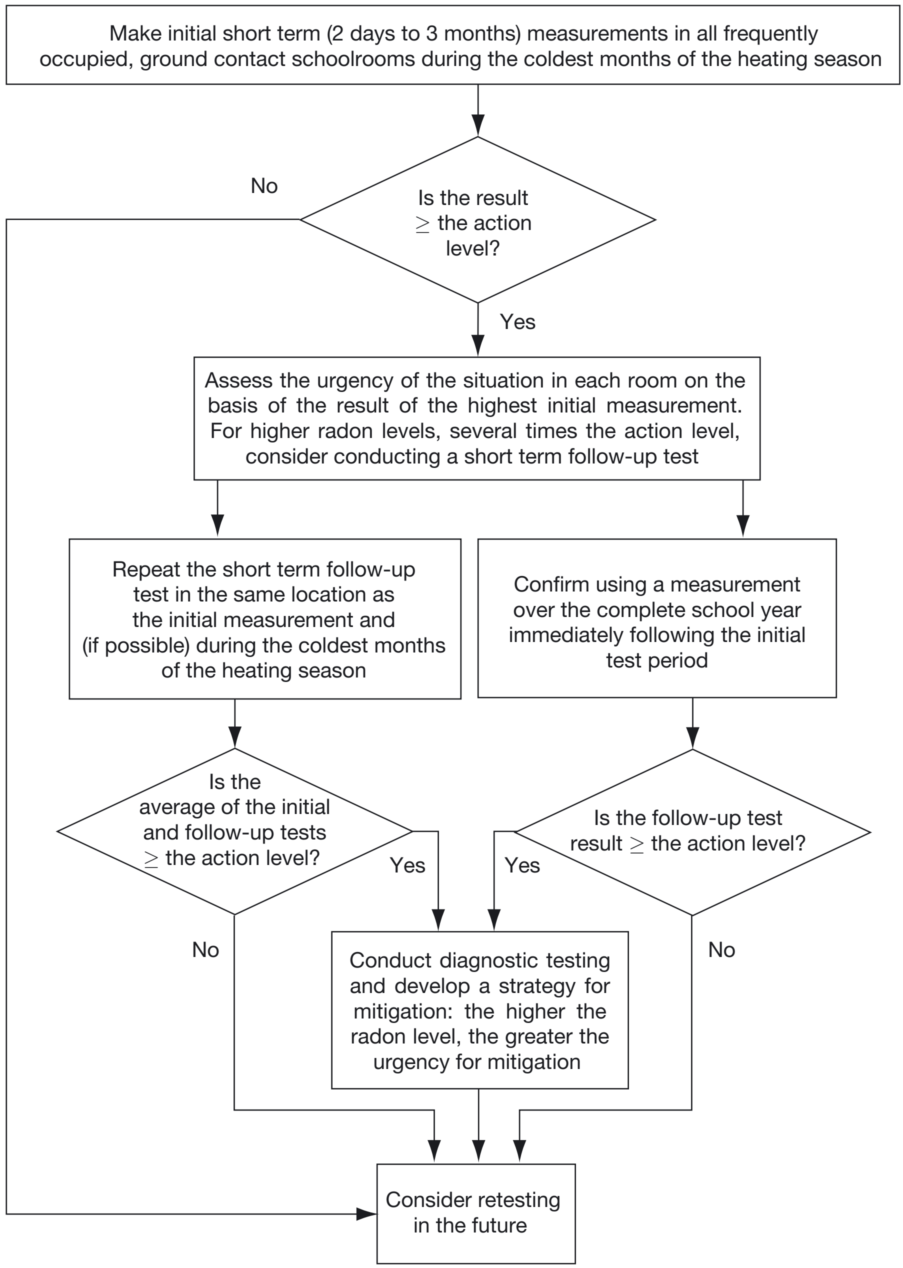

FIG. III-1. Model decision making flow chart for radon in schools.

STEP 2: FOLLOW-UP MEASUREMENTS

Follow-up tests are to be done simultaneously at the same locations and under ventilation conditions as close as possible to those of the initial test.

Make a short term follow-up measurement if results are needed quickly.

If the initial measurements exceed several times the action level, a short term follow-up test is to be done as soon as possible so that any necessary remedial action will not be delayed.

Make a long term follow-up test to better understand the average radon concentration for a school year.

If a room's initial test shows a result only slightly above the action level, a long term test, preferably taken over the entire school year, will best characterize the average exposure.

Once initial and follow-up testing is complete, the EPA recommends that steps be taken to reduce radon levels if both initial and follow-up short term tests exceed the action level or a single long term test exceeds the action level.

This basic testing plan has been incorporated into a flow chart that may facilitate the decision making process (Fig. III–1).

REFERENCE TO ANNEX III

[III–1] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Radon Measurements in Schools, revised edition, Rep. EPA-402-R-92-014, EPA, Washington, DC (1993).

Annex IV

EXAMPLE OF CONTROL OF RADON IN ABOVE-GROUND WORKPLACES IN THE UNITED KINGDOM

Annex IV gives an account of the procedures used to control radon in above ground workplaces in the United Kingdom. The measurements were undertaken by the United Kingdom's National Radiological Protection Board (NRPB) in conjunction with the appropriate government department or agency. The development of procedures for occupational radon control in the United Kingdom was greatly aided by the well developed programme of domestic radon measurements. This provided a detailed framework of data on radon levels in buildings. Nevertheless, a substantial survey of radon levels in several hundred workplaces was undertaken. It was found that radon levels in small shops and offices in the United Kingdom were generally similar to those in homes. Radon levels in large premises such as factories and warehouses were generally found to be lower. The results of these surveys were used to direct the later programme of measurement, designed to identify specific workplaces where radon levels are high.

A radon gas concentration of 400 Bq/m^3 is taken as the United Kingdom action level. If radon concentrations above this level are found, the employer needs to undertake remedial action to reduce the radon concentrations to below the action level or, if this is not possible, apply the normal system of radiation protection.

IV–1. RESULTS OF RADON TESTING IN ABOVE GROUND WORKPLACES IN THE UNITED KINGDOM

To date radon concentrations have been measured in approximately 8000 workplaces in the United Kingdom [IV–1]. The buildings measured included schools, offices, factories and a wide range of retail premises such as shops and banks. Measurements were made using passive alpha track detectors placed for three months. At least two monitors were placed in each building with more in larger ones, about five on average. The mean annually corrected radon concentration was about 100 Bq/m^3 but this is heavily biased with results from high radon areas. The maximum annual average level found in a workplace was 7500 Bq/m^3. To date the data on workplaces have been largely collected during commercial surveys for employers rather than as part of a systematic programme and cannot therefore be considered to be representative.

TABLE IV–I. WORKPLACES MONITORED FOR RADON IN THE UNITED KINGDOM [IV–1]

Type of workplace	Action level (>400 Bq/m^3)		
	Workplaces	Number	Percentage
Medical	180	40	22%
Industrial	520	70	13%
Educational	1350	200	15%
Commercial	1950	290	15%
Miscellaneous	800	110	14%
Total	4800	710	15%

It is estimated that there are about 1 700 000 workplaces in the United Kingdom. Of these about 5000 may have radon concentrations above the action level. Roughly half the workplaces above the action level are thought to be in Devon or Cornwall.

In an earlier phase of these surveys, 4800 workplaces had been surveyed. Reference [IV–1] gives a summary of the findings at that time. The mean radon concentration was 210 Bq/m^3 and in 710 cases the radon concentration exceeded the action level of 400 Bq/m^3. As is usual with radon measurements, the distribution of radon in workplace measurements is found to be log normal, with geometric mean 82 Bq/m^3 and geometrical standard deviation 3.6. A breakdown by type of premises is given in Table IV–I.

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Annex V

WORKPLACES WHERE SPECIAL CONSIDERATIONS APPLY

Two cases where special circumstances apply to the control of radon exposures are radon spas and show caves.

V–1. RADON SPAS

In the special situation of radon spas, the presence of the radon in treatment rooms or galleries is held to be necessary by the balneological medical community to achieve the desired effect. The radon either enters the air directly from the native rock or transfers to air from spa water, or both. In many spas radon in air or water is transferred into treatment rooms by pipes. Although radon treatment is not endorsed by the international radiation protection community, the operators of radon spas would not wish to reduce radon in the treatment rooms nor would the methods developed for buildings be effective. In this case the operating and maintenance staffs must be protected by other means [V–1]. Separate, well ventilated areas need to be provided for the staff to use at times when they do not need to be in the treatment room. Pipes used to transfer radon to treatment rooms need to be well sealed to prevent leakage of radon into other rooms. Anterooms or other separation methods need to be provided so that radon from the treatment rooms does not reach non-treatment areas in significant quantities. The time spent by staff in the treatment areas needs to be minimized. If it is not possible to reduce the doses to the staff to below the action level, the normal scheme for controlling the exposure of workers applies.

Where radiation is used medically for diagnostic or therapeutic purposes, it is to be done in accordance with Ref. [V–2]. Reference [V–2] quite clearly requires that “no patient be administered a therapeutic medical exposure unless the exposure is prescribed by a medical practitioner”. Notwithstanding the opinions of the balneological medical community as to the general efficacy and benefits of radon spa treatments, such treatments are only to be administered to an individual if clinically indicated for that individual by a medical practitioner. Any radon spa treatments given without such individual assessment would clearly be in breach of Ref. [V–2].

V–2. CAVES AND SHOW MINES OPERATED FOR TOURISTS

Developed caves in which guides provide tours for the general public also present a unique problem. Although the presence of radon is not necessary, as it is for radon spas, reduction of radon by reducing pressure in the source rock or sealing may not be practicable. However, the amount of radon may possibly be reduced by installing partitions to isolate unused cave galleys from those areas frequented by guides and the public, and by a measured increase in ventilation. Great care is needed, however, because in some circumstances forced ventilation may alter the humidity in caves and destroy or diminish the beauty of the formations that attract tourists [V–3, V–4]. Partitioning and increased ventilation has, however, been used successfully in some caves, particularly in the United Kingdom. If radon levels cannot be successfully reduced, the only option may be to subject cave guides and other cave workers to an appropriate system of radiation protection and possibly to limit exposure by restricting the amount of time spent in the cave. Former mines used as tourist attractions (show mines) can be treated in much the same way as tourist caves. Ventilation may be more practical for show mines because there is no concern for damage of delicate formations by altered humidity. In the case of both tourist caves and show mines radon concentrations of some thousands of Bq/m^3 are not uncommon [V–5 to V–9].

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Annex VI

EXAMPLE OF RADON REMEDIES USED BY THE NATIONAL RADIOLOGICAL PROTECTION BOARD, UNITED KINGDOM

Remedial measure	Radon levels ≤300 Bq/m^3	Radon levels 300–1000 Bq/m^3	Radon levels >1000 Bq/m^3
Solid floors (no underfloor space)			
Extraction using sump.	Virtually certain to work.	Very likely to work, sealing large gaps will help.	Should reduce levels at least tenfold provided that underfloor permeability is good and underfloor pressure field is uniform. Seal all gaps.
Indoor ventilation with conditioning unit.	Very likely to work.	Should work, particularly in single storey property, unless it is very draughty; less likely to work above 600 Bq/m^3.	Will occasionally work under particularly favourable conditions.
Permanent room ventilation with trickle vents.	Should work, particularly if property is well insulated and has high heating level.	Unlikely to work.	Not recommended as sole method.
Sealing.	Only as secondary method.	Only as secondary method.	Only as secondary method.
Suspended floors (space under the whole floor)			
Extraction using fan assisted underfloor ventilation.	Very likely to work.	Should work, but depends critically on local circumstances; specialized design may be needed.	Good reductions can usually be achieved with fan blowing inwards and clear underfloor space; additional air bricks and sealing may be required.

Remedial measure	≤300 Bq/m^3	Radon levels 300–1000 Bq/m^3	>1000 Bq/m^3
Indoor ventilation with conditioning unit.	Very likely to work.	Should work, particularly in single storey property, unless it is very draughty; less likely to work above 600 Bq/m^3.	Will occasionally work under particularly favourable conditions.
Natural underfloor ventilation with air bricks.	Should work if existing air bricks are few, small or blocked; best if underfloor space is completely clear.	Unlikely to work unless existing underfloor ventilation is very poor.	Not recommended as sole method.
Permanent room ventilation with trickle vents.	Should work, particularly if property is well insulated and has high heating level.	Unlikely to work.	Not recommended as sole method.
Sealing.	Not recommended.	Not recommended.	Not recommended.
Mixed floors (space under parts of the floor)			
Extraction using sump and/or assisted underfloor ventilation for respective parts of floor.	A single underfloor method should work provided the radon source is localized.	Dual underfloor methods should work but specialized design may be needed.	Dual underfloor methods might work, but may also need above floor methods.
Indoor ventilation with conditioning unit.	Very likely to work.	Should work, particularly in single storey property, unless it is very draughty; less likely to work above 600 Bq/m^3.	Will occasionally work under particularly favourable conditions.

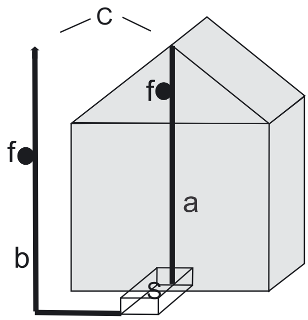
Remedial measure	Radon levels ≤ 300 Bq/m^3	Radon levels 300–1000 Bq/m^3	>1000 Bq/m^3
Natural underfloor ventilation with air bricks.	Might work if existing air bricks are few, small or blocked so that ventilation is poor.	Unlikely to work unless existing underfloor ventilation is very poor.	Not recommended as sole method.
Permanent room ventilation with trickle vents.	Should work, particularly if property is well insulated and has high heating level.	Unlikely to work.	Not recommended as sole method.
Sealing.	Not recommended.	Not recommended.	Not recommended.
	Preferred methods to achieve lowest radon level.		
	Less effective method.		
	Unsuitable method for the circumstances.		

Note: The choice of remedial measures can be more complicated in buildings with features such as stepped foundations, basements or extensions.

BRIEF DETAILS OF REMEDIAL MEASURES FOR RADON EXPOSURE/LEVELS

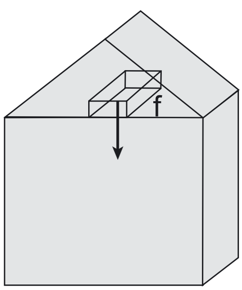
Radon sump

A sump (s) (an empty space about the volume of a bucket) is dug out under a solid floor. This can sometimes be done from outside the building. A pipe, normally 10 mm in diameter, is taken from the sump to the outside air. This is either up through the inside (a) or up the outside of the building (b). A ridge vent or cowling prevents rain from entering the pipe (c). A fan (f) is installed near the open end of the pipe.



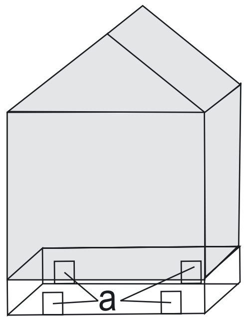
Positive pressure or positive ventilation

This method involves blowing air into a working area. Most commonly, a specially installed fan unit (f) blows air from the loft space into the working area. A fan blowing in fresh air from outside would have a similar effect.



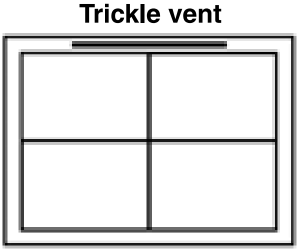
Ventilation under a suspended floor

The ventilation of the underfloor space is increased by ensuring that all the air bricks (a) are clear, replacing old vents in poor condition with modern plastic ones and maybe adding extra ones. To increase the airflow, an electric fan can be installed to either draw air out of the underfloor space or blow fresh air into the underfloor space.



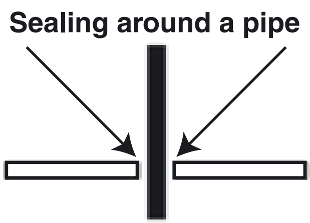
Additional permanent ventilation

This is the least effective way to reduce radon levels, but it can work when the levels are not too high. It includes such measures as trickle vents in windows or lockable catches that hold windows permanently open. To be continually effective, such measures should be designed so that it is not possible to fully close the vents or windows.



Sealing

For sealing to be effective, every last crack and gap in a solid floor must be sealed using a flexible sealant. This is often not feasible. However, sealing major cracks can be a useful addition to other methods. This method is not suitable for timber floors, as preventing air circulation around timbers may cause rot and the floor may collapse.



DEFINITIONS

action level. The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations (for example, chronic exposure to radon in the workplace).

dose limit. The value of the **effective dose** or the **equivalent dose** to individuals from controlled practices that shall not be exceeded.

effective dose. The quantity E, defined as a summation of the tissue **equivalent doses**, each multiplied by the appropriate tissue weighting factor:
where H_T is the **equivalent dose** in tissue T and w_T is the tissue weighting factor for tissue T

$$E = \sum_T w_T \cdot H_T$$

From the definition of **equivalent dose**, it follows that:

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

where w_R is the radiation weighting factor for radiation R, and $D_{T,R}$ is the average absorbed dose in the organ or tissue T.
The unit of **effective dose** is $J \cdot kg^{-1}$, termed the sievert (Sv).

Effective dose is a measure of dose designed to reflect the amount of radiation detriment likely to result from the dose.

equilibrium equivalent concentration of radon (EEC radon). The potential alpha energy concentration of any mixture of radon progeny in air can be expressed in terms of the so-called equilibrium equivalent concentration of their parent nuclide, ^{222}Rn (radon). The equilibrium equivalent concentration, corresponding to a non-equilibrium mixture of radon progeny in air, is the activity concentration of radon in radioactive equilibrium with its short lived progeny that has the same potential alpha energy concentration as the actual non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq/m^3:

EEC radon = 0.104 C(^{218}Po) + 0.514 C(^{214}Pb) + 0.382 C(^{214}Bi)
with C( ) the concentration of the nuclide in air
1 Bq/m^3 EEC radon corresponds to 5.56×10^{-6} mJ/m^3
1 Bq/m^3 EEC radon is equivalent to 2.5 Bq/m^3 radon gas, assuming an equilibrium factor of 0.4.

equilibrium equivalent concentration of thoron (EEC thoron). The potential alpha energy concentration of any mixture of thoron progeny in air can be expressed in terms of the so-called equilibrium equivalent concentration of their parent nuclide, ^{220}Rn (thoron). The equilibrium equivalent concentration, corresponding to a non-equilibrium mixture of thoron progeny in air, is the activity concentration of thoron in radioactive equilibrium with its short lived progeny that has the same potential alpha energy concentration as the actual non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq/m^3:

EEC thoron = 0.913 C(^{212}Pb) + 0.087 C(^{212}Bi)
with C( ) the concentration of the nuclide in air
1 Bq/m^3 EEC thoron corresponds to 7.5×10^{-5} mJ/m^3.

equilibrium factor. The ratio F of the **equilibrium equivalent concentration of radon** (EEC radon) to the actual radon concentration.

equivalent dose. The quantity $H_{T,R}$, defined as:

$$H = D_{T,R} \cdot w_R$$

where $D_{T,R}$ is the absorbed dose delivered by radiation of type R averaged over a tissue or organ T and w_R is the radiation weighting factor for radiation type R.

When the radiation field is composed of radiations with different values of w_R, the **equivalent dose** is:

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

The unit of **equivalent dose** is J·kg^{-1}, termed sievert (Sv).

radon progeny. The short lived radioactive decay products of ^{222}Rn. Namely, ^{218}Po (sometimes called radium A), ^{214}Pb (radium B), ^{214}Bi (radium C) and ^{214}Po (radium C′). ^{210}Pb (radium D), which has a half-life of 22.3 a, and its radioactive progeny — ^{210}Bi (radium E) and ^{210}Po (radium F), plus traces of ^{206}Hg and ^{205}Tm — are, strictly, progeny of ^{222}Rn, but are not normally included in the meaning of the term **radon progeny** because they will not normally be present in significant amounts in airborne form. The stable decay product ^{206}Pb is sometimes known as radium G.

regulatory body. An authority or authorities designated or otherwise recognized by a government for regulatory purposes in connection with protection and safety.

working level. A unit for potential alpha energy concentration (i.e. the potential alpha energy per unit volume of air) resulting from the presence of **radon progeny** or thoron progeny equal to 1.3×10^5 MeV per litre.

1 WL is equal to an EEC radon of 3700 Bq/m^3 or an EEC thoron of 275 Bq/m^3. In SI units the WL corresponds to 2.1×10^{-5} J·m^{-3}.

working level month (WLM). The exposure to **radon progeny** or thoron progeny which would be incurred during a working month (170 hours) in a constant potential alpha energy concentration of one **working level**. In SI units, a **working level month** is 3.54 mJ·h·m^{-3}.

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Consultants Meetings

Vienna, Austria: 7–10 November 1994,
4–8 December 1995, 14–18 December 1998,
14–18 May 2001

Advisory Group Meetings

Vienna, Austria: 19–22 December 1994, February 1995