IAEA Safety Standards
for protecting people and the environment

Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation

Jointly sponsored by the IAEA, WHO

IAEA WHO

Specific Safety Guide
No. SSG-32

IAEA
International Atomic Energy Agency

IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available on the IAEA Internet site

http://www-ns.iaea.org/standards/

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at: Vienna International Centre, PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Emergency Preparedness and Response** publications, **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

The **IAEA Nuclear Energy Series** comprises informational publications to encourage and assist research on, and the development and practical application of, nuclear energy for peaceful purposes. It includes reports and guides on the status of and advances in technology, and on experience, good practices and practical examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

PROTECTION OF THE PUBLIC AGAINST EXPOSURE INDOORS DUE TO RADON AND OTHER NATURAL SOURCES OF RADIATION

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA SAFETY STANDARDS SERIES No. SSG-32

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SPECIFIC SAFETY GUIDE

JOINTLY SPONSORED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY AND THE
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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
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fax: +43 1 2600 29302
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FOREWORD

by Yukiya Amano
Director General

The IAEA's Statute authorizes the Agency to "establish or adopt… standards of safety for protection of health and minimization of danger to life and property" — standards that the IAEA must use in its own operations, and which States can apply by means of their regulatory provisions for nuclear and radiation safety. The IAEA does this in consultation with the competent organs of the United Nations and with the specialized agencies concerned. A comprehensive set of high quality standards under regular review is a key element of a stable and sustainable global safety regime, as is the IAEA's assistance in their application.

The IAEA commenced its safety standards programme in 1958. The emphasis placed on quality, fitness for purpose and continuous improvement has led to the widespread use of the IAEA standards throughout the world. The Safety Standards Series now includes unified Fundamental Safety Principles, which represent an international consensus on what must constitute a high level of protection and safety. With the strong support of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its standards.

Standards are only effective if they are properly applied in practice. The IAEA's safety services encompass design, siting and engineering safety, operational safety, radiation safety, safe transport of radioactive material and safe management of radioactive waste, as well as governmental organization, regulatory matters and safety culture in organizations. These safety services assist Member States in the application of the standards and enable valuable experience and insights to be shared.

Regulating safety is a national responsibility, and many States have decided to adopt the IAEA's standards for use in their national regulations. For parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by regulatory bodies and operators around the world to enhance safety in nuclear power generation and in nuclear applications in medicine, industry, agriculture and research.

Safety is not an end in itself but a prerequisite for the purpose of the protection of people in all States and of the environment — now and in the future. The risks associated with ionizing radiation must be assessed and controlled without unduly limiting the contribution of nuclear energy to equitable and sustainable development. Governments, regulatory bodies and operators everywhere must ensure that nuclear material and radiation sources are used beneficially, safely and ethically. The IAEA safety standards are designed to facilitate this, and I encourage all Member States to make use of them.

PREFACE

Requirements for the protection of people from harmful consequences of exposure to ionizing radiation, for the safety of radiation sources and for protection of the environment are established in the IAEA Safety Requirements for Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (IAEA Safety Standards Series No. GSR Part 3). Safety Standards Series No. GSR Part 3 is jointly sponsored by the European Commission, the Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the International Labour Organization (ILO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO), the United Nations Environment Programme (UNEP) and the World Health Organization (WHO).

The present Safety Guide provides recommendations and guidance on meeting the requirements of GSR Part 3 for protection of the public against exposure indoors due to natural sources of ionizing radiation. Recommendations and guidance are provided on application of the requirements for justification and for optimization of protection by national authorities in considering the control of natural sources of radiation indoors, such as radon gas and radionuclides of natural origin in building materials. Recommendations and guidance are also provided on the establishment by States of national 'radon action plans' for the control of exposure of the public indoors due to radon.

This Safety Guide is jointly sponsored by the IAEA and the WHO. The IAEA gratefully acknowledges the contribution of experts from several States and from the WHO to the drafting and review of the text.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures[1] have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. Requirements, including numbered 'overarching' requirements, are expressed as 'shall' statements. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

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[1] See also publications issued in the IAEA Nuclear Security Series.

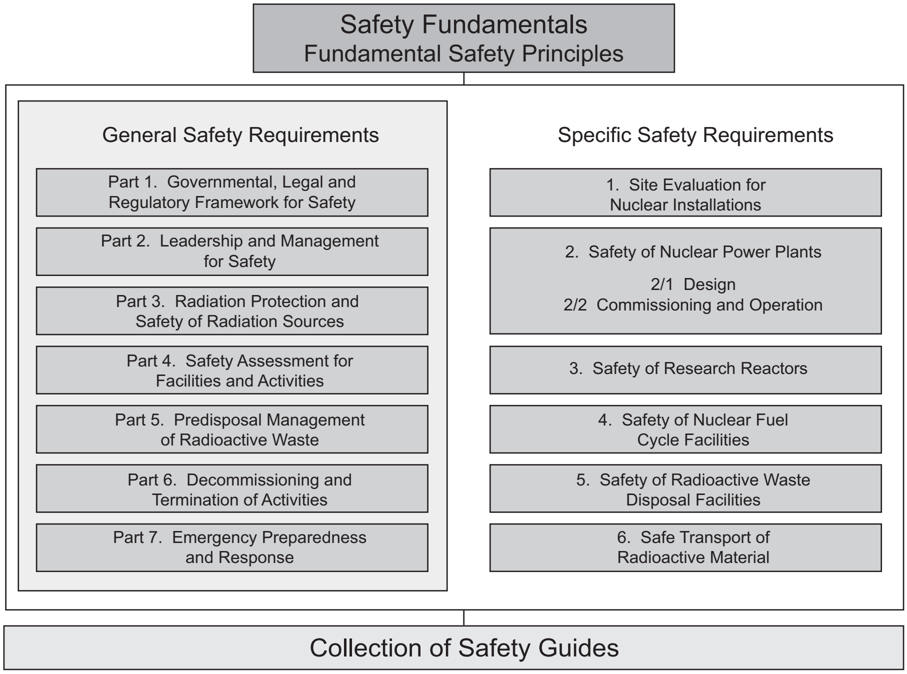

FIG. 1. The long term structure of the IAEA Safety Standards Series.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as 'should' statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and four safety standards committees, for nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and

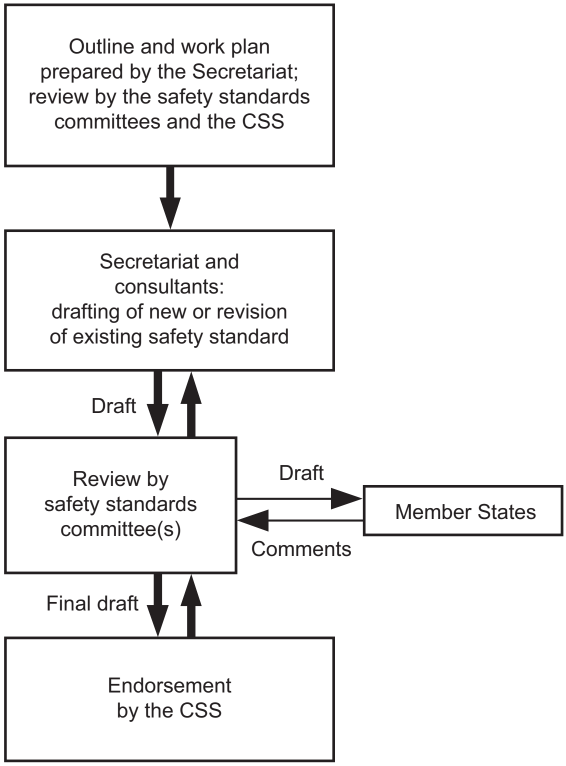

FIG. 2. The process for developing a new safety standard or revising an existing standard.

includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards. It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Safety Glossary (see http://www-ns.iaea.org/standards/safety-glossary.htm). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. The IAEA Safety Fundamentals publication Fundamental Safety Principles [1] establishes the safety objective and safety principles for the protection of people and the environment from harmful effects of ionizing radiation. Principle 10 states that: “Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.” One type of situation covered by this principle is exposure due to natural sources of radiation, including exposure due to radon[1] in dwellings and workplaces, and external gamma exposure due to radionuclides of natural origin in building materials.

1.2. The IAEA Safety Requirements publication Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (GSR Part 3) [2] specifies requirements for the protection of people against exposure to ionizing radiation (hereinafter termed radiation) and for the safety of radiation sources. IAEA Safety Standards Series No. GSR Part 3, the requirements of which are based on information on the detrimental effects attributed to radiation exposure provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [3] and the recommendations of the International Commission on Radiological Protection (ICRP) [4] are intended to provide the basis for the regulation of radiation protection.

1.3. Protection of the public, as specified in GSR Part 3, has always been part of the radiation protection requirements. However, there has been relatively little guidance provided specifically on the protection of the public against exposure due to natural sources of radiation. This Safety Guide is intended to fill that gap by focusing on the identification and implementation of appropriate measures for protection of members of the public against exposure indoors due to natural sources of radiation. Exposure indoors is usually higher than exposure outdoors, but is more readily controllable.

1.4. In Publication 103 [4], the ICRP specifically addresses public exposure indoors due to radon as an area where recommendations are necessary on the application of the requirements for radiation protection. In Publication 65 [5],

[1] In this Safety Guide, as in GSR Part 3, the term ‘radon’ is used to mean any combination of the two main isotopes of the element radon (^{222}Rn and ^{220}Rn).

the ICRP presents its recommendations for action levels in existing dwellings, new dwellings and aboveground and underground workplaces, as well as its recommendations for identifying radon prone areas, and for applying preventive measures and corrective actions. In its Statement on Radon in 2009 [6], the ICRP suggests an annual effective dose of around 10 mSv from ^{222}Rn as a level at which action would almost certainly be warranted to reduce exposure. The ICRP, taking account of the new findings, revised the upper value for the reference level for radon gas in dwellings from 600 Bq/m^3 — the value suggested in its 2007 Recommendations — to 300 Bq/m^3.

1.5. The World Health Organization (WHO) addressed public health aspects of exposure indoors due to ^{222}Rn [7] by reflecting the epidemiological evidence that public exposure indoors due to ^{222}Rn is responsible for a substantial number of lung cancers in the general population. The WHO Handbook on Indoor Radon provides detailed recommendations on reducing health risks due to ^{222}Rn as well as policy options for preventing and reducing ^{222}Rn exposures. The WHO proposes a reference level of 100 Bq/m^3 to minimize health hazards of exposure indoors due to ^{222}Rn, adding that “if this level cannot be reached under the prevailing country specific conditions, the chosen reference level should not exceed 300 Bq/m^3”.

1.6. In Publication 82 [8], the ICRP addresses exposure due to gamma emitting radionuclides of natural origin in building materials and in the ground. The ICRP recommends a reference level of dose of around 1 mSv from a dominant type of commodity amenable to control by intervention — such as some building materials — which could in some circumstances be a significant cause of prolonged exposure. The ICRP recommends that concerned national and, as appropriate, relevant international organizations should derive reference levels for commodities, in particular for specific building materials.

1.7. The exposure of members of the public due to radionuclides of natural origin in food is generally low and is not usually amenable to control. If the concentration of radionuclides of natural origin in foodstuffs is enhanced, such as by discharges from the operation of a facility or from an activity, this is subject to the requirements for planned exposure situations. Guideline levels for radionuclides in foods traded internationally and destined for human consumption have been published by the Joint FAO/WHO Codex Alimentarius Commission [9], for foods that could have been contaminated following a nuclear or radiological emergency.

1.8. The presence of radionuclides of natural origin in drinking water has been addressed by the WHO in the most recent revision of its guidelines for drinking water quality [10]. The WHO has outlined an approach to controlling the ingestion of both radionuclides of natural origin and radionuclides of artificial origin in drinking water by using screening levels. It also sets out an approach to controlling the inhalation of radon released from drinking water into indoor air.

OBJECTIVE

1.9. This Safety Guide provides recommendations on meeting the requirements of Ref. [2] for exposure of the public indoors due to natural sources of radiation. Guidance is provided on the application of the requirements for justification and optimization of protection by national authorities when considering control of natural sources of radiation such as radon indoors and radionuclides of natural origin in building materials.

SCOPE

1.10. The scope of this Safety Guide covers exposure of the public indoors due to natural sources of radiation. It provides recommendations and guidance to be followed by the regulatory body and all other authorities and organizations with responsibilities in relation to exposure to radiation from natural sources (hereinafter referred to as the 'national authority' and defined in para. 2.3) in meeting the requirements of Ref. [2]. Specifically, the recommendations and guidance cover the following:

(a) Public exposure due to ^{222}Rn in dwellings and other buildings with high occupancy factors for the public. This includes buildings such as kindergartens, schools and hospitals. High total occupancy by individuals (Ref. [1], para. 3.23) as well as high occupancy factors need to be considered. The exposure pathways considered are: ingress of ^{222}Rn from the soil; ^{222}Rn released from building materials used in the construction of the dwelling; and ^{222}Rn entering the dwelling via the water supply.
(b) Public exposure due to ^{220}Rn in dwellings. The exposure pathways considered are: ^{220}Rn released from soil, and ^{220}Rn released from building materials used in the construction of the dwelling. Radon-220 entering the dwelling via the water supply is seldom a source of significant radiation exposure.

(c) Public exposure to external gamma radiation from radionuclides of natural origin in the soil and in building materials. ‘Building materials’ are construction materials that are used for the construction of buildings such as dwellings, and offices, industrial premises and other workplaces.

1.11. This Safety Guide does not cover the following:

(a) Exposure due to ^{40}K in the body and exposure due to cosmic radiation at the surface of the earth, which are considered not to be amenable to control and are therefore excluded from the scope of Ref. [2] (see Ref. [2], para. 1.42, footnote 7).
(b) Occupational exposure of workers due to natural sources of radiation (see Ref. [2], para. 3.4(a)). Occupational exposure due to ^{222}Rn and ^{220}Rn can take place in workplaces such as offices and factories. The management of such occupational exposure is mentioned in this Safety Guide, but recommendations and guidance are provided in a Safety Guide on occupational radiation protection that is under development [11].
(c) Public exposure due to discharges and public exposure due to the management of radioactive waste arising from natural sources (see Ref. [2], para. 3.4(b)). These public exposures are to be covered in Safety Guides on the regulatory control of radioactive discharges to the environment [12] and on the management of radioactive residues from mining, mineral processing and other NORM related activities [13].
(d) Public exposure to cosmic radiation during airline travel. This is considered not to be amenable to control and it is therefore outside the scope of Ref. [2] and this Safety Guide.
(e) Public exposure due to radionuclides of natural origin in foodstuffs and in drinking water.
(f) Public exposure due to radon in workplaces with low occupancy factors for members of the public, such as offices and factories. Visitors to caves in which guides provide tours for the general public are likely to be exposed to radon for a short period only and this will usually not necessitate control.
(g) Public exposure due to radionuclides of natural origin in construction materials that are used for the construction of infrastructural elements of the built environment such as roads, bridges, dams and sea defences. These do not give rise to significant exposure of the public because of the short time of exposure.

STRUCTURE

1.12. Section 2 provides recommendations and guidance on the governmental, legal and regulatory framework relating to policy development in this area and the role of the national authority. Section 3 gives an overview of exposures arising from ^{222}Rn and ^{220}Rn and provides recommendations and guidance on approaches to their management. Section 4 provides recommendations and guidance on the regulatory approach for controlling exposure to gamma radiation emitted by building materials.

1.13. Six annexes provide further guidance, in particular, on radon as the main contributor to exposure due to natural sources of radiation. Annex I provides guidance on surveys of radon indoors. Annex II discusses techniques for the measurement of radon. Annex III provides guidance on construction techniques to prevent the accumulation of radon in new dwellings and other buildings. Annex IV discusses corrective actions to reduce high concentrations of radon in existing dwellings and other buildings. Annex V gives an overview of public information programmes to raise awareness of risks associated with radon. Annex VI provides examples of the application of algorithms for controlling exposure indoors to gamma radiation from radionuclides of natural origin present in building materials.

2. NATIONAL POLICY AND THE ROLE OF THE NATIONAL AUTHORITY

2.1. Reference [14] requires that "The government shall establish an effective system for protective actions to reduce undue radiation risks associated with unregulated sources (of natural or artificial origin) and contamination from past activities or events, consistent with the principles of justification and optimization" (Ref. [14], Requirement 9). Such unregulated sources of natural origin include ^{222}Rn and ^{220}Rn in dwellings and other buildings with high occupancy factors, and radionuclides of natural origin present in building materials.

2.2. Reference [2] requires that "The government shall ensure that existing exposure situations that have been identified are evaluated to determine which occupational exposures and public exposures are of concern from the point of view of radiation protection" (Ref. [2], Requirement 47). For such situations, the government is required to ensure that responsibilities for protection and safety are assigned and appropriate reference levels are established (Ref. [2], para. 5.2).

2.3. The implementation of an effective programme for protection of the public against exposure indoors due to natural sources of radiation could involve several different organizations. In this Safety Guide, the term ‘national authority’ is used to refer collectively to the regulatory body and all the other authorities and organizations with responsibilities in relation to exposure to radiation from natural sources. These organizations can include, but are not limited to, organizations involved in radiation protection and public health policy, public and private bodies specializing in radiation measurements, and bodies that set and implement building standards. Normally, the lead organization should be the organization responsible for radiation protection.

2.4. The national authority should initiate an assessment to determine whether exposure indoors due to natural sources of radiation such as ^{222}Rn, ^{220}Rn and gamma rays in dwellings necessitates the development of strategies for radiation protection measures to reduce exposure.

2.5. Once such an assessment has been performed and if a need for further action has been established, a comprehensive policy should be developed to ensure optimal protection of the public against exposure indoors due to natural sources of radiation.

2.6. The national authority is required to ensure that the protection strategy for the programme to protect the public against exposure indoors due to natural sources of radiation is commensurate with the radiation risks associated with the natural sources of radiation. The national authority is also required to ensure that the protective actions to be taken are expected to yield sufficient benefits to outweigh the detriments associated with taking them, including detriments in the form of radiation risks; i.e. it is required to ensure that the protective actions are justified (Ref. [2], para. 5.7). The national authority is also required to ensure that the form, scale and duration of such protective actions are optimized (Ref. [2], para. 5.8).

2.7. Exposure of the population indoors due to natural sources of radiation is usually dominated by ^{222}Rn. The national authority should determine the extent of ^{222}Rn exposure of the population by undertaking national and regional surveys using national and international standards that describe test methods for ^{222}Rn [15]. Such surveys are also useful to identify areas with higher than average concentrations of ^{222}Rn, often designated as ^{222}Rn prone areas (see paras 3.42–3.45). Surveys of ^{220}Rn exposure (see paras 3.62–3.64) and surveys of exposure to gamma radiation from building materials (see Section 4) may be useful in some circumstances.

2.8. If the results obtained following completion of the actions outlined in para. 2.7 indicate that it is necessary, the national authority should:

(a) Set reference levels for ^{222}Rn and, if considered necessary, for ^{220}Rn for dwellings[2] (see paras 3.35–3.40 and 3.65);
(b) Set national standards for concentrations of radionuclides of natural origin in building materials on the basis of activity concentration levels specified in GSR Part 3 [2] (see Section 4);
(c) Put in place measurement programmes to identify existing dwellings and other buildings with high occupancy factors for the public in which the reference levels for radon are exceeded;
(d) Establish a programme to identify building materials that could lead to exposure of members of the public that is higher than the reference level for building materials;
(e) Develop and put in place a framework for reducing exposure due to ^{222}Rn and ^{220}Rn in existing dwellings and new dwellings and in other buildings with high occupancy factors for the public (see paras 3.23–3.59, 3.65–3.67), and for the control of radionuclides in building materials (see paras 4.17–4.27). This framework should include approaches to evaluate the success of programmes for reducing concentrations of ^{222}Rn and ^{220}Rn indoors as well as economic evaluations that take into account the full range of costs associated with the programmes.

2.9. There are situations in which the national authority should consider whether regulation, as a means of controlling or reducing exposure indoors due to natural sources of radiation, would be appropriate. Recommendations and guidance for such situations are provided in Sections 3 and 4. In deciding on the need for regulation, the national authority should take account of the societal and economic consequences to be expected and of the potential difficulties in enforcement. In addition, the requirements for optimization will apply.

[2] The reference level for dwellings also applies to other buildings with high occupancy factors for the public.

3. CONTROL OF EXPOSURE INDOORS DUE TO RADON

GENERAL

3.1. Three radioactive isotopes of radon occur naturally in significant quantities: ^{222}Rn, ^{220}Rn and ^{219}Rn. Radon-222 has a half-life of 3.82 days and is derived from the natural radioactive decay chain headed by ^{238}U. Radon-220 has a half-life of 55.6 seconds and is derived from the natural radioactive decay chain headed by ^{232}Th. Radon-219 has a half-life of 3.96 seconds and is derived from the natural radioactive decay chain headed by ^{235}U. Owing to its short half-life and the usually low concentrations of ^{235}U in soils, the dose from exposure due to ^{219}Rn is negligible and is therefore not of radiological concern.

3.2. The radionuclides that give rise to ^{222}Rn and ^{220}Rn may be present in the environment naturally or as a result of past practices, or as a combination of both. In terms of the protection to be provided, no differentiation is made between these different causes of exposure. However, when action is required to reduce exposure, different approaches should be considered, depending on the exposure pathway.

EXPOSURE DUE TO ^{222}Rn

Origin and concentrations of ^{222}Rn indoors

3.3. Radon-222 is potentially the most significant source for radiation exposure indoors, because its half-life is long enough to allow it to accumulate indoors and because ^{238}U can be present in relatively high concentrations in the ground. Radon-222 is constantly released from the ground as a result of the radioactive decay of ^{226}Ra. When ^{222}Rn is released into the open air, it is quickly diluted to harmless concentrations. Typical concentrations of ^{222}Rn outdoors are 10 Bq/m^3 [16], although a range of long term average concentrations from 1 Bq/m^3 to in excess of 100 Bq/m^3 have been reported [17].

3.4. In the great majority of cases, the main origin of ^{222}Rn indoors is the ground underneath a building. Building materials can also be an origin of ^{222}Rn indoors, though usually they are a much less significant origin than the ground.

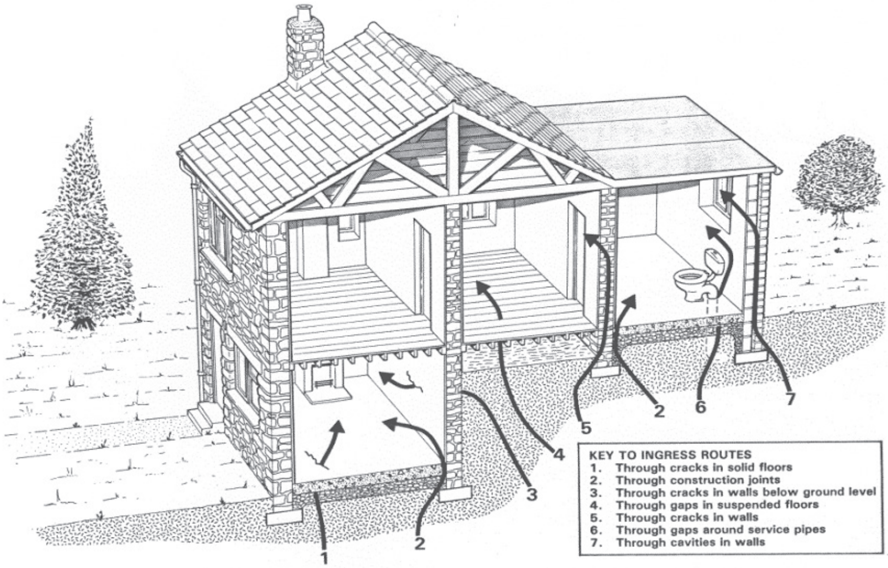

FIG. 1. Radon access routes (image courtesy of the Building Research Establishment (BRE), United Kingdom; reproduced with permission).

In some cases ^{222}Rn is carried indoors in the water supply and released when water is used.[3]

3.5. The air pressure at ground level in most buildings is slightly lower than the outdoor air pressure, as the indoor air is usually warmer. This causes air from the ground to be drawn into buildings, carrying ^{222}Rn with it. The access routes are principally gaps between floors and walls, cracks in floors and gaps around pipes and cables (see Fig. 1). There are seasonal variations in the indoor ^{222}Rn levels which correspond to variations in the average outdoor temperature (i.e. the ^{222}Rn levels in winter are usually higher than the levels in summer).

3.6. The distribution of concentrations of ^{222}Rn indoors in dwellings is very wide, typically covering several orders of magnitude. Distributions of concentrations of ^{222}Rn are often found to be log-normal, or close to log-normal, within a State or within a region of a State. In some instances, dwellings may have such high

[3] Criteria for controlling exposure due to radon in drinking water can be found in Section 9 of the current WHO Guidelines for Drinking-water Quality [10].

concentrations of ^{222}Rn that the radiation doses received by the residents far exceed the annual dose limits that apply for occupational exposure.

3.7. The population weighted worldwide arithmetic mean concentration of ^{222}Rn of all origins in dwellings is estimated to be 39 Bq/m^3 [16].

3.8. Emanation of ^{222}Rn from the radium present in building materials will also contribute to the concentration of ^{222}Rn indoors. The relative contribution from building materials is generally more important where the total concentration of ^{222}Rn indoors is low. Radon-222 released from building materials is rarely the dominant contributor to high concentrations of ^{222}Rn indoors.

3.9. Calculations made for a model masonry house indicate that emanation of ^{222}Rn from building materials contributes, on average, about 10 Bq/m^3 to the concentration of ^{222}Rn indoors [17]. This represents approximately 25% of the worldwide average concentration of ^{222}Rn indoors. In the European Union, the typical contribution from building materials to concentrations of ^{222}Rn indoors is estimated to be in the range of 10–20 Bq/m^3 [18], corresponding to an annual individual effective dose in the range 0.3–0.6 mSv. In the USA, the contribution from building materials to concentrations of ^{222}Rn indoors is estimated to be in the range of 4–7 Bq/m^3 [19].

3.10. In some exceptional cases, the contribution of ^{222}Rn emanating from building materials to the concentration of ^{222}Rn indoors may be up to 1000 Bq/m^3 or higher [18]. In such cases, the corresponding effective dose rate from gamma radiation indoors is highly likely to exceed the maximum value of the reference level for building materials of about 1 mSv/a as specified in para. 5.22 of Ref. [2]. This is discussed in greater detail in para. 3.55 and in Section 4. Radon-222 emanation from building materials can also be controlled.

3.11. Surface waters usually contain ^{222}Rn in very low concentrations. Elevated concentrations of ^{222}Rn can be found in water drawn from groundwater and from private supplies. The contribution of ^{222}Rn from drinking water to the total concentration of ^{222}Rn indoors is not constant as emanation occurs only while water is being discharged through taps or showers. For this reason, ^{222}Rn released from water is seldom the dominant origin of ^{222}Rn in high concentrations indoors, although high concentrations may occur in the short term. The ingestion of water containing ^{222}Rn is also a potential exposure pathway. Information on reducing high concentrations of ^{222}Rn in drinking water supplies can be found in the WHO Guidelines for Drinking-water Quality [10].

3.12. It has been reported by UNSCEAR [3] that inhalation of ^{222}Rn released from drinking water contributes, on average, 90% of the estimated dose due to ^{222}Rn in drinking water. In addition, the average effective dose from inhalation of ^{222}Rn released from drinking water into air indoors is approximately 0.025 mSv/a, compared with an average total effective dose due to inhalation of 1.1 mSv/a from ^{222}Rn of all origins and its decay products [3, 17][4]. Therefore, while inhalation is the dominant pathway by which exposure due to ^{222}Rn present in drinking water can occur, the average doses received are usually only a small fraction of the doses from ^{222}Rn indoors of other origins. However, for households with a water supply from deep drilled wells in uranium rich bedrock, the household water supply can be the most important contributor to elevated concentrations of radon in air indoors, giving rise to individual doses of several millisieverts [20, 21].

Provision of information on radon

3.13. Requirement 50 of Ref. [2] states that: "The government shall provide information on levels of radon indoors and the associated health risks and, if appropriate, shall establish and implement an action plan for controlling public exposure due to radon indoors."

3.14. The requirement to provide public information applies irrespective of whether or not radon measurements are being carried out or are planned. Examples of the type of material to be provided include: generic information on the distribution of radon worldwide and its variability; scientific evidence on the health risks arising from long term exposure due to radon indoors, including the synergistic relationship between exposure due to radon and inhalation of tobacco smoke; the basics of preventing the accumulation of radon in new buildings and of implementing corrective actions to reduce high concentrations of radon in existing buildings; the relationship between policy on radon and policy on the quality of indoor air; and the possible conflict between provisions for energy saving and protective actions for radon. Where reliable data exist in the State on concentrations of radon indoors, such information should be made available

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[4] Reference [17] sets out the calculation of the total inhalation dose from ^{222}Rn. The calculation assumes equilibrium factors for ^{222}Rn of 0.4 indoors and 0.6 outdoors, an average activity concentration for ^{222}Rn indoors of 40 Bq/m^3 and an average activity concentration for ^{222}Rn outdoors of 10 Bq/m^3, an occupancy factor per year of 7000 hours indoors and 1760 hours outdoors, and a dose conversion factor of 9 nSv/(Bq·h·m^{-3}) for equivalent equilibrium concentration.

to the public. Ideally, information should be made available on-line so that it can be accessed and downloaded by interested parties.

3.15. There is a well established synergy between lung cancer from smoking and radon exposure. Smokers and more recent ex-smokers have a much higher baseline risk of lung cancer than lifelong non-smokers. Radon exposure increases this risk still further. It is therefore appropriate for the national authority to consider these combined risks when providing information and advice about radon, and to coordinate with national tobacco control programmes [7].

3.16. Prior to carrying out radon measurement surveys, the national authority should prepare and distribute information of interest to householders, in particular to those householders who may be invited to participate in such surveys. This should include general information on the risks from radon as well as information on how the radon measurements will be carried out and how the results will be communicated to householders. Issues of the confidentiality of householders' radon measurements should also be covered. If a reference level has already been set, this should also be explained. In particular, it should be explained how concentrations of radon above the reference level can be reduced.

3.17. If a national policy to control public exposure due to radon needs to be developed, the national authority should prepare information and make it available to all interested parties. This includes decision makers, medical practitioners, building professionals (including architects, engineers, quantity surveyors and builders) and the public. Since the national authority may consist of a number of different agencies and government departments, each of which is responsible for different aspects of the national policy, there should be close coordination to ensure that all information provided is clear and consistent. Decision makers at both national level and local level should be kept fully informed.

Surveys of radon indoors

3.18. The government is required to ensure that "Information is gathered on activity concentrations of radon in dwellings and other buildings with high occupancy factors for members of the public through appropriate means, such as representative radon surveys" (Ref. [2], para. 5.19(a)). As a first step in evaluating the extent of measures that may be necessary for controlling public exposure indoors due to radon, the national authority should review any existing data on concentrations of radon indoors, in particular, measurements made in those areas of the State where high concentrations of radon indoors might be expected. This includes regions where the local geology indicates that there might be elevated concentrations of uranium in the soil and regions of karstic limestone in which underground waters might contain elevated concentrations of radon originating from mineral deposits. In addition, high concentrations of radon indoors might be expected in areas where soil permeability is exceptionally high (such as eskers or ridges composed of permeable gravel), even when the uranium concentration in the soil is not elevated.

3.19. If no such data are available, the national authority should consider organizing localized surveys. In deciding on the areas where such surveys might be initiated, in addition to the geological criteria indicated in para. 3.18, the national authority should also evaluate the available information on concentrations of radon indoors in neighbouring States. The benefit of carrying out such localized surveys is that they might assist in making decisions about the sampling density necessary for a national survey. For example, if high concentrations of radon indoors have been identified and there are known to be many other areas with similar geological features within the State, a high density of measurements in the national survey would be justified. On the other hand, if only low concentrations of radon indoors have been identified in areas where high concentrations of radon indoors might be expected, a lower density of measurements in the national survey may suffice.

3.20. Even if a review of the existing data and the outcomes of localized surveys initiated by the national authority do not reveal elevated concentrations of radon indoors, the national authority should still evaluate the degree to which the population is exposed. Such an evaluation is referred to as a national radon survey. There are two principal considerations in undertaking a national radon survey:

(a) To identify areas where a greater proportion of homes are expected to have high concentrations of radon indoors. This can be achieved by carrying out a geographically based survey. The results can be used to develop maps for the risks due to radon and to identify radon prone areas (see Annex II).
(b) To estimate the average exposure of the population due to radon, and the range of exposures occurring, for purposes of comparison with exposures due to other sources of radiation. The most appropriate basis for this is a national survey of concentrations of radon indoors in randomly selected dwellings, with account taken of population density [5].

3.21. With careful consideration, a single survey can be designed to address both 3.20(a) and (b) simultaneously. Measurements for such surveys should be carried out over a period of several months, and ideally over a period of one year, in each dwelling surveyed, to minimize uncertainties [22]. The results obtained will define the levels of radon exposure and will provide the basis for future decisions on the development and implementation of a national policy to control public exposure due to radon. Collectively, the various components of such a policy are referred to as an action plan (see paras 3.23–3.59).

3.22. The surveys described above will show the variation in the concentrations of radon in dwellings, irrespective of the origin of the radon. In the great majority of cases, the radon will originate in the ground underneath dwellings, but in some cases, it will originate in the building materials or in the water supply. The national authority should carry out separate surveys to identify and investigate situations in which radon from building materials or from the water supply could make a significant contribution to the concentration of radon in indoor air.

Action plan on radon

General considerations

3.23. "Where activity concentrations of radon that are of concern for public health are identified…, the government shall ensure that an action plan is established comprising coordinated actions to reduce activity concentrations of radon in existing buildings and in future buildings" (Ref. [2], para. 5.20). Such an action plan should be implemented by the national authority and would require the national authority to do the following:

(a) To establish "an appropriate reference level for ^{222}Rn for dwellings and other buildings with high occupancy factors for members of the public" (Ref. [2], para. 5.20(a)).
(b) To decide which other types of buildings with high occupancy factors for members of the public, such as kindergartens, schools and hospitals, are included in the scope of the action plan for radon.
(c) To establish an appropriate reference level for ^{222}Rn for workplaces such as offices and factories.
(d) To facilitate the measurement of ^{222}Rn in dwellings and other buildings with high occupancy factors for the public.
(e) To identify ^{222}Rn prone areas.
(f) To give "priority to actions to reduce activity concentrations of ^{222}Rn in those situations for which such action is likely to be most effective" (see Ref. [2], para. 5.20(c)). This should include measures to reduce concentrations of ^{222}Rn in drinking water supplies and to control the radium content of building materials, where appropriate.

(g) To include “in building codes appropriate preventive measures and corrective actions to prevent the ingress of ^{222}Rn and to facilitate further actions wherever necessary” (see Ref. [2], para. 5.20(d)).
(h) To implement measures to control and reduce exposure due to ^{222}Rn, including determining the circumstances under which such measures are to be mandatory or to be voluntary.
(i) To evaluate the success of the action plan.

Further guidance on the preparation of an action plan on radon can be found in the WHO Handbook on Indoor Radon [7]. Examples of national action plans on radon can be found in Refs [23–26].

3.24. The national authority should ensure that the action plan on radon is closely coordinated with other national programmes for indoor air quality and energy efficiency. For example, the construction of energy efficient homes can result in a lower rate of exchange of air than for existing homes. This could result in either an increase or a decrease in the flow of soil gas (containing ^{222}Rn) into the building, depending on the requirements in national building codes. By improving the thermal efficiency in a building, the higher temperature of the air indoors may result in a decrease in the pressure inside the building and thus may lead to an increased inflow of ^{222}Rn from the soil into the building. Changes in building practices, such as those relating to indoor air quality or energy efficiency, should be investigated with regard to their effects on concentrations of radon indoors and on the performance of corrective actions and preventive measures for radon. Where such changes in building practices could lead to increases in concentrations of radon indoors, consideration should be given to further changes in building practices in the national building codes.

Justification and optimization of strategies for radiation protection measures

3.25. The government and the regulatory body or other relevant authority are required to ensure that corrective actions and protective actions are justified, and to ensure that protection and safety is optimized (Ref. [2], Requirement 48).

3.26. The protection strategy for the programme to reduce concentrations of radon indoors should achieve sufficient individual or societal benefit to offset the detriment that it causes. The responsibility for decisions on justification for implementing radiation protection measures rests with governments or with national authorities.

3.27. Arguments for the justification of radiation protection measures include: radon is a significant cause of radiation exposure and is the second most important cause of lung cancer in the general population after smoking tobacco; feasible techniques are available to reduce high concentrations of radon indoors; policy on radon supports other public health policies such as policy on indoor air quality, when other pollutants are also present, or on smoking [7, 27].

3.28. The optimization of protection below a reference level should be implemented through an ongoing, cyclical process that involves: evaluation of the situation to identify the need for action (framing of the process); identification of the possible protective actions based on the latest technical knowledge to keep exposures as low as reasonably achievable; selection of the best option under the prevailing circumstances; implementation of the selected option; and regular review to evaluate whether the prevailing circumstances necessitate corrective actions [28].

3.29. The optimization process is implemented through the national action plan on radon. The process should be applied to achieve concentrations of radon that are as low as reasonably achievable below the reference level.

3.30. Optimization of protection against exposure due to radon indoors can be carried out using standard cost–benefit techniques. Comparisons can be made between the financial costs associated with the estimated number of cases of lung cancer likely to be due to radon at different levels of exposure, the selection of protective actions, and the costs of preventive measures and corrective actions to reduce exposure due to radon indoors. Such analyses can be used to inform decisions on the cost effectiveness of measures to reduce concentrations of radon in existing buildings and in new buildings [7].

Measurement of concentrations of ^{222}Rn

3.31. Radon measurements in dwellings are required for national and regional surveys, and to determine whether individual dwellings have unacceptably high concentrations of radon [15]. Concentrations of radon can vary greatly between dwellings, so a low or high concentration of radon in one dwelling cannot be taken as a guide to the concentrations of radon in nearby dwellings. Measurements of concentrations of radon can also be carried out to confirm that measures taken to reduce high concentrations of radon have been effective [15]. These measurements could be carried out by the national authority or by other organizations such as technical support organizations, academic institutions or private companies, or by a combination of these.

3.32. For radon measurements in dwellings and other buildings with high occupancy factors for the public, the national authority should specify:

(a) The minimum measurement period;
(b) Quality standards for radon detectors;
(c) The measurement protocols to be applied;
(d) Whether measurements should be limited to certain seasons;
(e) Whether or not seasonal correction factors should be applied to the results;
(f) Quality standards for reporting results to owners of the dwellings and other buildings with high occupancy factors for the public;
(g) The advice that should be offered to owners of dwellings and other buildings with high occupancy factors for the public that have concentrations of radon in excess of the reference level.

These criteria may vary depending on the purpose for which the radon measurements are intended. Measurement techniques for radon are dealt with in Annex II.

3.33. The national authority should ensure that a quality management system is in place to ensure a high degree of confidence in the results of radon measurements. All organizations that make radon measurements should be required to demonstrate their competence to measure radon levels accurately and should participate regularly in intercomparison exercises [29].

3.34. If a private company makes radon measurements, provision should be made, if possible, to make the results available to the national authority. The national authority has overall responsibility for the formulation of policy on radon, and it could use the data from radon measurements to identify radon prone areas. Issues of the confidentiality of householders' radon measurements should be considered.

Setting a reference level for ^{222}Rn

3.35. Once public exposure due to ^{222}Rn has been assessed through appropriate surveys, it should be determined whether the activity concentrations of radon are of concern for public health. If so, the national authority is required to select and formally adopt a reference level for ^{222}Rn for dwellings and other buildings with high occupancy factors for members of the public. GSR Part 3 [2] (para. 5.20(a)) requires that an appropriate reference level is established with account taken of the prevailing social and economic circumstances that in general will not exceed an annual average activity concentration due to ^{222}Rn of 300 Bq/m^3.[5] The reference level should be applied to dwellings and to other buildings with a high occupancy factor for members of the public.

3.36. In its Handbook on Indoor Radon [7], the WHO proposes a reference level of 100 Bq/m^3 to minimize health hazards due to ^{222}Rn exposure indoors, stating that "if this level cannot be reached under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq/m^3".

3.37. When setting a reference level, the national authority should consult interested parties. Reference levels should be selected such that the resulting activities are seen to be practicable and manageable. For example, it would be impractical to set a reference level such that corrective actions would be necessary for the majority of existing dwellings. The percentages of dwellings that would require corrective actions under different reference levels should be considered in the choice of an appropriate reference level.

3.38. Reference levels should not be seen as a dividing line between safety and harm. Rather, they should be used as guidance values which, once exceeded, should prompt the consideration of possible actions to lower exposure due to ^{222}Rn. The national authority could decide to compare risks associated with ^{222}Rn with other everyday risks.

3.39. Most national authorities establish a single reference level for both existing dwellings and other buildings with high occupancy factors for members of the public and for new dwellings and other buildings with high occupancy factors for members of the public, on the grounds of simplicity and consistency. In some cases, national authorities have set a lower reference level for new dwellings and other buildings with high occupancy factors for members of the public than for existing dwellings and other buildings with high occupancy factors for members of the public. In general, it is more cost effective to achieve low concentrations of ^{222}Rn in new dwellings than in existing dwellings and it is easier to take the necessary measures.

3.40. GSR Part 3 [2] requires that the reference level for dwellings and other buildings with high occupancy factors for members of the public in general will not exceed an annual average activity concentration due to ^{222}Rn

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[5] On the assumption of an equilibrium factor for ^{222}Rn of 0.4 and an annual occupancy rate of 7000 hours, the value of activity concentration of 300 Bq/m^3 corresponds to an annual effective dose of the order of 10 mSv.

of 300 Bq/m^3. If national data indicate that in a given State either the equilibrium factor or the occupancy factor are significantly different from the assumed values, then a reference level higher than 300 Bq/m^3 might be appropriate, provided that an annual effective dose of the order of 10 mSv is not exceeded. However, such a decision should be based on the situation in the State as a whole, and should only be taken in exceptional circumstances. It is not appropriate to set different reference levels for different regions within the same State as it can lead to practical difficulties.

3.41. In buildings with low occupancy factors by members of the public, such as offices, shops and public libraries, exposure of both workers and the public is managed by controlling occupational exposure. Information on managing exposure to radon in such workplaces is provided in the box on page 21.

Radon prone areas

3.42. When radon maps have been developed (see Annex I), it is possible to identify those areas where concentrations of ^{222}Rn are likely to be higher than average. These areas are often designated as being 'radon prone'[6]. The highest individual concentrations of ^{222}Rn will tend to be found in areas with the highest average concentrations of ^{222}Rn. There will also be dwellings with concentrations of ^{222}Rn above the reference level outside specified radon prone areas.

3.43. The national authority should define radon prone areas within its territories and it should consider specific measures to be applied within these areas. Various definitions of radon prone areas have been proposed. The ICRP [5] suggested that radon prone areas could be defined as those where more than a certain percentage of dwellings have a concentration of ^{222}Rn exceeding ten times the national average value. Some States define radon prone areas as those areas for which it is estimated that more than a certain percentage of dwellings are predicted to have concentrations of ^{222}Rn exceeding the reference level. Once decided, the definition of a radon prone area should not be changed without serious consideration; however, the areas so designated should be amended as more information becomes available.

3.44. An alternative approach to protection against radon exposure indoors for new buildings is based on direct in situ measurements of ^{222}Rn in soil gas and of soil permeability. Preventive measures are then designed with regard to the

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[6] In some States, such areas are referred to as 'high radon areas' or 'radon affected areas'.

measured properties of the soil at a given building area and the design of the building. Simple low cost sampling and measurement methods are available for this purpose. This approach has been used in the Czech Republic since 1991 [30, 31].

3.45. The concept of radon prone areas is a tool for use by the national authority and it can be used in various ways. For example, the national authority should consider how the identification of radon prone areas can be used in publicizing the risks from exposure due to ^{222}Rn and in encouraging householders to have radon measurements carried out. In addition, in radon prone areas the national authority should require the use of building techniques that will minimize ^{222}Rn entry and will facilitate post-construction removal of ^{222}Rn should it become necessary. In certain circumstances, it may be cost effective to introduce building techniques that will minimize ^{222}Rn entry in all areas, especially if other air quality issues are also considered. Details are provided in Annexes III and IV.

Control and reduction of exposure due to ^{222}Rn

3.46. The national authority is required to ensure that a protection strategy defines the objectives to be achieved (Ref. [2], para. 5.4(a)). One objective that should be achieved by means of the protection strategy is to identify those dwellings with concentrations of ^{222}Rn above the reference level and to reduce their concentrations of ^{222}Rn. The second objective that should be achieved is to reduce average concentrations of ^{222}Rn in dwellings. Average concentrations of ^{222}Rn can be significantly reduced only by introducing building codes and adopting practices in the construction of new dwellings that limit the ingress of ^{222}Rn into the dwellings. Such changes will, over a period of time, reduce average concentrations of ^{222}Rn and consequent exposures, and reduce the public health impacts of radon.

3.47. The national authority is required to arrange for “evaluation of the available remedial actions and protective actions for achieving the objectives” (Ref. [2], para. 5.5(a)). The availability of control measures that are effective, reliable, cost effective and relatively easy to take is an essential component of any action plan on radon. The national authority should establish requirements that will ensure that the companies providing services for reducing activity concentrations of radon indoors are knowledgeable in their field and that their work will meet the needs of their clients. The effectiveness of all techniques should be tested and proven under realistic working conditions and their long term effectiveness should be evaluated. The national authority should consider the development of an authorization process or certification process for companies offering services for reducing exposure due to radon. Corrective actions to reduce activity concentrations of ^{222}Rn in existing dwellings are discussed in Annex IV.

3.48. The government is required to determine “the circumstances under which actions are to be mandatory or are to be voluntary, with account taken of legal requirements and of the prevailing social and economic circumstances” (Ref. [2], para. 5.21(b)).

MANAGING RADON IN WORKPLACES WITH LOW OCCUPANCY BY THE PUBLIC

For workplaces such as offices and factories in which exposure to radon is not managed as a planned exposure situation, the national authority is required to set a reference level for ^{222}Rn that does not exceed an annual average activity concentration of ^{222}Rn of 1000 Bq/m^3 (Ref. [2], para. 5.27). The criteria for choosing the value of the reference level are the same as those that apply to dwellings and the value chosen should be based on an evaluation of the distribution of concentrations of ^{222}Rn in such workplaces. The national authority should also define the measurement criteria for workplaces in the same manner as outlined in para. 3.32 for dwellings.

A different approach to controlling ^{222}Rn exposure in workplaces is to set the same reference level for all indoor environments, i.e. the same reference level would apply to all dwellings, other buildings with high occupancy factors for members of the public and workplaces [27]. Such an approach is only appropriate if the distribution of ^{222}Rn indoors in workplaces is similar to that in dwellings, which may or may not be the case. Nevertheless, the national authority could consider whether this approach is appropriate and can be implemented.

In situations where the reference level for workplaces is exceeded, the employer is required to take all reasonable steps to reduce the concentration of ^{222}Rn to below the reference level (Ref. [2], para. 5.28). One approach is to limit the number of hours spent by workers in specific areas, but this can be difficult to achieve and to monitor. In some specific workplaces, such as underground caves, changes to the rate of ventilation may reduce the concentration of ^{222}Rn, but such changes may have unacceptable consequences associated with them (e.g. ancient hand-painted wall murals may be damaged or sites of touristic interest such as show caves may be destroyed). If, for whatever reason, it is not possible to reduce concentrations of ^{222}Rn below the reference level, the national authority is required to ensure that workers are protected by applying the relevant requirements for occupational exposure (Ref. [2], para. 5.27). in planned exposure situations using a graded approach.

Guidance on the protection of workers is provided in Ref. [11].

3.49. In line with the application of a graded approach, the action plan on radon should include provisions giving priority to carrying out corrective actions on dwellings with activity concentrations of ^{222}Rn that greatly exceed the reference level over dwellings with activity concentrations of ^{222}Rn that are marginally above the reference level, and it should set a timescale for such work. The ICRP [8] has stated that an existing annual dose rising towards 100 mSv would almost always justify intervention. The national authority should consider requiring corrective actions for ^{222}Rn to be mandatory for those dwellings and other buildings with high occupancy factors where the activity concentrations of ^{222}Rn are likely to give rise to an annual dose of greater than 100 mSv.

3.50. Decisions on whether or not to reduce activity concentrations of ^{222}Rn that are above the reference level are usually left to owners of dwellings who, in most States, would also have to pay for corrective actions. The costs of the actions could deter owners of dwellings from taking corrective actions to reduce their exposure due to ^{222}Rn. The government may consider the possibility of reimbursing the owners of dwellings for part or all of the costs of corrective actions, in particular owners of those dwellings with very high activity concentrations of ^{222}Rn. If such financial support is provided, a provision for follow-up measurements to assess the effectiveness of the corrective actions should be included in the financial support agreements.

3.51. In the case of rental accommodation, the national authority should consider setting a mandatory requirement for the owners of dwellings to ensure that activity concentrations of ^{222}Rn are below the reference level. It should be ensured that any requirements in this regard are in compliance with existing legislation in relation to rental accommodation. Furthermore, the national authority should be satisfied that legislation in relation to ^{222}Rn can be implemented in practice.

3.52. The national authority should consider requiring measurements of activity concentrations of ^{222}Rn to be made and, where necessary, corrective actions to be taken at the time of sale of dwellings. A requirement for measurement of activity concentrations of ^{222}Rn at the time of sale of existing dwellings could be beneficial, not only in terms of increasing the number of dwellings measured for ^{222}Rn, but also in ensuring that corrective actions are taken for dwellings with activity concentrations of ^{222}Rn exceeding the reference level. Appropriate protocols and procedures should be developed, consistent with the national legal framework. Guidance for establishing such protocols and procedures can be found for testing methods [22] and for methods for investigations in buildings [15]. In addition, where legislation and prevailing social conditions permit, the national authority should ensure that the banking and insurance sectors are fully involved in the process.

3.53. The national authority should make arrangements for the introduction of building codes and construction practices to prevent the accumulation of ^{222}Rn in new dwellings. Such codes should include requirements for the measurement of ^{222}Rn in new dwellings within 6–12 months following the dwelling being occupied. Compliance with these codes should be mandatory. In deciding whether such building codes are to apply in all areas or only in those areas designated as being radon prone, the national authority should consider the cost effectiveness of preventive measures for ^{222}Rn for new dwellings in comparison with other public health measures. The methods used to prevent ^{222}Rn accumulation in new dwellings are discussed in Annex III.

3.54. The national authority should ensure cooperation with the authorities responsible for the regulation of the planning and construction of buildings when incorporating preventive measures for ^{222}Rn into national building codes. This includes those authorities responsible for addressing other aspects of indoor air quality and energy efficiency. Site inspection forms an important part of building regulation. Such building regulation should include communication with and training of both building inspectors and professionals in the construction industry.

3.55. Those building materials that have most often been found to be significant in terms of emanation of ^{222}Rn are alum shale concretes, volcanic tuffs, granites and phosphogypsum. While it is possible to measure ^{222}Rn emanation from samples of building materials, it is not always straightforward to relate the results of emanation measurements to activity concentrations of ^{222}Rn indoors after construction. Therefore, when studies indicate that it is necessary to do so, the national authority should control the amount of ^{222}Rn emanating from building materials by placing a limitation on their ^{226}Ra content.[7]

3.56. Where radon measurement programmes have indicated the need to reduce the activity concentration of ^{222}Rn in certain drinking water supplies, this should be undertaken in a manner consistent with the recommendations and approach outlined by the WHO [10].

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[7] Studies [18] have shown that when doses due to gamma radiation are limited to levels below 1 mSv/a, the activity concentrations of ^{226}Ra in building materials have to be limited, in practice, to levels that are unlikely to cause activity concentrations of ^{222}Rn indoors to exceed 200 Bq/m^3.

Monitoring the effectiveness of the action plan on radon

3.57. The national authority should assess the effectiveness of its action plan on radon. Radon reduction programmes will not generate immediate public health gains in a population, since the main averted health risk is the risk of lung cancer, with an induction time of up to 35 years. Even in the long term, the saving in lives will not be directly observable, as the reductions in risks will be spread over a very large number of people. For this reason, the success of a radon reduction programme should be estimated on the basis of the reduction of the activity concentrations of radon in dwellings and other buildings with high occupancy for members of the public, which can have additional benefits in terms of improved indoor air quality. Various indicators can be used, for example, the reduction in the number or the percentage of dwellings with activity concentrations of radon above the reference level or the reduction in average activity concentrations of radon in dwellings.

3.58. The numbers of existing dwellings with activity concentrations of radon measured or identified as above the reference level are poor guides to the success of an action plan on radon in saving lives, as many owners of dwellings do not take the advice to reduce concentrations of radon. However, such parameters may be used to set intermediate targets for a radon reduction programme. Other parameters could also be used to set intermediate targets, such as the level of awareness of radon among the public or among construction or medical professionals. The level of awareness may be evaluated on the basis of the number of requests for information or the number of requests for radon measurements to be made, or by means of market research surveys.

3.59. Public awareness of the risks of exposure due to ^{222}Rn is low in many States. However, a radon reduction programme requires the cooperation of the public in order to be successful in reducing high activity concentrations of radon in dwellings. As part of any action plan on radon, the national authority should develop strategies to inform the public about the risks due to radon and about preventive measures and corrective actions. These strategies should also target bodies and professional groups concerned with housing and with public health, such as builders, architects and regional and local government authorities and the medical profession. Details are provided in Annex V.

EXPOSURE DUE TO ^{220}Rn

Origins and concentrations of ^{220}Rn indoors

3.60. Radon-220 has a half-life of 55.6 seconds and radionuclides can only migrate a short distance before decay. For this reason, activity concentrations of ^{220}Rn indoors depend primarily on the emanation of ^{220}Rn from the surface layers of the materials of walls and floors rather than from more distant origins. In particular, earth walls and floors have in some cases been found to be significant origins of ^{220}Rn. The magnitude of the consequent doses will depend on the amount of ^{232}Th present in the soil and in building materials, the rate of emanation of ^{220}Rn and the occupancy factor for the building.

3.61. Data on the activity concentrations of ^{220}Rn and ^{220}Rn progeny in dwellings are extremely limited and are often based on short term measurements. UNSCEAR has estimated that a typical activity concentration of ^{220}Rn progeny in dwellings worldwide is around 0.3 Bq/m^3 equilibrium equivalent concentration[8], corresponding to an annual effective dose of 0.1 mSv [3]. Almost all of this dose can be attributed to the emanation of ^{220}Rn from building materials. Individual results as high as 76 Bq/m^3 equilibrium equivalent concentration have been found. These highest levels of ^{220}Rn equilibrium equivalent concentration indoors are associated with wooden houses and mud houses found in China and Japan in particular and with the use of building materials made from natural volcanic materials in Italy [32–35].

Surveys of ^{220}Rn indoors

3.62. The national authority should initially carry out limited surveys of dwellings in which high activity concentrations of ^{220}Rn would be expected to be found, such as dwellings with earth walls or floors. As with ^{222}Rn, the results of measurements of the emanation of ^{220}Rn from building materials can be difficult to interpret. Where necessary, it is preferable to control the activity concentrations of ^{220}Rn in indoor air by controlling the content of ^{232}Th in building materials.

3.63. There can be a very variable distribution of ^{220}Rn in a room. As ^{220}Rn present in indoor air is produced primarily as a result of emanation from building materials, the highest activity concentrations are likely to be found close

[8] Equilibrium equivalent concentration is the activity concentration of ^{222}Rn and ^{220}Rn in radioactive equilibrium with their short lived progeny that would have the same potential alpha energy concentration as the actual (non-equilibrium) mixture.

to walls containing such building materials. Because of its short half-life, most of the ^{220}Rn will decay before it can migrate. The activity concentration of ^{220}Rn therefore decreases sharply with distance from the building materials and it can be lower by a factor of 100 at a distance of 1 m [32].

3.64. Radon-220 may decay away almost completely indoors while activity concentrations of ^{220}Rn progeny remain significant. Activity concentrations of ^{220}Rn gas are therefore not a reliable guide to the doses delivered by its progeny. Although reliable passive measurement techniques are now available to measure ^{220}Rn gas, they may not provide a reliable estimate of activity concentrations of ^{220}Rn progeny, or therefore of associated doses.[9]

Control and reduction of exposure due to ^{220}Rn

3.65. National authorities in most States will not need to regulate exposure due to ^{220}Rn. In States where high activity concentrations of ^{220}Rn are found in some dwellings, the national authority should consider introducing a reference level for ^{220}Rn. The reference level should be specified in terms of equilibrium equivalent concentration of ^{220}Rn. The guidance given in paras 3.35–3.40 on the setting of a reference level for ^{222}Rn should also be followed in the setting of a reference level for ^{220}Rn.

3.66. Where certain building materials have been found to emit significant quantities of ^{220}Rn, the national authority should consider prohibiting the use of such building materials for the construction of dwellings, consistent with the criteria established in Section 4.

3.67. In cases where high activity concentrations of ^{220}Rn progeny are found in dwellings, the concentrations may be substantially reduced by applying paints or sealants to wall or floor surfaces that emit ^{220}Rn. Occupying areas of a room away from the walls and sleeping on beds raised from the floor are effective in reducing the inhalation of ^{220}Rn.

[9] Of the ^{220}Rn progeny, only ^{212}Pb and ^{212}Bi make a significant contribution to the potential alpha energy concentration [32]. The contribution per becquerel of the parent nuclide ^{220}Rn is nearly three orders of magnitude lower than that of ^{212}Pb. Since the majority of the potential alpha energy concentration is provided by ^{212}Pb, measurement of the activity concentration of ^{212}Pb in air usually allows a good estimate of the potential alpha energy concentration.

4. CONTROL OF EXPOSURE INDOORS DUE TO GAMMA RADIATION

NATURAL SOURCES OF GAMMA RADIATION

4.1. Radionuclides of natural origin such as ^{238}U and its progeny, ^{232}Th and its progeny and ^{40}K are present in soils and in building materials in varying amounts. The two principal exposure pathways for exposure to gamma radiation indoors are from radionuclides in the soil and from radionuclides in building materials. Recommendations and guidance on controlling exposure to gamma radiation via these two exposure pathways are presented in this Section.

4.2. There have been many surveys made to determine the background concentrations of radionuclides in soils [36–38]. The results of these surveys indicate that the gamma emitting radionuclides in the ^{238}U series, ^{232}Th series and ^{40}K make approximately equal contributions to the dose due to external gamma radiation to individuals in typical situations both outdoors and indoors. The median activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the earth's crust are 33, 45 and 410 Bq/kg, respectively [3]. Typical activity concentrations in building materials such as concrete are also relatively close to the activity concentrations in the earth's crust, with values of 40, 30 and 400 Bq/kg for ^{226}Ra, ^{232}Th and ^{40}K, respectively [18].

4.3. The worldwide average annual effective dose from external exposure due to terrestrial natural sources of radiation is 0.48 mSv, with 0.41 mSv relating to exposure indoors (assuming an occupancy factor of 80%) and 0.07 mSv relating to exposure outdoors (assuming an occupancy factor of 20%) [3]. National average values of annual effective dose from external exposure due to terrestrial natural sources of radiation are mostly in the range of 0.3 to 0.6 mSv.

4.4. The nature of radiation exposure for people living or working in a building differs in comparison with exposure outdoors. The shielding provided by the building will decrease exposure due to radionuclides in soil. However, radionuclides of natural origin that are present in building materials will increase the dose rate due to gamma radiation inside the building. The building will also shield the occupants from cosmic radiation, but this effect is generally small. According to UNSCEAR, the worldwide average dose rate due to gamma radiation is 1.4 times higher indoors than outdoors, with regional ratios ranging from 0.8 to 2.0 [3].

4.5. Concrete is one of the most commonly used building materials. The variation in concentrations of radionuclides of natural origin in concrete will depend on the types of ballast materials and chemical additives used in its manufacture. Commonly used ballast materials are sand, gravel and shingle, which do not usually enhance the radioactive content of the concrete. There are also other ballast materials used, however, such as pumice stone, with a high activity concentration of ^{226}Ra, and granite, which often has a high activity concentration of both ^{40}K and ^{238}U. The use of these ballast materials can and does enhance the radioactive content of the concrete.

4.6. Aerated, or lightweight, concrete consists mainly of the same materials as ordinary concrete, but a small quantity of aluminium powder is added to create the cell structure in the final product. Alum shale, which has been used in the past as ballast material in ordinary and aerated concrete, has a particularly high activity concentration of ^{226}Ra. The activity concentration of ^{226}Ra in aerated concrete made using alum shale is up to 2600 Bq/kg [18].

4.7. Industrial by-products and residues are sometimes used in the manufacture of building materials. Materials used include fly ash (from the burning of coal and peat), blast furnace slag and phosphogypsum. These materials may have enhanced concentrations of radionuclides of natural origin through concentration processes taking place during the generation of the residues [3].

4.8. Natural building materials such as granite and marble have high concentrations of ^{226}Ra and granite may also have a high concentration of both ^{232}Th and ^{40}K [3].

4.9. Soils containing extremely high concentrations of radionuclides of natural origin have been identified in some parts of the world [3]. For example, in parts of Azerbaijan, Brazil, China, the Czech Republic, Egypt, India, Indonesia, Italy and Romania, the presence of elevated concentrations of radionuclides of natural origin in soil gives rise to annual effective doses from gamma radiation of several mSv. The annual effective doses can exceed 10 mSv in some parts of the Czech Republic, the Islamic Republic of Iran and Spain [3]. In such places, the soil may be the principal cause of exposure to gamma radiation of the population.

METHODS FOR THE MEASUREMENT OF GAMMA RADIATION

4.10. The choice of measurement technique depends on whether one wishes to measure only the total gamma radiation exposure outdoors or in a building, or to identify and quantify the radionuclides present in a building material giving rise to exposure of this type [38].

4.11. Gamma dose rates indoors are usually measured directly using a Geiger–Müller counter, an ionization chamber or a scintillation counter. Alternatively, integrated measurements can be made in dwellings by using thermoluminescent glass dosimeters or detectors. The operation and relative merits of these types of detector are discussed in more detail in Ref. [39].

4.12. Detection and quantification of the presence of specific radionuclides is usually made by laboratory analysis of representative samples. Gamma spectrometry is the preferred test method, using either a sodium iodide or a germanium detector. Hyperpure germanium (HPGe) detectors are now commonly used in test laboratories or by those in charge of in situ measurements in dwellings [38, 40, 41].

SURVEYS OF GAMMA RADIATION

4.13. The national authority should use the data generated in surveys of levels of outdoor gamma radiation to identify areas where radionuclides of natural origin in the soil could make a significant contribution to the exposure of building occupants to gamma radiation indoors. Where there are only limited data available on levels of gamma radiation outdoors, the national authority should make arrangements for a survey to be carried out.

4.14. The national authority should use the data generated in surveys of the levels of radionuclides of natural origin in building materials to identify those radionuclides that may make a significant contribution to exposure to gamma radiation indoors. Where there are only limited data available on levels of radionuclides in building materials, the national authority should make arrangements for a survey to be carried out, and/or it should require manufacturers of building materials and suppliers of imported building materials to provide it with such data.

Gamma radiation from soils

4.15. The national authority should consider whether to introduce controls to restrict the construction of new buildings in areas with particularly high levels of natural background radiation. The ICRP [8] has stated that an existing annual dose rising towards 100 mSv would almost always justify intervention. The term ‘existing annual dose’ includes doses from exposures due to all sources, including doses from external exposure due to building materials and soil, and from internal exposure due to radon and due to radionuclides in food.

4.16. In the rare situations in which radionuclides of natural origin present in the ground give rise to high dose rates due to gamma radiation indoors, the national authority should provide guidance to the occupants of existing buildings on means of reducing radiation exposure. This guidance could include the option of relocation, but for this option societal and economic factors should also be considered.

Gamma radiation from building materials

4.17. Reference [2] requires the establishment of “specific reference levels for exposure due to radionuclides in commodities such as construction material,… which shall typically be expressed as, or be based on, an annual effective dose to the representative person that generally does not exceed a value of about 1 mSv” (Ref. [2], para. 5.22). The reference level of about 1 mSv applies to the dose received from exposure to gamma radiation from the building materials only (i.e. excluding any additional dose from ^{222}Rn or ^{220}Rn released from building materials into indoor air).

4.18. The major contributions to the dose from exposure to gamma radiation from building materials are from ^{226}Ra and ^{232}Th and their progeny, and ^{40}K. Several States have introduced guidelines or regulations to control the amount of radionuclides of natural origin in building materials. Åkerblom [42] shows that regulations or guidelines for building materials are mainly based on an activity concentration index relating to the activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th in building materials. The approach to specifying and applying an activity concentration index differs between States. For those building materials with high emanation coefficients, the national authority should add criteria for the radium content of the building material to control the emanation rate of radon.

4.19. The national authority should establish a process to determine the compliance of building materials containing radionuclides of natural origin with the reference level. An example of such a process for a reference level of 1 mSv from external exposure to gamma radiation is set out in the following paragraphs. If a different value for the reference level is used in a State, the determination of restricted building materials in that State will be different from this process. The process requires the determination of the activity concentrations of radionuclides of natural origin in the building material, followed by the determination of the activity concentration index. The activity concentration index relates to the exposure to gamma radiation in a building constructed using the specified building material. The activity concentration index is a screening tool for identifying building materials that might need to be subject to restriction.

4.20. An example of an activity concentration index I that should be considered by the national authority is given in the following formula [18][10]:

$$I = \frac{C_{\mathrm{Ra}}}{300\ \mathrm{Bq/kg}} + \frac{C_{\mathrm{Th}}}{200\ \mathrm{Bq/kg}} + \frac{C_{\mathrm{K}}}{3000\ \mathrm{Bq/kg}} \tag{1}$$

where:

C_{Ra} is the activity concentration of ^{226}Ra in the building material in Bq/kg;

C_{Th} is the activity concentration of ^{232}Th in the building material in Bq/kg;

and C_{K} is the activity concentration of ^{40}K in the building material in Bq/kg.

4.21. If the activity concentration index I is less than 1 for bulk materials, such as concrete and bricks, and if I is less than 6 for superficial materials such as tiles, the annual effective dose from exposure to gamma radiation from radionuclides in building materials will be less than the reference level of about 1 mSv. Such building materials should not be subject to restrictions on their use. Experience has shown that for the majority of building materials, these respective values for the activity concentration index are not exceeded [18, 43]. For building materials for which the values of $I = 1$ or $I = 6$, respectively, are exceeded, further assessment is required before they can be used.

[10] The derivation of the activity concentration index, and the derivation of the upper values for the activity concentration index (see para. 4.21), can be found in annex I of Ref. [18].

4.22. For those building materials that require further assessment, the national authority should require the calculation of doses from external exposure to gamma radiation that would arise from the use of the building materials. Such an assessment should be based on scenarios where the material is used in a typical way for the type of material in question. The dose assessment should allow for the background levels of external exposure outdoors due to radionuclides of natural origin in undisturbed soil. Such an assessment should preferably be prepared by the manufacturer of the building materials and should be submitted to the national authority.

4.23. An example of a method for calculating doses from external exposure to gamma radiation from building materials is provided in Annex VI [18].

4.24. For the building materials requiring assessment, the calculated effective dose E from external exposure to gamma radiation due to the building material should be compared with the reference level. If the calculated effective dose is less than the reference level of 1 mSv, the building material should not be subject to restrictions on its use. If the calculated effective dose exceeds the reference level of 1 mSv, the national authority should decide on appropriate measures, which may include setting specific restrictions on the uses envisaged for such building materials.

4.25. Some traditionally used natural building materials contain radionuclides of natural origin at activity concentrations such that the annual effective dose of 1 mSv from external exposure to gamma radiation might be exceeded. Some such materials have been in use for decades or centuries. For such cases, the detriments and costs, including both financial and social costs, that would be associated with preventing the use of such materials in new buildings should be evaluated.

4.26. A flow chart describing the recommended system of control of building materials with regard to external exposure to gamma radiation is shown in Fig. 2.

4.27. Residues from NORM industries, such as fly ash and phosphogypsum, are used in the manufacture of building materials of different types. The method of dose assessment based on determination of the activity concentration index or an alternative method should be applied to manufactured building materials; it is not intended to be applied to the constituents making up the material. However, where the residue may contain radionuclides of natural origin other than ^{226}Ra, ^{232}Th and ^{40}K, an assessment of the exposure due to such radionuclides should also be made. Furthermore, if the activity concentrations of ^{232}Th and

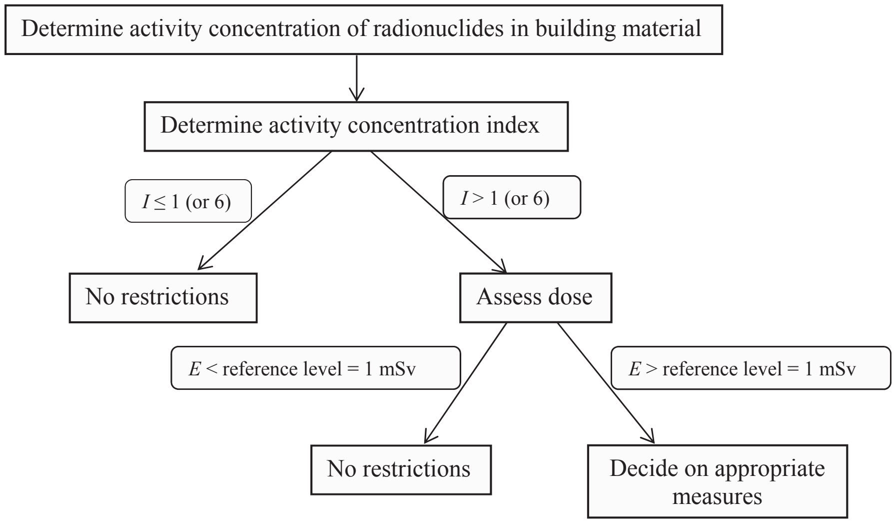

FIG. 2. Flow chart of the recommended system of control of building materials with regard to external exposure to gamma radiation.

^{228}Ra are not in equilibrium in the residue, then the activity concentration of ^{228}Ra should be used instead of the activity concentration of ^{232}Th in the formula given in para. 4.20 (Eq. (1)).

Gamma radiation from building materials in existing buildings

4.28. Protective actions may be necessary for existing buildings in which there are high levels of annual effective dose from exposure to gamma radiation due to radionuclides in building materials. If it is considered necessary, the national authority should establish reference levels for exposure to gamma radiation emanating from building materials in existing buildings. Reference [2] requires the national authority to ensure that protective actions are justified and that protection and safety is optimized (Ref. [2], Requirement 48). It also requires the national authority to ensure that the protection strategy for the management of such situations be commensurate with the radiation risks associated with occupation of the buildings (Ref. [2], para. 5.7).

4.29. In cases where high levels of gamma radiation are found in buildings, the levels may be reduced by applying shielding materials to walls or floor surfaces. Values for the attenuation of gamma radiation by means of various shielding materials are presented in Table 1 [44].

4.30. The ICRP [8] has stated that an existing annual dose rising towards 100 mSv would almost always justify intervention. The national authority should consider requiring protective actions to be mandatory for those dwellings and other buildings with high occupancy factors for which the levels of effective dose exceed 100 mSv. A possible, but extreme, intervention is demolition of the buildings and relocation of the occupants [8]. This action clearly carries serious economic and social penalties and should not be taken without careful consideration.

TABLE 1. EFFECTIVENESS OF SHIELDING MATERIALS: THICKNESS OF THE SHIELDING MATERIAL (mm) NECESSARY TO PROVIDE THE ATTENUATION INDICATED [44]

Shielding material	Thickness of shielding material (mm) necessary for given attenuation factors in the range 0.9–0.1								
	Attenuation factor								
	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Lead (ρ = 11 300 kg/m^3)	0.9	2.3	4.0	6.3	9.3	13	18	26	38
Iron (ρ = 7800 kg/m^3)	6.1	11	17	23	29	37	46	59	81
Barite (ρ = 3300 kg/m^3)	12	24	37	50	65	83	100	130	180
Barite (ρ = 2800 kg/m^3)	18	34	50	66	84	100	130	160	220
Concrete (ρ = 2300 kg/m^3)	30	50	69	89	110	130	160	200	270
Solid brick (ρ = 1800 kg/m^3)	46	72	100	130	160	190	230	280	370

REFERENCES

[1] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).

[2] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[3] UNITED NATIONS, Sources and Effects of Ionizing Radiation (2008 Report to the General Assembly), Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2010).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Elsevier, Oxford and New York (2007).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection Against Radon-222 at Home and at Work, Publication 65, Pergamon Press, Oxford (1993).

[6] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Lung Cancer Risk from Radon and Progeny and Statement on Radon, Publication 115, Elsevier, Oxford (2010).

[7] WORLD HEALTH ORGANIZATION, WHO Handbook on Indoor Radon: A Public Health Perspective, WHO, Geneva (2009).

[8] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Public in Situations of Prolonged Radiation Exposure, Publication 82, Pergamon, Oxford (1999).

[9] WORLD HEALTH ORGANIZATION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, JOINT FAO/WHO FOOD STANDARDS PROGRAMME, CODEX ALIMENTARIUS COMMISSION, Codex General Standard for Contaminants and Toxins in Foods, Schedule 1 — Radionuclides, CODEX STAN 193–1995, CAC, Rome (2013).

[10] WORLD HEALTH ORGANIZATION, Guidelines for Drinking-water Quality, 4th edn, WHO, Geneva (2011).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Occupational Radiation Protection, IAEA Safety Standards Series No. RS-G-1.1, IAEA, Vienna (1999).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulatory Control of Radioactive Discharges to the Environment, IAEA Safety Standards Series No. WS-G-2.3, IAEA, Vienna (2000).
[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Radioactive Waste from the Mining and Milling of Ores, IAEA Safety Standards Series No. WS-G-1.2, IAEA, Vienna (2002).
[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1, IAEA, Vienna (2010).
[15] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 8: Methodologies for Initial and Additional Investigations in Buildings, ISO Standard 11665-8:2012, ISO, Geneva (2012).
[16] UNITED NATIONS, Effects of Ionizing Radiation (2006 Report to the General Assembly), Annex E: Sources-to-Effects Assessment for Radon in Homes and Workplaces, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2009).
[17] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), Annex B: Exposures from Natural Radiation Sources, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).
[18] EUROPEAN COMMISSION, Radiation Protection 112, Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials (1999), http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/112.pdf
[19] INGERSOLL, J.G., A survey of radionuclide content and radon emanation rates in building materials used in the U.S., Health Phys. **45** (1983) 363–368.
[20] JENSEN, C.L., STRAND, T., RAMBERG, G., RUDEN, L., ANESTAD, K., The Norwegian Radon Mapping and Remediation Program, IRPA, Madrid (2004).
[21] EK, B., THUNHOLM, B., OSTERGREN, I., FALK, R., MJONES, L., Naturligt radioaktiva *ämnen*, arsenik och andra metaller i dricksvatten från enskilda brunnar (2008), http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Rapport/Stralskydd/2008/ssi-rapp-2008-15.pdf (summary in English).
[22] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 4: Integrated Measurement Methods for Determining Average Activity Concentration Using Passive Sampling and Delayed Analysis, ISO Standard 11665-4:2012, ISO, Geneva (2012).
[23] RADIATION PROTECTION INSTITUTE OF IRELAND, Action Plan to Identify and Remedy Irish Houses with Radon Concentrations above the National Reference Level (2006),
http://www.epa.ie/pubs/reports/radiation/RPII_Rad_Action_Plan_06.pdf
[24] L'AUTORITÉ DE SÛRETÉ NUCLÉAIRE, National Action Plan 2011–2015 for Management of Radon-related Risks (2012), http://www.french-nuclear-safety.fr/Information/News-releases/ASN-s-national-action-plan-for-management-of-the-radon-risk

[25] SWISS FEDERAL OFFICE OF PUBLIC HEALTH, National Action Plan concerning Radon, 2012 – 2020 (2011), http://www.bag.admin.ch/themen/strahlung/00046/11649/index.html?lang=en&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1ad1IZn4Z2qZpnO2Yuq2Z6gpJCKdH14f2ym162epYbg2c_JjKbNoKSn6A--
[26] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Protecting People and Families from Radon: A Federal Action Plan for Saving Lives (2011), http://www.epa.gov/radon/pdfs/Federal_Radon_Action_Plan.pdf
[27] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiological Protection against Radon Exposure, Publication 126, Elsevier, Oxford (2014).
[28] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The Optimisation of Radiological Protection, Publication 101b, Elsevier, Oxford (2006).
[29] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2005, ISO, Geneva (2005).
[30] NEZNAL, M., NEZNAL, M., ŠMARDA, J., "Radon infiltration risk from the ground in Chabry, Prague", Radon Investigations in Czechoslovakia (BARNET, I., Ed.), Vol. 2, Czech Geological Survey, Prague (1991) 34–39.
[31] NEZNAL, M., NEZNAL, M., MAOTLIN, M., BARNET, I., MIKSOVA, J., The New Method for Assessing the Radon Risk of Building Sites, Czech Geological Survey Special Papers 16, Czech Geological Survey, Prague (2004).
[32] MCLAUGHLIN, J., An overview of thoron and its progeny in the indoor environment, Radiat. Prot. Dosim. **141** (2010) 316–321.
[33] GUO, Q., SHIMO, M., IKEBE, Y., MINATO, S., The study of thoron and radon progeny concentrations in dwellings in Japan, Radiat. Prot. Dosim. **45** (1992) 357–359.
[34] TOKONAMI, S., et al., Radon and thoron exposures for cave residents in Shanxi and Shaanxi provinces, Radiat. Res. **162** (2004) 390–396.
[35] YAMASAKI, T., LIDA, T., Measurements of thoron progeny concentration using a potential alpha-energy monitor in Japan, Health Phys. **68** (1995) 840–844.
[36] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil — Part 1: General Guidelines and Definitions, ISO Standard 18589-1:2005, ISO, Geneva (2005).
[37] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil — Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples, ISO Standard 18589-2:2007, ISO, Geneva (2007).
[38] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil — Part 3: Measurement of Gamma-Emitting Radionuclides, ISO Standard 18589-3:2007, ISO, Geneva (2007).
[39] KNOLL, G.F., Radiation Detection and Measurement, 4th edn, J. Wiley and Sons, New York (2011).

[40] INTERNATIONAL ELECTROTECHNICAL ORGANIZATION, Nuclear Instrumentation — Measurement of Gamma-Ray Emission Rates of Radionuclides — Calibration and Use of Germanium Spectrometers, IEC Standard 61452, IEC, Geneva (1995).
[41] INTERNATIONAL ELECTROTECHNICAL ORGANIZATION, Radiation Protection Instrumentation — Measurement of Discrete Radionuclides in the Environment — In Situ Photon Spectrometry System Using a Germanium Detector, IEC Standard 61275, IEC, Geneva (2013).
[42] ÅKERBLOM, G., Radon Legislation and National Guidelines, SSI Report No. 99:18, Swedish Radiation Protection Institute, Stockholm (1999).
[43] TREVISI, R., RISICA, S., D'ALESSANDRO, M., PARADISO, D., NUCCETELLI, C., Natural radioactivity in building materials in the European Union: a database and an estimate of radiological significance, J. Environ. Radioact. **105** (2012) 11–20.
[44] CZECH OFFICE FOR STANDARDS, Protection of Buildings against Radon and Gamma Radiation from Building Materials, CSN 73 0602, Czech Office for Standards, Metrology and Testing, Prague (2006).

Annex I

RADON SURVEYS AND MAPPING OF ^{222}Rn PRONE AREAS

I–1. Measures to control the public health risk from radon must be determined on the basis of knowledge of concentrations of radon indoors in a State. A number of international authorities have pointed to the need to understand concentrations of radon and their variations from place to place in determining the exposure due to radon of a population [I–1, I–2]. This implies the need for radon surveys and ^{222}Rn mapping. WHO has carried out a radon survey of a number of States [I–3].

I–2. High concentrations of ^{222}Rn indoors almost always derive ultimately from uranium in the ground. In some cases, building materials may give rise to high concentrations of radon indoors, but this is not the usual situation. Relatively high concentrations of ^{222}Rn are associated with particular types of bedrock and unconsolidated deposits, for example, certain granites, phosphatic rocks and shales rich in organic materials. The uranium content is not the only determinant of the rate of ^{222}Rn emission from rocks: permeability, the extent of fracturing and faulting, and weathering are also important factors. The impact of human activities such as mining also needs to be considered. Once ^{222}Rn gas is released, its migration to the surface is governed by a number of complex processes. The movement of ^{222}Rn from soil gas to indoor air is dependent on a number of factors which may vary greatly from building to building and with time.

I–3. Concentrations of ^{222}Rn in soil gas may vary from one region to another depending on the concentrations of uranium in rocks and soils and on the way that gases move within and between geological structures [I–4]. The same broad class of factors, acting on a much smaller scale, interact with the detailed construction and use of individual buildings to determine the concentrations of ^{222}Rn within them. These concentrations of ^{222}Rn can vary significantly from one building to another, and also from hour to hour and from day to day, depending on climatic factors such as wind speed and direction, atmospheric pressure and temperature [I–5, I–6]. The behaviour of occupants can also influence the concentrations of ^{222}Rn indoors.

I–4. The concentrations of ^{222}Rn in buildings depend on the concentration of radon in soil gas and the soil permeability and on the way in which buildings are constructed and used. Studies have been undertaken to try to correlate the concentrations of ^{222}Rn in soil gas with concentrations of ^{222}Rn indoors. Such studies have had limited success as not all factors influencing concentrations of radon indoors were taken into account.

I–5. The wide variability in concentrations of ^{222}Rn indoors means that careful surveys of ^{222}Rn are necessary in order to determine the scale and nature of the ^{222}Rn problem in any State or region. The results of such surveys are generally best presented as maps. Comprehensive reviews of surveys of ^{222}Rn and of radon mapping in Europe have been carried out by Synnott and Fenton [I–7] and by Dubois [I–8]. In view of the results, and in particular the large methodical heterogeneity of maps which makes comparison between States nearly impossible, a large scale European radon mapping project was started in 2006. An interim version of the European indoor radon map (which is an ongoing project given that surveys are still under way in many States) has been published [I–9 to I–11]. A summary of the national surveys of ^{222}Rn described by Dubois is given in Table I–1 [I–8, I–12 to I–46]. Large amounts of radon data have been acquired since Ref. [I–8] was published. Many States also publish data on local concentrations of ^{222}Rn indoors at the regional and local levels. Worldwide data are reported by UNSCEAR, most recently in 2006 [I–47].

TABLE I–1. PROGRAMMES FOR MAPPING CONCENTRATIONS OF ^{222}Rn INDOORS IN EUROPE *(Based on Dubois [I–8])*

State	Selected reference	State	Selected reference
Austria	[I–12]	Luxembourg	[I–29]
Belgium	[I–13]	Malta	[I–30]
Croatia	[I–14]	Netherlands	[I–31]
Cyprus	[I–15]	Norway	[I–32]
Czech Republic	[I–16]	Poland	[I–33]
Denmark	[I–17]	Portugal	[I–34]
Estonia	[I–18]	Romania	[I–35]
Finland	[I–19, I–20]	Serbia (Vojvodina only)	[I–36]
France	[I–21]	Slovakia	[I–37]
Germany	[I–22]	Slovenia	[I–38]
Greece	[I–23]	Spain	[I–39]
Hungary	[I–24]	Sweden	[I–40]
Ireland	[I–25]	Switzerland	[I–41]
Italy	[I–26]	The Former Yugoslav Republic of Macedonia	[I–42]
Latvia	[I–27]	United Kingdom	[I–43 to I–46]
Lithuania	[I–28]		

I–6. Surveys of ^{222}Rn may be population based, i.e. designed to provide information about exposure of people due to ^{222}Rn, or area based, i.e. concerned with the typical concentrations of ^{222}Rn in geographical areas regardless of population. The two are distinct, although they are of course related. A population based survey is useful in helping to understand the public health consequences of exposures due to ^{222}Rn. A map is required when making decisions about the need for preventive measures for ^{222}Rn in new buildings, or for directing surveys to find existing buildings with high concentrations of ^{222}Rn. A population based survey could include measurements in, for example, one in every thousand buildings in the area of interest, no matter how close together or how far apart those buildings might be. In an area based survey it is necessary to take a fixed number of measurements per geographical unit, regardless of how many buildings that unit might contain.

I–7. The sampling schemes described are simple and logical. However, as soon as measurements are taken that are not the result of a formal sampling scheme, the situation becomes more complex. If measurements are commissioned and paid for by the owners of buildings, there are likely to be socioeconomic differences between those who do commission such measurements and those who do not.

I–8. In constructing maps of concentrations of ^{222}Rn, it will be necessary to present results on the basis of geographical units of some kind. As noted above, concentrations of ^{222}Rn are determined ultimately by geological factors and by the ways in which dwellings are constructed and used. Users of such maps might find them most convenient if they are presented in terms of administrative units; for example, local government boundaries or simple rectangular grid squares. Mapping by local government boundaries is more practical with regard to regulations. The underlying physical processes suggest that better results would be obtained by combining results that relate to the same geological unit. However, the potential for high concentrations of ^{222}Rn indoors can also vary significantly within geological units.

EXAMPLE OF THE APPROACH TO MAPPING ^{222}Rn IN THE UNITED KINGDOM

I–9. Experience with mapping ^{222}Rn in the United Kingdom illustrates some of these matters. The results of initial population based surveys were presented as maps of mean concentrations of ^{222}Rn in 10 km grid squares. However, many grid squares remained without information, and it was clear that a more complete and detailed radon map was required to help shape policy on ^{222}Rn and for directing priorities for campaigns on ^{222}Rn [I–48]. Accordingly, measurements of concentrations of ^{222}Rn aimed at detailed mapping were undertaken, starting with those parts of the United Kingdom that had been found to have the highest concentrations of ^{222}Rn. Additional measurements of concentrations of ^{222}Rn were made in these areas, with the aim of achieving a minimum of five results in each 5 km grid square.

I–10. The distribution of the results of measurements of ^{222}Rn within grid squares was found to be close to log-normal. To characterize this distribution, it is necessary to determine only two parameters for each grid square: the geometric mean and the geometric standard deviation. Techniques were developed to allow data from adjacent squares to be used to estimate these parameters if there were insufficient results of measurements for any particular square [I–49, I–50]. The results are presented as probability maps that indicate the probability of the action level for radon being exceeded in an individual dwelling in the grid square.

I–11. In some areas, intensive campaigns for measurement to identify dwellings with high concentrations of ^{222}Rn produced an average of 15 results for ^{222}Rn per 1 km grid square, although they were very unevenly distributed. Such a high density of results allows for a more detailed mapping of concentrations of ^{222}Rn at a resolution of 1 km grid squares. It was found that the methods developed for mapping concentrations of ^{222}Rn at 5 km resolution were not appropriate for 1 km resolution, because the measurements are distributed so unevenly at the finer scale. A new method of analysing the data was developed to allow for mapping of concentrations of ^{222}Rn using 1 km grid squares [I–51].

I–12. The maps of concentrations of ^{222}Rn in the United Kingdom described, above all, ^{222}Rn measurements grouped by rectangular grid squares. Alternative maps of concentrations of ^{222}Rn were developed in which all ^{222}Rn measurements that fell within the same geological unit were grouped together and treated as a single distribution [I–52]. The boundaries of the geological units were taken from digital geological maps.

I–13. Both mapping methods, grid square based and geologically based, have strengths and weaknesses. As the potential for high concentrations of ^{222}Rn indoors clearly differs between geological units, grouping of results for concentrations of ^{222}Rn by geological unit is an obvious approach. However, substantial variations in concentrations of ^{222}Rn indoors are often found within geological units, and such variations are ignored by geological mapping. Grid square mapping ignores differences between geological units, but it can reveal variations within geological units that do not appear on the geologically based maps of concentrations of ^{222}Rn.

I–14. To determine whether it is possible to combine the different strengths of geological mapping and grid square mapping of concentrations of ^{222}Rn, the results of measurements of concentrations of ^{222}Rn in dwellings are grouped together first by geological unit. The 1 km grid square mapping method is then applied to map variations in concentrations of ^{222}Rn indoors separately within each unit. The different maps of concentrations of ^{222}Rn indoors for all geological units are then combined to cover the whole area of the study [I–53].

I–15. Other States in Europe also attach importance to programmes for mapping concentrations of ^{222}Rn indoors (see Table I–1). A review of techniques for mapping ^{222}Rn that have been applied in a number of European States has been produced [I–7]. There is also some experience of mapping ^{222}Rn in the United States of America [I–54]. Mapping techniques have developed considerably over the last few years with increased availability and familiarity of geographic information systems and geostatistical methods.

REFERENCES TO ANNEX I

[I–1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection against Radon-222 at Home and at Work, Publication 65, Pergamon Press, Oxford (1993).

[I–2] WORLD HEALTH ORGANIZATION, WHO Handbook on Indoor Radon: A Public Health Perspective, WHO, Geneva (2009).

[I–3] ZEEB, H., Survey on Radon Guidelines, Programmes and Activities, WHO Report WHO/HSE/RAD/07.01, WHO, Geneva (2007).

[I–4] BARNET, I., PACHEROVÁ, P., NEZNAL, M., NEZNAL, M., Radon in geological environment - Czech experience, Special Papers No. 19, Czech Geological Survey, Prague (2008).

[I–5] ROBINSON, A.L., SEXTRO, R.G., Radon entry into buildings driven by atmospheric pressure fluctuations, Environ. Sci. Technol. **31** 6 (1997) 1742–1748.

[I–6] SUN, Q., TOKONAMI, S., YAMADA, Y., AKIBA, S., Main meteorological parameters to influence indoor radon level, Radioisot. **51** 3 (2002) 120–126.

[I–7] SYNNOTT, H., FENTON, D., An Evaluation of Radon Reference Levels and Radon Measurement Techniques and Protocols in European Countries (2005), https://www.epa.ie/pubs/reports/radiation/RPII_ERRICA_Measure_Report_05.pdf

[I–8] DUBOIS, G., An Overview of Radon Surveys in Europe (2005), http://rem.jrc.ec.europa.eu/RemWeb/publications/EUR_RADON.pdf

[I–9] TOLLEFSEN, T., GRUBER, V., BOSSEW, P., DE CORT, M., Status of the European indoor radon map, Radiat. Prot. Dosim. **145** (2011) 110–116.

[I–10] DE CORT, M., GRUBER, V., TOLLEFSEN, T., BOSSEW, P., JANSSENS, A., Towards a European atlas of natural radiation: Goal, status and future perspectives, Radioprot. **46** (2011) S737–S743.

[I–11] GRUBER, V., TOLLEFSEN, T., BOSSEW, P., DE CORT, M., The European indoor radon map and beyond, Carpathian J. Earth & Environ. Sci. **8** (2013) 169–176.

[I–12] FRIEDMANN, H., et al., “The Austrian radon project”, Sci. Total Environ. **272** 1–3 (2001) 211–212 (abstract).

[I–13] VANMARCKE, H., MOL, H., PARIDAENS, J., EGGERMONT, G., “Exposure of the Belgian Population to Ionizing Radiation”, IRPA 11: 11th international congress of the International Radiation Protection Association (Proc. Int. Congr. Madrid, 2004) SENDA, Madrid (2004).

[I–14] RADOLIC, V., et al., National survey of indoor radon levels in Croatia, J. Radioanal. Nucl. Chem. **269** (2006) 87–90.

[I–15] SARROU, I., PASHILIDIS, I., Radon Levels in Cyprus, J. Environ. Radioact. **68** (2003) 269–277.

[I–16] HULKA, J., THOMAS, J., “National radon programme: 20 years of experience in Czech Republic”, IRPA 11: 11th international congress of the International Radiation Protection Association (Proc. Int. Congr. Madrid, 2004) SENDA, Madrid (2004).

[I–17] ANDERSEN, C.E., ULBAK, K., DAMKJÆR, A., KIRKEGAARD, P., GRAVESEN, P., Mapping indoor radon-222 in Denmark: Design and test of the statistical model used in the second nationwide survey, Sci. Total Environ. **272** 1–3 (2001) 231–241.

[I–18] PAHAPILL, L., RULKOV, A., RAJAMÄE, R., ÅKERBLOM, G., Radon in Estonian Dwellings, Results from a National Radon Survey, SSI Report No. 2003:16, Swedish Radiation Protection Authority, Stockholm (2003).

[I–19] VALMARI, T., MÄKELÄINEN, I., REISBACKA, H., ARVELA, H., Suomen Radonkartasto — Radon Atlas of Finland, STUKA245, Oy Edita Ab., Helsinki (2010).

[I–20] MÄKELÄINEN, I., VALMARI, T., REISBACKA, H., KINNUNEN, T., ARVELA, H., “Indoor radon and construction practices in Finnish homes from the 20th to the 21st century”, Third European IRPA Congress (Proc. Int. Congr. Helsinki, 2010) Nordic Society for Radiation Protection, Helsinki (2011) 561–569.

[I–21] BILLON, S., et al., French population exposure to radon, terrestrial gamma and cosmic rays, Radiat. Prot. Dosim. **113** 3 (2005) 314–320.

[I–22] LEHMANN, R., KEMSKI, J., SIEHL, A., STEGEMANN, R., VALDIVIA-MANCHEGO, M., The regional distribution of indoor radon concentration in Germany, Int. Congr. Ser. **1225** (2002) 55–61.

[I–23] CLOUVAS, A., XANTHOS, S., ANTONOPOULOS-DOMIS, M., A combination study of indoor radon and in situ gamma spectrometry measurements in Greek dwellings, Radiat. Prot. Dosim. **103** 4 (2003) 363–366.

[I–24] HÁMORI, K., TÓTH, E., KÖTELES, G., PÁL, L., A Magyarországi lakások radonszintje (1994–2004), Egészstud. **48** (1994) 283–299.

[I–25] FENNELL, S.G., et al., Radon in Dwellings, The Irish National Radon Survey, RPII-02/1, Radiological Protection Institute of Ireland, Dublin (2002).

[I–26] BOCHICCHIO, F., et al., Results of the representative Italian national survey on radon indoors, Health Phys. **71** 5 (1996) 741–748.

[I–27] DAMBIS, M., “Radon in Latvia’s dwellings”, Radiation and Society: Comprehending Radiation Risk (Proc. Int. Conf. Paris, 1994) IAEA, Vienna (1996) 379–382.

[I–28] MORKUNAS, G., ÅKERBLOM, G., “The outcome of the Lithuanian radon survey”, Sci. Total Environ. **272** (2001) 243–244 (abstract).

[I–29] KIES, A., FEIDER, M., BIELL, A., Indoor radon concentrations in the Grand Duchy of Luxembourg, Ann. Assoc. Belg. Radioprot. **19** (1994) 189–201.

[I–30] MIFSUD, I., SAMMUT, M., A survey on radon levels in local dwellings, Xjenza **4** (1999) 40–41.

[I–31] STOOP, P., GLASTRA, P., HIEMSTRA, Y., DE VRIES, L., LEMBRECHTS, J., Results of the Second Dutch National Survey on Radon in Dwellings, RIVM Report No. 610058006, National Institute of Public Health and the Environment, Bilthoven, Netherlands (1998).

[I–32] STRAND, T., GREEN, B.M.R., LOMAS, P.R., Radon in Norwegian dwellings, Radiat. Prot. Dosim. **45** (1992) 503–508.

[I–33] STAWARZ, O., ISAJENKO, K., LIPINSKI, P., MAMONT-CIESLA, K., The radon concentration investigations in dwellings of Rzeszow area with the aim of completing missing data in radon atlas of Poland, Activity Report 2008-2009, 25-31, Central Laboratory for Radiological Protection, Warsaw (2010).

[I–34] FAÍSCA, M.C., TEIXEIRA, M.M.G.R., BETTENCOURT, A.O., Indoor radon concentrations in Portugal — a national survey, Radiat. Prot. Dosim. **45** (1992) 465–467.

[I–35] CUCULEANU, V., SONOC, S., GEORGESCU, M., Radioactivity of radon and thoron daughters in Romania, Radiat. Prot. Dosim. **45** (1992) 483–485.

[I–36] CURCIC, S., et al., “The first radon map of Vojvodina”, IRPA 11: 11th international congress of the International Radiation Protection Association (Proc. Int. Congr., Madrid, 2004) SENDA, Madrid (2004).

[I–37] VICANOVÁ, M., DURCÍK, M., NIKODEMOVÁ, D., Radiation Load from Radon Exposure in Slovakia (1999), http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/017/30017847.pdf

[I–38] KRIŽMAN, M., ILIC, R., SKVARC, J., JERAN, Z., “A survey of indoor radon concentrations in dwellings in Slovenia”, Proceedings of the IRPA Regional Congress (Proc. Congr. Portorož, 1995), (GLAVIC-CINDRO, D., Ed.), J. Stefan Institute, Ljubljana (1995) 66–70.

[I–39] QUINDÓS PONCELA, L.S., et al., Natural external gamma radiation map (MARNA) and indoor radon levels in Spain, Environ. Int. **29** (2004) 1091–1096.

[I–40] SWEDISH RADON COMMISSION, Proposal for a New Radon Programme for Sweden, The Swedish Radon 2000 Commission’s Report SOU 001:7, Swedish Government Offices, Stockholm (2001).

[I–41] SWISS FEDERAL OFFICE OF PUBLIC HEALTH, Jahresbericht 2013 der Abteilung Strahlenschutz (2013), http://www.bag.admin.ch/themen/strahlung/00043/00065/02236/index.html?lang=de

[I–42] REPUBLIC INSTITUTE FOR HEALTH PROTECTION, Radon in Living and Working Environment, Report No. 40096895, RIHP, Skopje (1998).

[I–43] GREEN, B.M.R., MILES, J.C.H., BRADLEY, E.J., REES, D.M., Radon Atlas of England and Wales, NRPB-W26, National Radiological Protection Board, Chilton (2002).

[I–44] MILES, J.C.H., et al., Indicative Atlas of England and Wales, Report No. HPA-RPD-033, Health Protection Agency, Didcot (2007).

[I–45] MILES, J.C.H., et al., Indicative Atlas of Radon in Scotland, Report No. HPA-CRCE-023, Health Protection Agency, London (2011).

[I–46] GREEN, B.M.R., LARMOUR, R., MILES, J.C.H., REES, D.M., LEDGERWOOD, F.K., Radon in Dwellings in Northern Ireland, Report No. HPA-RPD-061, Health Protection Agency, Chilton (2009).

[I–47] UNITED NATIONS, Effects of Ionizing Radiation (2006 Report to the General Assembly), Annex E: Sources-to-Effects Assessment for Radon in Homes and Workplaces, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2009).

[I–48] KENDALL, G.M., GREEN, B.M.R., MILES, J.C.H., DIXON, D.W., The development of the UK radon programme, J. Radiol. Prot. **25** 4 (2005) 475–492.

[I–49] MILES, J.C.H., Mapping the proportion of the housing stock exceeding a radon reference level, Radiat. Prot. Dosim. **56** (1994) 207–210.

[I–50] MILES, J.C.H., Mapping radon-prone areas by lognormal modelling of house radon data, Health Phys. **74** (1998) 370–378.

[I–51] MILES, J.C.H., Development of maps of radon-prone areas using radon measurements in houses, J. Hazard. Mater. **61** (1998) 53–58.

[I–52] APPLETON, J.D., BALL, T.K., “Geological radon potential mapping”, Geoenvironmental Mapping: Methods, Theory and Practice (BOBROWSKY, P. T., Ed.), Balkema, Rotterdam (2002) 577–613.

[I–53] MILES, J.C.H., APPLETON, J.D., Mapping variation in radon potential both between and within geological units, J. Radiol. Prot. **25** (2005) 257–276.

[I–54] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Map of Radon Zones (2012),
http://www.epa.gov/radon/zonemap.html

Annex II

MEASUREMENT TECHNIQUES FOR ^{222}Rn AND ^{220}Rn

MEASUREMENT TECHNIQUES FOR ^{222}Rn

II–1. The health risks from inhaling radon and its progeny will depend on the mixture of radionuclides present in the air inhaled. Radionuclides that emit alpha particles are of particular importance since alpha particles cause more biological damage than do beta particles or gamma radiation when inside the body. Usually it is radon progeny rather than radon gas itself that give rise to most of the risk; radon progeny can become trapped in the lung, whereas most radon gas that is inhaled will be exhaled again. It has been shown that the concentration of radon gas is usually a good indicator of the associated risk [II–1]. Measurement of radon progeny remains an important topic. However, where attention is focused on practical measures for radiation protection, measurements of concentrations of radon gas are usually made.

II–2. The risk that someone exposed to radon will develop lung cancer depends on their cumulative exposure over many years. It would be convenient if such exposure could be estimated from a quick measurement. However, measurements of radon can be misleading because concentrations of radon may vary, sometimes quite significantly, from hour to hour, from day to day and from month to month, depending on climatic factors and other factors [II–2 to II–4]. Spot [II–5], short term [II–6] or continuous [II–7] measurements of concentrations of radon may be useful for screening purposes and diagnostic purposes or for determining the full temporal variation of concentrations of radon. However, knowledge of the long term average activity concentration of radon, or the average activity concentration of radon integrated over a long period, is necessary in order to assess health risks. Ideally, measurements of radon concentrations would take place over a full year, to cover any seasonal variations that might exist. The annual average activity concentration of radon varies between years [II–8]. However, detectors might be misplaced if left in a dwelling for such a long period; problems with the performance of the detectors might arise and householders might be unwilling to wait so long for results. For these reasons, measurements are usually made over a period of several months, and the annual average is estimated using correction factors on the basis of typical seasonal variations. The patterns of seasonal variations in concentrations of ^{222}Rn have been investigated by a number of authors [II–9 to II–12]. Concentrations of ^{222}Rn are generally higher in the colder months and in some States ^{222}Rn measurements are carried out during the winter to be conservative.

II–3. It is important that well designed and well specified measurement protocols are followed [II–4]. At the international level, the International Organization for Standardization has published a standard on test methods for ^{222}Rn that was issued in different parts, each part adapted to a particular situation and objectives and taking into account the related objectives for data quality [II–3, II–5 to II–7, II–13 to II–20]. In the United States of America, for example, the Environmental Protection Agency has published advice [II–21], and guidance has also been provided in other States, for example, in the United Kingdom [II–22] and in France [II–23, II–24]. In most States, the advice given is that a measurement of ^{222}Rn concentration is carried out over several months to assess the exposure and to compare with the reference level. However, shorter term measurements can be used provided that strict protocols are followed in the interpretation of the results. This approach has been used in some States [II–21, II–25] and it can give a rapid indication of whether ^{222}Rn activity concentrations are very high or very low. However, the information such measurements provide cannot currently be used for comparison with reference levels. There can also be significant year to year variations in activity concentrations of ^{222}Rn in any given building [II–26]. However, it is not usually feasible to conduct year-long measurements [II–16] except in the case of epidemiological studies or for research purposes.

II–4. Various types of detector for ^{222}Rn are described briefly in the following sections. In all cases, the instruments work by detecting the alpha radiation or gamma radiation emitted by ^{222}Rn or its progeny. A detailed review of measurement techniques for ^{222}Rn has been published [II–20, II–27].

II–5. Detectors for ^{222}Rn may be divided into two types: active and passive. Passive detectors require no electrical power and have obvious advantages for large scale use. Most measurements of concentrations of ^{222}Rn in dwellings have been made with solid state nuclear track detectors or with activated charcoal detectors, both of which are passive detectors.

SOLID STATE NUCLEAR TRACK DETECTORS

II–6. Solid state nuclear track detectors usually consist of a plastic detector in a small container. Radon gas diffuses into the container and decays, emitting alpha particles that leave damage tracks in the plastic detector. To determine the amount of radon to which the detector has been exposed, the plastic is etched in a caustic solution, producing tracks where it has been damaged by the alpha particle radiation. The tracks can be counted automatically under a microscope or with a slide scanner, for example. The most commonly used sensitive plastic is poly allyl diglycol carbonate (PADC, also known as CR-39). One of the first descriptions of the principle was by Geiger in Ref. [II–28]. A detailed discussion of applications of solid state nuclear track detectors is given in Ref. [II–29] and an international standard describes their use [II–6].

II–7. Solid state nuclear track detectors are small, cheap, simple, non-toxic and non-hazardous. They can be sent through the post with instructions for their placement and return. Two detectors are usually used for measurements in dwellings to assess the exposure of the occupants; one is placed in an occupied bedroom, the other in the main living area. They are typically left in place for a minimum period of three months and then returned for processing. Alternative placement methods for the assessment of the exposure of the occupants due to radon and possible exposure due to radon levels in the basement are also made in some States. This is done by placing the detectors in a room on the lowest occupied storey and also in the basement or in a cellar below the building.

II–8. Most solid state nuclear track detectors are filtered to prevent radon progeny entering and contributing to the signal. However, some detectors are of bare design and detect both radon gas and radon progeny. This might appear to be an advantage, but in fact such open detectors are very sensitive to a number of factors (e.g. sunlight, dust) that affect the proportion of the progeny that is detected. ‘Open’ detectors can also be closed during the measurement period and therefore it is important that the exposure time (i.e. the period of time for which the detector is open) is noted.

II–9. Radiation due to ^{220}Rn can affect the results of some closed and all open solid state nuclear track detectors [II–30]. This is a disadvantage, as it affects their accuracy in measuring concentrations of ^{222}Rn. Closed solid state nuclear track detectors preferably have a half-time for entry of ^{222}Rn that is long compared with the half-life of ^{220}Rn (55.6 seconds) but short compared with the half-life of ^{222}Rn (3.82 days). If detectors meet this criterion, ^{220}Rn will almost entirely decay before entering the detector, but ^{222}Rn will not decay significantly before entering the detector.

II–10. Etched track detectors have many advantages, but careful attention has to be paid to quality assurance when they are used. This is because the response of the plastic to alpha particle damage can vary from one batch of plastic to the next and is also very sensitive to the etching conditions [II–31]. For these reasons, laboratories that are newly setting up production and processing facilities for etched track detectors often experience difficulties in reaching a high standard of accuracy. It is possible to minimize the difficulties by purchasing a complete service of supply and processing of etched track detectors from a validated or accredited laboratory. These options are also likely to be less expensive than setting up a laboratory for etched track detectors for all but the largest measurement programmes for ^{222}Rn. Purchasers of such detectors or turnkey systems need to ensure that the detectors have performed well in international intercomparisons of passive ^{222}Rn detectors and that they comply with the standards set by the national authority for ^{222}Rn measurements [II–22].

ACTIVATED CHARCOAL DETECTORS

II–11. Activated charcoal detectors are sometimes more formally referred to as activated charcoal adsorption devices. They consist of a small container of activated charcoal that adsorbs ^{222}Rn present in the air; the charcoal is covered by a screen and usually by a diffusion barrier. After use, the detector is sealed and returned to the laboratory for analysis using a scintillation detector. The normal method of analysis is to measure gamma radiation emissions from the short lived ^{222}Rn progeny [II–6].

II–12. Radon-222 has a half-life of 3.82 days, and ^{222}Rn adsorbed by the charcoal at the beginning of its use decays to levels which render determination of radon activity concentration for common indoor radon concentrations with the required accuracy difficult after a week or so. In addition, ^{222}Rn that has been adsorbed onto the charcoal may be lost again. Luetzelschwab et al. [II–32] investigated the response of charcoal dosimeters and reported that detectors without a diffusion barrier were very dependent on temperature levels and humidity levels and are not to be used for more than two days. The response was better if a diffusion barrier was used. The duration of measurement is limited to less than one week. An early description of the principle of detecting ^{222}Rn by adsorption onto charcoal is given by Hursh [II–33].

II–13. Charcoal detectors are not suitable for long term measurements, but they can be used for screening purposes; for example, to give an indication of the effectiveness of preventive measures and corrective actions or to indicate whether a building has a significant problem with ^{222}Rn. To better estimate long term exposure due to ^{222}Rn, a confirmatory long term measurement needs to be conducted.

ELECTRET IONIZATION CHAMBERS

II–14. An electret ionization chamber contains a polytetrafluoroethylene (PTFE) electret disc that has been positively charged, to a potential typically of about 700 V [II–34]. The electret holds this electrostatic charge which is gradually neutralized by ionization of the air in the chamber by alpha particles emitted by ^{222}Rn and its progeny. Measuring the charge on the electret at the beginning and at the end of a period allows the concentration of ^{222}Rn to be calculated. In making this calculation, allowance must be made for ionization caused by natural background radiation since the ambient gamma dose rate at the measurement position of the detector contributes to a determinate drop in voltage of the electret. Moreover, the response is not linear in terms of voltage, and careful calibration has to be applied. Different types of electret and different sizes of chamber are available, suitable for measurements over periods of a few days to a few months [II–6].

II–15. Electret ionization chambers need to be handled with care, as dropping them or touching the electret's sensitive surface can cause a partial or total discharge, and thus an overestimation of the concentration of ^{222}Rn. Electret ionization chambers are also sensitive to environmental conditions such as air pressure or a high level of air humidity leading to water condensation on the internal surfaces. In principle, they are not too large to be sent through the postal service, but their sensitivity, in particular to mechanical shocks, would reduce their practicability. Electrets are usually used for screening and diagnostic measurements. The detectors are not usually used for large scale surveys.

CONTINUOUS RADON MONITORS

II–16. Various types of electronic continuous radon monitor are available, utilizing spectrometric or non-spectrometric detection principles. They sample the air continuously and measure either radon or its progeny using active sampling or the diffusive transport of radon laden air into the sensitive volume of the detectors. Test methods using monitors of these types are described in an international standard [II–7]. In the case of a radon gas monitor, a filter is used to remove radon progeny and dust from the sampled air. The filter could also be used for quasi-continuous measurement of radon progeny. The measurement is repeated over successive time periods. This allows the variation in the concentration of radon with time to be determined.

II–17. If very accurate measurements, particularly of very low radon concentrations, are necessary, then a pulse ionization chamber is likely to be the instrument of choice [II–35]. Such equipment is expensive and complex and it is generally not practicable for large scale use. However, it can be invaluable if a detailed study of factors affecting concentrations of radon in a particular building is to be undertaken. Measurement systems using active sampling are expensive in terms of staff time and data analysis and for this reason are usually used only in diagnostic or research applications.

RETROSPECTIVE ^{222}Rn MEASUREMENTS

II–18. The technique of retrospective measurement of ^{222}Rn is a passive method that uses alpha track detectors to estimate the surface activity of ^{210}Po, a decay product of ^{222}Rn, deposited on suitable glass objects in a room [II–36]. Two types of alpha track detectors are commonly used: one is made from PADC, commonly referred to as CR-39, and the other is made from cellulose nitrate and sold commercially under the name of LR-115. The LR-115 detector is sensitive to alpha particles in the range of 1.2–4.8 MeV and will not record the 5.3 MeV alpha particles emitted by the ^{210}Po implanted into the glass; instead, it produces tracks proportional to the intrinsic alpha activity of the glass itself. The CR-39 detector records the tracks due to both the surface activity of ^{210}Po implanted into the glass and the intrinsic activity of the glass itself. The difference in the track densities between the two detectors allows an estimate to be made of ^{210}Po implanted into the glass after the deposition onto the surface of the glass and the decay of the first decay product ^{218}Po (mostly in nanometric form). In this way, it is possible to estimate the decay of ^{222}Rn in the room over the lifetime of the glass.

II–19. From the measured surface activity of ^{210}Po implanted into the glass, the age of the glass and information on room parameters (e.g. the average concentrations of aerosols, the ventilation rate), the average concentration of ^{222}Rn to which the glass has been exposed can be estimated using available models.

II–20. Suitable glass objects are those that would have moved from house to house with the occupants and can therefore provide a history of exposure due to ^{222}Rn. These are most often family photographs that can be accurately dated.

II–21. An additional method of assessing exposures due to ^{222}Rn retrospectively is by assessing the damage due to alpha particles incident on compact discs [II–37, II–38].

MEASUREMENT TECHNIQUES FOR ^{220}Rn

II–22. Owing to the short half-life of ^{220}Rn (55.6 s), the equilibrium between ^{220}Rn and its progeny nuclides can be extremely variable. It is more meaningful in terms of radiation protection, and it may be more convenient, easier and more appropriate, to measure concentrations of ^{220}Rn progeny rather than concentrations of ^{220}Rn gas. For ^{220}Rn, there can be severe disequilibrium between the gas and its progeny in dwellings and in other indoor and outdoor environments. Concentrations of ^{220}Rn in ordinary buildings are likely to be significant only if there are elevated concentrations of its parent radionuclide in construction materials that come into contact with the interior air space. In general, the short half-life of ^{220}Rn precludes its transport or diffusion from soil through a masonry foundation to interior spaces. In addition, there is often a considerable difference between the spatial distribution of the gas and the spatial distribution of its progeny in indoor air. This is primarily because of the short half-life of ^{220}Rn in comparison with that of some of its progeny. This difference in spatial distribution makes an assessment of the ^{220}Rn equilibrium more difficult than for ^{222}Rn.

II–23. Various measuring techniques are available for the measurement of ^{220}Rn and its progeny. These techniques are mainly based on the detection of alpha particles emitted in the decay chain, and to a lesser extent they utilize the gamma energies. The alpha detectors used include scintillator ZnS(Ag) detectors, surface barrier type detectors, ionization chambers, electrets and solid state nuclear track detectors.

II–24. For ^{220}Rn gas, a technique using a passive alpha track detector has been developed that measures both ^{222}Rn and ^{220}Rn [II–39, II–40]. In this technique, a dual discriminative alpha track detector utilizing the diffusion properties of ^{222}Rn and ^{220}Rn is used. One of the detectors is placed in a chamber with a high air exchange rate, resulting in a low diffusion barrier to ^{220}Rn and ^{222}Rn. The other detector is constructed to have a low air exchange rate and it acts as a high diffusion barrier to ^{220}Rn but not to ^{222}Rn. From the alpha tracks registered on the two detectors, and by using calibration factors determined using standard calibration chambers, concentrations of both ^{220}Rn and ^{222}Rn can be measured.

II–25. The technique based on the electret ion chamber, generally used to measure ^{222}Rn, has been modified to measure ^{220}Rn [II–34].

II–26. Active techniques such as techniques using Lucas scintillation cells and ionization chambers are also used to measure ^{220}Rn. Because of the different half-lives in the ^{222}Rn and ^{220}Rn decay chains, techniques have been developed in which time differences between the pulses from these series in detectors can be used to distinguish between the radioisotopes and to measure their activities separately [II–41, II–42]. These techniques are based on an analysis of the alpha signals in the detector with respect to elapsed sampling and counting times. The ^{220}Rn radionuclides and their immediate progeny radionuclides ^{216}Po are mostly in secular equilibrium owing to the very short half-life of ^{216}Po (0.15 s). The alpha signals from these nuclides can therefore be electronically logged by a detector as delayed coincidences with the use of computer algorithms to analyse the pulses and to estimate the concentrations of ^{220}Rn gas. This is also useful in the presence of other alpha emitters from among ^{222}Rn or ^{220}Rn progeny. Some types of instrument use a combination of electrostatic collection of ^{220}Rn progeny nuclides on a surface barrier detector followed by alpha spectrometry to determine the concentration of ^{220}Rn gas [II–43]. In such instruments, the alpha energy of ^{216}Po (6.78 MeV) is used to estimate the concentration of ^{220}Rn.

II–27. The concentration of progeny of ^{220}Rn in air can easily be determined by the collection of air samples using a suction pump and alpha activity analysis using delayed counting time sequences [II–43, II–44]. Alpha analysis can be performed either by gross counting or by alpha spectrometry. The concentration of ^{220}Rn gas can also be determined by using a double filter technique [II–45]. In this technique, air is allowed to pass through a metallic tube that has minimum plateout effect of nuclides of ^{220}Rn progeny on the surface and has a designed length. Two filter papers are placed at the inlet and outlet of the tube. The first filter prevents progenies from entering the tube. The gas decays while in transit through the tube and the progenies are collected on the second filter. The second filter is analysed for alpha activity while in transient equilibrium and the concentration of ^{220}Rn gas is determined. For sampling inside dwellings, this technique may require tubes of large volume, which can be inconvenient to carry from one location to another.

II–28. The active methods will not provide data on a long term basis as sampling durations are usually short. There are therefore limitations in the use of active methods for large scale nationwide surveys for epidemiological studies. Sometimes, time integrated passive detection techniques are preferred for this purpose. Recent developments indicate that passive monitors that record alpha emissions from ^{212}Po (at 8.78 MeV, which is the highest alpha energy among the progeny nuclides of ^{222}Rn and ^{220}Rn) on solid state nuclear track detectors allow direct measurements for determining exposure due to ^{220}Rn progeny [II–46, II–47]. The use of aluminized plastic film and a protective film of polypropylene with a total thickness of 71 μm in this method allows only 8.78 MeV alpha particles to penetrate the films and to record tracks. A recent addition is a technique based on the deposition of ^{220}Rn progeny on etched track films with corresponding correlations with time integrating active measurements (by deposition monitors) to estimate the equilibrium equivalent concentration of ^{220}Rn.

II–29. The test method of the American Society for Testing and Materials provides a relatively simple method for the determination of the concentration of radon decay products without the need for specialized equipment built expressly for the purpose [II–48].

MEASUREMENTS FOR RADON DIAGNOSIS

II–30. Radon diagnosis is a complex set of various radon related and non-radon related measurement methods applied for the identification of origins of radon and for the qualitative and quantitative analysis of radon transport pathways [II–49, II–50]. Different measurement techniques and principles described in Annex II can be used as a basis for radon diagnosis focused on the assessment of radon indoors and in soil gas.

REFERENCES TO ANNEX II

[II–1] VANMARCKE, H., BERKEVENS, P., POFFIJN, A., Radon versus radon daughters, Health Phys. **56** (1989) 229–231.

[II–2] UNITED NATIONS, Effects of Ionizing Radiation (2006 Report to the General Assembly), Annex E: Sources-to-Effects Assessment for Radon in Homes and Workplaces, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2009).

[II–3] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 1: Origin of Radon and its Short-lived Decay Products and Associated Measurement Methods, ISO Standard 11665-1:2012, ISO, Geneva (2012).

[II–4] MILES, J.C.H., Temporal variation of radon levels in houses and implications for radon measurement strategies, Radiat. Prot. Dosim. **93** (2001) 369–375.

[II–5] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 6: Spot Measurement Method of the Activity Concentration, ISO Standard 11665-6:2012, ISO, Geneva (2012).

[II–6] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 4: Integrated Measurement Method for Determining Average Activity Concentration using Passive Sampling and Delayed Analysis, ISO Standard 11665-4:2012, ISO, Geneva (2012).
[II–7] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 5: Continuous Measurement Method of the Activity Concentration, ISO Standard 11665-5:2012, ISO, Geneva (2012).
[II–8] STECK, D.J., Annual average indoor radon variations over two decades, Health Phys. **96** (2009) 37–47.
[II–9] ARVELA, M., VOUTILAINEN, I., CASTREN, O., WINQVIST, K., Comparison of predicted and measured variations of radon indoor concentrations, Radiat. Prot. Dosim. **24** (1988) 231–235.
[II–10] WRIXON, A.D., GREEN, B.M.R., LOMAS, P.R., et al., Natural Radiation Exposure in UK Dwellings, NRPB-R190, National Radiological Protection Board, Chilton (1988).
[II–11] MAJBORN, B., Seasonal variations of radon concentrations in single-family houses with different sub-structures, Radiat. Prot. Dosim. **45** (1992) 443–447.
[II–12] PINEL, J., FEARN, T., DARBY, S.C., MILES, J.C.H., Seasonal correction factors for indoor radon measurements in the United Kingdom, Radiat. Prot. Dosim. **58** (1995) 127–132.
[II–13] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 2: Integrated Measurement Method for Determining Average Potential Alpha Energy Concentration of its Short-lived Decay Products, ISO Standard 11665-2:2012, ISO, Geneva (2012).
[II–14] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 3: Spot Measurement Methods of the Potential Alpha Energy Concentration of its Short-lived Decay Products, ISO Standard 11665-3:2012, ISO, Geneva (2012).
[II–15] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 7: Accumulation Methods for Estimating Surface Exhalation Rate, ISO Standard 11665-7:2012, ISO, Geneva (2012).
[II–16] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 8: Methodologies for Initial and Additional Investigations in Buildings, ISO Standard 11665-8:2012, ISO, Geneva (2012).
[II–17] INTERNATIONAL ELECTROTECHNICAL ORGANIZATION, Radiation Protection Instrumentation – Radon and Radon Decay Product Measuring Instruments – Part 1: General Principles, IEC Standard 61577-1, IEC, Geneva (2006).
[II–18] INTERNATIONAL ELECTROTECHNICAL ORGANIZATION, Radiation Protection Instrumentation – Radon and Radon Decay Product Measuring Instruments – Part 2: Specific Requirements for Radon Measuring Instruments, IEC Standard 61577-2, IEC, Geneva (2014).

[II–19] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Radiation Protection Instrumentation – Radon and Radon Decay Product Measuring Instruments – Part 3: Specific Requirements for Radon Decay Product Measuring Instruments, IEC Standard 61577-3, IEC, Geneva (2011).
[II–20] CALMET, D., et al., International standardisation work on the measurement of radon in air and water, Radiat. Prot. Dosim. **145** (2011) 267–272.
[II–21] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Protocols for Radon and Radon Decay Product Measurements in Homes (1993), http://www.epa.gov/radon/pdfs/homes_protocols.pdf
[II–22] HOWARTH, C.B., MILES, J.C.H., Validation Scheme for Organizations Making Measurements of Radon in Dwellings: 2008 Revision, HPA-RPD-047, HPA, Chilton (2008).
[II–23] AUTORITÉ DE SÛRETÉ NUCLÉAIRE, Recueil des dispositions législatives et réglementaires relatives à la radioprotection, Partie 1: Extraits du Code de la santé publique et du code du travail concernant la protection de la population, des patients et des travailleurs contre les dangers des rayonnements ionisants, ASN, Montrouge, France (2013).
[II–24] AUTORITÉ DE SÛRETÉ NUCLÉAIRE, Recueil des dispositions législatives et réglementaires relatives à la radioprotection, Partie 2 : Arrêtés et décisions pris en application du code de la santé publique et du code du travail concernant la protection de la population, des patients et des travailleurs contre les dangers des rayonnements ionisants, ASN, Montrouge, France (2012).
[II–25] IBRAHIMI, Z.-F., MILES, J.C.H., An etched track detector for short-term screening measurements of radon, J. Radiol. Prot. **29** (2009) 139–146.
[II–26] YU, K.N., YOUNG, E.C.M., LI, K.C., A study of factors affecting indoor radon properties, Health Phys. **71** (1996) 179–184.
[II–27] GEORGE, A.C., State of the art instruments for measuring radon/thoron and their progeny in dwellings — A review, Health Phys. **70** (1996) 451–463.
[II–28] GEIGER, E.L., Radon film badge, Health Phys. **13** (1967) 407–411.
[II–29] DURRANI, S.A., ILIĆ, R., Radon Measurements by Etched Track Detectors: Applications in Radiation Protection, Earth Sciences and the Environment, World Scientific Publishing, Singapore (1997).
[II–30] TOKONAMI, S., Why is ^{220}Rn (thoron) measurement important? Radiat. Prot. Dosim. **141** (2010) 335–339.
[II–31] MILES, J.C.H., KENDALL, G.M., IBRAHIMI, F., HOWARTH, C.B., Practical considerations for radon etched track dosimetry service, J. Radiol. Prot. **24** (2004) 165–171.
[II–32] LUETZELSCHWAB, J.W., HASTINGS, L., ELLIS, S.M., Adsorption of Rn-222 by open-faced and diffusion barrier canisters at different conditions of temperature and humidity, Health Phys. **66** (1994) 63–71.
[II–33] HURSH, J.B., The measurement of breath radon by charcoal absorption, Nucleonics **12** 1 (1954) 63–65.
[II–34] KOTRAPPA, P., E-PERM System Manual — Part II 11 — Modified E-PERM for Passive Measurements of Thoron in Air, Rad. Elec. Inc., Frederick, MD (1996).

[II–35] ISHIKAWA, T., Effects of thoron on a radon detector of pulse-ionization chamber type, Radiat. Prot. Dosim. **108** (2004) 327–330.
[II–36] McLAUGHLIN, J.P., The application of techniques to assess radon exposure retrospectively, Radiat. Prot. Dosim. **78** (1998) 1–6.
[II–37] PRESSYANOV, D.S., BUYSSE, J., POFFIJN, A., MEESEN, G., VAN DEYNSE, A., The compact disk as radon detector — a laboratory study of the method, Health Phys. **84** 5 (2003) 642–651.
[II–38] PRESSYANOV, D.S., Modeling a ^{222}Rn measurement technique based on absorption in polycarbonates and track-etch counting, Health Phys. **97** (2009) 604–612.
[II–39] DOI, M., KOBAYASHI, S., FUJIMOTO, K., A passive measurement technique for characterisation of high-risk houses in Japan due to enhanced levels of indoor radon and thoron concentrations, Radiat. Prot. Dosim. **45** (1992) 425–430.
[II–40] TOKONOMI, S., TAKAHASHI, H., KOBAYASHI, Y., ZHOU, W., HULBER, E., Up-to-date radon-thoron discriminative detector for large scale surveys, Rev. Sci. Instrum. **76** (2005) 113505–113509.
[II–41] FALK, R., MORE, H., NYBLOM, L., Measurements of ^{220}Rn in air using a flow-through Lucas cell and multiple time analysis of recorded pulse events, Radiat. Prot. Dosim. **45** (1992) 111–113.
[II–42] IIMOTO, T., KUROSAWA, R., A pulse coincidence ^{220}Rn monitor with three time-gates, Environ. Int. **22** Suppl. 1 (1996) S1139–S1145.
[II–43] McLAUGHLIN, J., An overview of thoron and its progeny in the indoor environment, Radiat. Prot. Dosim. **141** (2010) 316–321.
[II–44] HARIDASAN, P.P., PILLAI, P.M.B., TRIPATHI, R.M., PURANIK, V.D., Occupational radiation exposure due to NORM in a rare-earth compounds production facility, Radiat. Prot. Dosim. **131** (2008) 217–221.
[II–45] KOTRAPPA, P., et al., “Modified double-filter system for measuring radon/thoron in the environment and in exhaled breath”, Advances in Radiation Protection Monitoring (Proc. Symp. Stockholm, 1978), IAEA, Vienna (1979) 423.
[II–46] ZHOU, W., IIDA, T., Estimation of thoron progeny concentrations in dwellings with their deposition rate measurements, Jpn. J. Health Phys. **35** (2000) 365–370.
[II–47] MISHRA, R., MAYYA, Y.S., Study of deposition-based direct thoron progeny sensor (DTPS) technique for estimating equilibrium equivalent thoron concentration (EETC) in indoor environment, Radiat. Meas. **43** (2008) 1408–1416.
[II–48] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Method for Determination of Radon Decay Product Concentration and Working Level in Indoor Atmospheres by Active Sampling on a Filter, ASTM D6327 - 10, West Conshohocken, PA (2010).
[II–49] FROŇKA, A., MOUČKA, L., ČECHÁK, T., Application of the advanced radon diagnosis methods in the indoor building environment, Radiat. Prot. Dosim. **130** (2008) 172–175.
[II–50] FROŇKA, A., Indoor and soil gas radon simultaneous measurements for the purpose of detailed analysis of radon entry pathways into houses, Radiat. Prot. Dosim. **145** (2011) 117–122.

Annex III

PREVENTIVE MEASURES TO REDUCE CONCENTRATIONS OF ^{222}Rn FOR NEW DWELLINGS AND OTHER NEW BUILDINGS

III–1. In an increasing number of States, measures are being introduced in new buildings to prevent the accumulation of ^{222}Rn. It is usually cheaper and easier to incorporate preventive measures for radon into a new building at the time of construction than to take corrective actions for an existing dwelling. Such preventive measures for radon in new buildings will gradually reduce average concentrations of ^{222}Rn in the housing stock, thus helping to reduce the public health impact of long term exposure of the population due to ^{222}Rn indoors. In addition, such measures can improve other aspects of the quality of indoor air. The preventive measures for radon have been developed for world regions with four climatically distinct seasons, and they may need to be checked to ensure that their application in other parts of the world would be appropriate.

III–2. The inclusion of a continuous impermeable membrane designed to isolate the building from the ground over the whole floor area of the dwelling is an effective preventive measure for radon in new buildings. The effectiveness of the anti-radon membrane is very dependent on the care with which it is installed. It is desirable for the anti-radon membrane to be inspected, if possible, as part of the usual checks during the construction of new buildings. The integrity and the durability of the anti-radon membrane are generally more important than its barrier properties against the diffusion of radon. The diffusion coefficient for radon is a suitable parameter for selecting effective radon barriers from among the waterproof materials available on the building market [III–1]. Values of the diffusion coefficient for radon in common waterproof materials can be found in Ref. [III–2]. Measurement of the diffusion coefficient for radon can also be used for testing the airtightness of joints between prefabricated membranes.

III–3. In addition to a membrane, provision may be made for soil (sub-slab) ventilation or depressurization, or sub-floor void ventilation and/or depressurization. The aim of these systems is to dilute concentrations of radon beneath the membrane and to decrease the air pressure in the soil or within the floor void in comparison with the pressure indoors. Passive or active forms of operation of both systems are possible. The need for an exhaust fan depends on the permeability of the soil, the geometry of the foundations, the height of the floor void and the means of ventilation (i.e. with or without vertical exhaust). Passive systems can be activated by installing an extractor fan [III–3]. This can be done at a later stage if measurement of concentrations of radon after the building has been occupied shows that passive ventilation is not effective. Detailed practical advice on preventive measures for ^{222}Rn can be found in the publications of a number of national authorities [III–4 to III–11].

III–4. Preventive measures for ^{222}Rn in new buildings are generally implemented by means of national building codes. Examples of such codes are provided in Table III–1, which is based on Ref. [III–12]. One particularly important attribute of preventive measures for ^{222}Rn is that they will generally be effective in reducing concentrations of other pollutants that would otherwise enter the dwelling with soil gas. This is an important benefit, but one that it may be hard to quantify in a formal way.

III–5. In some States, measurements of concentrations of ^{222}Rn in soil gas and assessments of the permeability of the soil for building sites are made before construction commences so as to provide guidance on the extent of the preventive measures for ^{222}Rn to be included in the dwellings to be built [III–13]. Depending on particular conditions, such measurements can help in improving the efficiency of the design of preventive measures for ^{222}Rn. Building practices used in the construction of energy efficient homes can affect concentrations of ^{222}Rn indoors either positively or negatively. Ensuring that new buildings comply with national standards on airtightness tends to result in a lower rate of air exchange in comparison with existing buildings. By improving the thermal efficiency in a building, the higher temperature of the air indoors may result in a decrease in the pressure inside the building and thus may lead to an increased flow of ^{222}Rn from soil into the building. In some States, relevant building codes have been amended to ensure that high concentrations of ^{222}Rn indoors in energy efficient buildings are avoided.

TABLE III–1. LEGISLATION IN DIFFERENT STATES ON PREVENTIVE MEASURES FOR ^{222}Rn IN NEW BUILDINGS

(Based on work by Lund [III–12] and updated)

State	Regulatory body or national authority	Code, law or act reference no.	Date
Canada	Canadian Commission on Building and Fire Codes	National Building Code of Canada 1995 (Revised 1998)	1998
Czech Republic	State Office for Nuclear Safety	Atomic Law No. 18/1997, as amended Regulation No. 307/2002, as amended	1997 2002
	Czech Office for Standards, Metrology and Testing	Czech Building Standard CSN 730601	2006
Denmark	Ministry of Housing	Building Regulation for Small Dwellings	1998
Finland	Building Information Ltd, in cooperation with Ministry of Environment	Building Information RT — Radon Prevention in New Building RF-81-10791	2003
	Ministry of Environment	Building Code B3 Foundations, and D2 — Indoor Climate and Ventilation in Buildings	2003
Germany	Ministry of Interior of Saxony	Building Regulation of Saxony	1997
	Federal Ministry of Environment, Nature Conservation and Nuclear Safety, Ministries of Environment of the German Federal Lands	Radiation Protection Ordinance	2001
Ireland	Department of Environment	National Building Regulations, and related technical guidance documents	1997
	NSAI/Irish Agreement Board	Technical Assessment and Agreement Certification of radon proof membranes, SI No. 497	1997
Poland	Polish Atomic Energy Agency	No longer in force	Until 2002

TABLE III–1. LEGISLATION IN DIFFERENT STATES ON PREVENTIVE MEASURES FOR ^{222}Rn IN NEW BUILDINGS (cont.)

(Based on work by Lund [III–12] and updated)

State	Regulatory body or national authority	Code, law or act reference no.	Date
Slovenia	Ministry of the Environment and Spatial Planning	Rules on the Ventilation and Air Conditioning of Buildings (Off. Gazette No. 42/2002)	2002
Sweden	National Board of Housing Building and Planning	Building Regulations BFS 2014:3 BBR 21	2014
		Planning and Building Act	1987
Switzer-land	Swiss Federal Office of Public Health	Radiological Protection Act (SR 814.50)	1991
		Radiological Protection Ordinance (SR 814.501)	1994
	Swiss Association of Engineers and Architects (SIA)	Standard SIA 180 — Heat Insulation and Protection from Moisture in Building Construction	1999
United Kingdom	Office of the Deputy Prime Minister, Building Regulations Division	The Building Regulations for England and Wales	1999
	The Department of the Environment for Northern Ireland	The Building Regulations for Northern Ireland	2001
	The Scottish Executive	The Building Regulations for Scotland	1999

REFERENCES TO ANNEX III

[III–1] JIRÁNEK, M., ROVENSKA, K., Basic principles for the development of a common standardised method for determining the radon diffusion coefficient in waterproofing materials, Appl. Radiat. Isot. **70** (2012) 752–757.

[III–2] JIRÁNEK, M., KOTRBATÁ, M., Radon diffusion coefficients in 360 waterproof materials of different chemical composition, Radiat. Prot. Dosim. **145** 1 (2012) 178–183.

[III–3] ARVELA, H., HOLMGREN, O., REISBACKA, H., Radon prevention in new construction in Finland: a nationwide sample survey in 2009, Radiat. Prot. sim. **148** 4 (2012) 465–474.
[III–4] UNITED KINGDOM BUILDING RESEARCH ESTABLISHMENT, Radon: Guidance on Protective Measures for New Buildings, Report No. BR 211, BRE, Garston (2007).
[III–5] BUNDESUMWELTMINISTERIUM (BMU), BUNDESAMT FÜR STRAHLENSCHUTZ (BfS), Das Radon-Handbuch Deutschland, BMU, Bonn (2001).
[III–6] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Build Radon Out: a Step by Step Guide on How to Build Radon Resistant Homes (2001), http://www.epa.gov/radon/pdfs/buildradonout.pdf
[III–7] DEPARTMENT OF THE ENVIRONMENT AND LOCAL GOVERNMENT, Radon in Existing Buildings: Corrective Options, Dublin (2002), http://www.environ.ie/en/DevelopmentHousing/BuildingStandards/PublicationsDocuments/FileDownLoad,1656,en.pdf
[III–8] UNITED KINGDOM BUILDING RESEARCH ESTABLISHMENT, How to reduce radon levels in your home, UK BRE, Garston, Watford (2000), http://www.bre.co.uk/radon/reduce.html
[III–9] CZECH OFFICE FOR STANDARDS, Protection of Houses against Radon from the Soil, CSN 730601, Czech Office for Standards, Metrology and Testing, Prague (2006).
[III–10] SWISS FEDERAL OFFICE OF PUBLIC HEALTH, Recommandations de l'OFSP pour les bâtiments neufs (2012), http://www.bag.admin.ch/themen/strahlung/00046/11592/index.?lang=en&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1ad1IZn4Z2qZpnO2Yuq2Z6gpJCEfX5_f2ym162epYbg2c_JjKbNoKSn6A--
[III–11] ÖSTERREICHISCHE AGENTUR FÜR GESUNDHEIT UND ERNÄHRUNGSSICHERHEIT, MINISTERIUM FÜR UMWELT NATURSCHUTZ UND VERKEHR BADEN-WÜRTTEMBERG, BAYERISCHES LANDESAMT FÜR UMWELT, LANDESAGENTUR FÜR UMWELT BOZEN, SWISS FEDERAL OFFICE OF PUBLIC HEALTH, AMT DER OBERÖSTERREICHISCHE LANDESREGIERUNG, Radon: Precautions for New Buildings (2011), http://www.bag.admin.ch/themen/strahlung/00046/11592/index.html?lang=en&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1ad1IZn4Z2qZpnO2Yuq2Z6gpJCJfH18g2ym162epYbg2c_JjKbNoKSn6A--
[III–12] LUND, C.E., Protecting new buildings, Deliverable D7 of the ERRICCA Project, European Commission, Luxembourg (2004).
[III–13] NEZNAL, M., NEZNAL, M., MAOTLIN, M., BARNET, I., MIKSOVA, J., The New Method for Assessing the Radon Risk of Building Sites, Czech Geological Survey Special Papers 16, Czech Geological Survey, Prague (2004).

Annex IV

CORRECTIVE ACTIONS TO REDUCE CONCENTRATIONS OF ^{222}Rn IN EXISTING DWELLINGS AND OTHER BUILDINGS

CORRECTIVE ACTIONS TO REDUCE CONCENTRATIONS OF ^{222}Rn

IV–1. The reduction of high concentrations of ^{222}Rn in existing dwellings by means of corrective actions has been demonstrated to be feasible. The corrective actions are designed either to prevent the entry of ^{222}Rn from the soil into a building or to remove ^{222}Rn from the building by means of improved indoor ventilation. The effectiveness of any corrective actions depends on the construction of the dwelling and the climate as well as the lifestyle of the occupants. The corrective actions have been developed for world regions with four climatically distinct seasons, and they may need to be checked to ensure that their application in other parts of the world would be appropriate.

IV–2. Corrective actions are described as active or passive. Passive corrective actions do not require any form of mechanical assistance whereas active corrective actions rely on mechanical assistance to achieve optimum performance. Examples of passive corrective actions include the use of impermeable ^{222}Rn barriers, wall vents and window vents. Examples of active measures include the use of fan assisted underfloor depressurization for ^{222}Rn, fan assisted underfloor ventilation and mechanical indoor ventilation of the building. The main drawbacks of active measures are their costs and the need for regular checks of their proper functioning and long term maintenance. Passive measures are generally less costly but also less effective than active measures, and they can be completely or partially ineffective.

IV–3. The practical application and the effectiveness of such corrective actions are described below. Use of these measures needs to be guided by more detailed technical information which can be obtained elsewhere [IV–1 to IV–4]. A number of national authorities have published advice on corrective actions for ^{222}Rn [IV–5] and an important review of this and other ^{222}Rn related matters in Europe has been published [IV–6]. The corrective actions may vary from State to State, and corrective actions may need to be developed by some States to take account of national building practices.

IV–4. In some instances, tests may be carried out to help determine the most appropriate corrective actions [IV–3]. The principle of optimization has to be applied so that a determined effort is made to reduce concentrations of ^{222}Rn significantly, rather than to just below the reference level. An example of cost effectiveness and cost–benefit analysis applied to corrective actions is provided in Ref. [IV–7].

IV–5. Following corrective actions, concentrations of ^{222}Rn need to be measured in order to verify that they have been reduced sufficiently.

IV–6. In a few cases, the origin of ^{222}Rn indoors may be building materials rather than the ground beneath the building [IV–8]. In these circumstances, a restriction on the use of certain building materials may need to be considered. If building materials are the main origin of radon in existing buildings, concentrations of radon indoors can be reduced by removing building materials with a high rate of exhalation of radon; by creating a ventilated air gap around the building materials with a high rate of exhalation of radon; or by increasing indoor ventilation [IV–9]. The application of impermeable surface coatings onto the surface of building materials is to be avoided, because its effectiveness is very low for ^{222}Rn. However, surface coatings may be effective for reducing ^{220}Rn emanation (see para. 3.67).

IV–7. Building practices used in the retrofitting of buildings to make them energy efficient can affect the concentrations of ^{222}Rn indoors either positively or negatively [IV–10, IV–II]. Improving the airtightness of buildings reduces the mixing between indoor air and outdoor air. By improving the thermal efficiency in a building, the higher temperature of the air indoors may result in a decrease in the pressure inside the building and thus may lead to an increased flow of ^{222}Rn from soil into the building. Some States have amended relevant building codes to ensure that high concentrations of ^{222}Rn indoors in retrofitted buildings are avoided. An example of advice provided by a national authority on the effect of retrofitting thermal insulation is given in reference [IV–12].

SOIL VENTILATION AND DEPRESSURIZATION

IV–8. Systems for soil ventilation and depressurization can have the forms of:

(a) Perforated pipes placed into the drainage layer under the new floor, if the existing floor is to be replaced by a new one.
(b) Perforated tubes inserted by drilling into the original ground below the existing floor without disrupting the floor; insertion into the ground

is possible from the cellar, from an assembly pit in one of the rooms, or from the exterior.

(c) A radon sump that is a cavity about the size of a bucket in the ground immediately under the floor slab which is linked by pipework to the outside; the sump may be constructed by excavating through the floor slab or by inserting a pipe through the foundation wall from outside the dwelling.

(d) A radon well that is constructed under the building or in its proximity. The depth for the radon well is usually 3–5 m. Such a well has a permeable construction that allows air to be drawn from the adjacent soil.

These systems for soil ventilation and depressurization operate by reversing the pressure differential between the soil under the floor and the room above.

IV–9. A small electric fan in the pipeline is usually used to control the underpressure and systems using such fans are known as active systems. Where a fan is not used, the arrangement is referred to as a passive system. Passive systems rely on natural pressure differentials caused by temperature differences and winds for their effectiveness. A passive system has the advantage of having no operating costs and being absolutely silent and usually not needing regular checks or long term maintenance. However, passive systems are generally less effective than an active system. Where concentrations of ^{222}Rn are several hundred becquerel per cubic metre or higher, an active system is likely to be the most effective solution.

INCREASED UNDERFLOOR VENTILATION

IV–10. For dwellings with suspended wooden or concrete floors, increasing the flow of air beneath the floor can reduce the amounts of ^{222}Rn entering the building. An increase in the flow of air can be achieved by the installation of additional underfloor vents or airbricks or the clearing or replacement of existing ones. Plastic airbricks are now available with a larger open surface than clay airbricks of the same size. The position of the airbricks can have a significant influence on the reduction in concentrations of ^{222}Rn achieved, as placing the airbricks in dead spaces with no flow of air will reduce their effectiveness.

IV–11. If it is found that the desired reduction in concentrations of ^{222}Rn has not been achieved by using passive measures, installing a fan can increase underfloor ventilation further. Fans can be installed to blow air into the underground space (supply ventilation) or to exhaust air from the underground space (extraction ventilation). When installing a fan, attention has to be paid to the possible dangers of condensation of moisture or of frost in the pipework, leading to damage to the fan.

POSITIVE PRESSURIZATION

IV–12. The method of positive pressurization as a corrective action for ^{222}Rn involves blowing air into the dwelling or into the basement by means of a specially installed fan in the attic. This reduces or even reverses the normal underpressure in the dwelling in relation to outside air, which reduces the entry of ^{222}Rn. Air may be drawn from the attic itself or from outside. In either case, considerably colder air is drawn into the dwelling which necessitates increased heating.

IV–13. Positive pressurization is best applied in relatively airtight dwellings and has been found to be most effective in single storey dwellings [IV–4]. Positive pressurization systems are straightforward to install and require no major structural intrusion, but they have the great disadvantage of causing condensation. This measure is therefore not suitable in cold climates. Furthermore, the running costs of such a system are likely to be greater than for an active soil depressurization system.

AIR GAP VENTILATION OR DEPRESSURIZATION

IV–14. Air gaps are created around constructions (walls and floors) that are in direct contact with the soil. Ventilating or inducing a slight underpressure in these gaps reduces the transport of radon from the soil into the house. Passive or active forms of ventilation are possible. Air gaps are very effective in cases where there is not only entry of ^{222}Rn but also damp affecting the construction.

INCREASING INDOOR VENTILATION

IV–15. It might be possible to increase the ventilation in a dwelling by unblocking air vents, providing additional wall vents or installing window trickle vents. Increasing the ventilation mixes indoor air rich in ^{222}Rn with outdoor air, thereby reducing the concentrations of ^{222}Rn in indoor air. Installing or unblocking air vents also reduces the underpressure in a dwelling and so reduces the tendency for ^{222}Rn to be drawn into the dwelling from the ground.

IV–16. Increasing the background ventilation as a corrective action against ^{222}Rn needs to be done only at the ground floor level. Increasing the ventilation in upper floors could result in higher concentrations of ^{222}Rn. This is because increasing the ventilation on upper floors could cause a stack effect, which draws air up through the dwelling.

IV–17. Concentrations of ^{222}Rn tend to be highest where the temperature differential between indoors and outdoors is greatest, so increased ventilation is unlikely to be an effective solution unless the householder is prepared to maintain the high ventilation rate throughout the winter [IV–7].

IV–18. Increased natural ventilation has the advantage of being fully passive and so does not require long term maintenance. It may also help to improve the quality of indoor air in general.

IV–19. A heat recovery ventilation system (with air-to-air heat exchanger) is a powered system to increase the ventilation in a dwelling while heating (or, if necessary, cooling) the incoming air with the air that is being extracted. Such systems can also help to reduce concentrations of ^{222}Rn in indoor air.

IV–20. Air conditioning systems can affect the entry of ^{222}Rn into dwellings from the ground. It is important to ensure that the balance between incoming air and outgoing air is maintained to ensure that the air conditioning system does not create an underpressure in the dwelling but, if possible, creates a slight overpressure. If the air conditioning system increases the ventilation rate of a dwelling, it will also contribute to reducing concentrations of ^{222}Rn by diluting the ^{222}Rn indoors.

SEALING OF FLOORS AND WALLS

IV–21. In theory, it is possible to prevent ^{222}Rn from entering a dwelling from the ground by sealing all ^{222}Rn entry points, such as cracks in solid floors, cracks or openings in walls in contact with the ground and gaps around cables and pipes. In practice, however, effective sealing is often extremely difficult to achieve and it is more likely to be useful if applied in conjunction with other methods rather than on its own.

IV–22. Sealing all possible entry routes for ^{222}Rn into a dwelling from the ground involves removing floor coverings and skirting boards and then sealing all cracks and joints with a suitable sealant. The sealant must be durable and flexible enough to accommodate future movements of building structures.

IV–23. For this sealing method to be successful, effectively, all gaps have to be sealed. However, some gaps may not be visible and over time new cracks and openings can develop. There could also be an increased flow of ^{222}Rn through any remaining gaps. As a result, it could be that only slight reductions in concentrations of ^{222}Rn are achieved.

IV–24. If it is possible to cover the ground beneath a suspended floor with a membrane (for a dwelling with a crawl space, for example), then this could be a useful corrective action to reduce concentrations of ^{222}Rn, in particular if it is combined with use of a pump to reduce the pressure beneath the membrane (as with a sump). Great care must be taken in applying a membrane directly to a wooden floor as this could cause the wood to rot.

REFERENCES TO ANNEX IV

[IV–1] SCIVYER, C., Surveying Dwellings with High Indoor Radon Levels: A BRE Guide to Radon Remedial Measures in Existing Dwellings, Building Research Establishment, BRE Report No. 250, BRE, Garston (1993).

[IV–2] UNITED KINGDOM BUILDING RESEARCH ESTABLISHMENT, “Buildings and radon”, BRE Good Building Guides and Good Repair Guides: A Library of Information for all Construction Professionals, BRE, Garston (2013).

[IV–3] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Consumer’s Guide to Radon Reduction (2013), http://www.epa.gov/radon/pubs/consguid.html

[IV–4] NAISMITH, S.P., MILES, J.C.H., SCIVYER, C.R., The influence of house characteristics on the effectiveness of radon remedial measures, Health Phys. 75 (1998) 410–416.

[IV–5] ÖSTERREICHISCHE AGENTUR FÜR GESUNDHEIT UND ERNÄHRUNGSSICHERHEIT, MINISTERIUM FÜR UMWELT NATURSCHUTZ UND VERKEHR BADEN-WÜRTTEMBERG, BAYERISCHES LANDESAMT FÜR UMWELT, LANDESAGENTUR FÜR UMWELT BOZEN, SWISS FEDERAL OFFICE OF PUBLIC HEALTH, AMT DER OBERÖSTERREICHISCHE LANDESREGIERUNG, Radon – Mitigation measures in existing buildings (2011), http://www.bag.admin.ch/themen/strahlung/00046/11592/index.html?lang=en&download=NHzLpZig7t,lnp6I0NTU042l2Z6ln1ad1IZn4Z2qZpnO2Yuq2Z6gpJCJfH19e2ym162dpYbUzd,Gpd6emK2Oz9aGodetmqaN19XI2IdvoaCVZ,s-

[IV–6] SWEDJEMARK, G.A., The history of radon from a Swedish perspective, Radiat. Prot. Dosim. 109 (2004) 421–426.

[IV–7] JIRÁNEK, M., ROVENSKÁ, K., Limited applicability of cost-effectiveness and cost-benefit analyses for the optimization of radon remedial measures, J. Hazard. Mater. 182 (2010) 439–446.

[IV–8] CZECH OFFICE FOR STANDARDS, Protection of Buildings against Radon from the Soil, Czech Office for Standards, Metrology and Testing, CSN 730601 (2006).

[IV–9] CZECH OFFICE FOR STANDARDS, Protection of Buildings against Radon and Gamma Radiation from Building Materials, Czech Office for Standards, Metrology and Testing, CSN 730602 (2000).

[IV–10] JIRANEK, M., KACMARIKOVA, V., Dealing with the increased radon concentration in thermally retrofitted buildings, Radiat. Prot. Dosim. 160 (2014) 43–47.

[IV–11] FOJTIKOVA, I., NAVRATILOVA ROVENSKA, K., Influence of energy-saving measures on the radon concentration in some kindergartens in the Czech Republic, Radiat. Prot. Dosim. **160** (2014) 149–153.

[IV–12] ÖSTERREICHISCHE AGENTUR FÜR GESUNDHEIT UND ERNÄHRUNGSSICHERHEIT, MINISTERIUM FÜR UMWELT NATURSCHUTZ UND VERKEHR BADEN-WÜRTTEMBERG, BAYERISCHES LANDESAMT FÜR UMWELT, LANDESAGENTUR FÜR UMWELT BOZEN, SWISS FEDERAL OFFICE OF PUBLIC HEALTH, AMT DER OBERÖSTERREICHISCHE LANDESREGIERUNG, Radon – The effect of retrofitting thermal insulation (2011),
http://www.bag.admin.ch/themen/strahlung/00046/11592/index.html?lang=en&download=NHzLpZig7t,lnp6I0NTU042l2Z6ln1ad1IZn4Z2qZpnO2Yuq2Z6gpJCJfH18gWym162dpYbUzd,Gpd6emK2Oz9aGodetmqaN19XI2IdvoaCVZ,s-

Annex V

PUBLIC INFORMATION PROGRAMMES ON RISKS DUE TO RADON

V–1. Public concern about radon is generally lower than public concern about other comparable risks, or about much lower risks such as those associated with artificial radiation. Lee [V–1] reported that the public tends to be most concerned about hazards that are:

(a) Human made rather than natural;
(b) Imposed by a human agency rather than arising by chance;
(c) Able to cause harm to groups rather than individuals;
(d) Obvious, immediate and 'dread' rather than covert, delayed and familiar.

V–2. None of the four above mentioned factors that would increase concern apply to radon, and a study has found that householders often deny that a health risk exists [V–2]. For this reason, public information programmes are necessary for the risks due to radon to be taken seriously.

V–3. Authorities in many States have recognized the need for public information programmes on radon, and have taken steps to increase public awareness of the risks due to radon. Whatever the specific approach taken to increasing public awareness, progress requires the long term efforts of several parties: national and local government, health authorities, national and international radiation protection and environmental organizations, regulatory bodies and the public themselves. Activities for awareness of radon in Europe are described by Scivyer [V–3, V–4] and through the work of the European Commission Radon Prevention and Remediation group, whose work includes risk communication [V–5].

V–4. Perhaps the most important group to be targeted by activities for awareness of radon are building owners, but other important groups include local authority staff, surveyors, builders, housing professionals, estate agents, solicitors, health and safety professionals and the medical profession. The broad message to be conveyed is the same in all cases but the specified focus and the degree of detail and packaging needs to be tailored to their specific needs.

V–5. One particularly important point is the provision of simply written material (possibly web based) aimed at the non-specialist. Examples include:

— A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon [V–6];

— Home Buyer's and Seller's Guide to Radon [V–7];
— Radon: A Guide for Canadian Homeowners [V–8];
— Understanding Radon Remediation: A Householder's Guide [V–9];
— Radon — Hauptursache der natürlichen Strahlenexposition (Radon — Main Source of Natural Radiation); Radon in Häusern (Radon in Houses); Maßnahmen zum Schutz vor erhöhten Radonkonzentrationen in Gebäuden (Measures to protect against high concentrations of radon in buildings) [V–10];
— Das Radon-Handbuch Deutschland (Radon Handbook Germany) [V–11];
— Radon - Don't Live with the Risk [V–12];
— Vågen till ett radonfritt boende (Living safely with radon) [V–13];
— Rischio radon: cosa è, come si previene, come si misura, come si interviene — 13 quesiti sul problema Radon (The Hazard of Radon: What it is, how it is prevented, how it is measured, how it is mitigated — 13 questions on the radon problem) [V–14];
— The Risks to Your Health from Radon [V–15];
— Le radon dans le bâtiment — Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves (Radon in buildings — Guide for remediation in existing constructions and prevention in new constructions) [V–16];
— National Action Plan concerning Radon 2012 – 2020 [V–17];
— Radon: Informations sur un thème "rayonnant" (Radon: Information on a 'radiating' topic) [V–18].

V–6. 'Radon campaigns' at a national level are useful in raising awareness of exposure due to radon as a public health issue. However, measurement campaigns and corrective action campaigns can be more effective if they are carried out at the local level [V–19, V–20]. This is both because the public and officials are more familiar with circumstances in their own local area and because there may be less scepticism among the public towards a message delivered by local officials. Local campaigns allow the possibility of a leaflet targeted specifically at local concerns and open up the possibility of cheap and effective methods of delivery such as display stands in libraries and public offices. The establishment of radon campaigns involving professionals who are aware of the radon issue can have a significant impact in helping to reduce the risks due to radon by promoting radon measurements and corrective actions. Such professionals include local authority staff, surveyors, builders, housing professionals, estate agents, solicitors, health and safety professionals and the medical profession.

V–7. The involvement of electronic and print media is an important part of radon campaigns. The message in the national and local press needs to be consistent. Local radio can also play an important part. Articles in specialist publications and newsletters targeting specific authorities and professional audiences are important in their own right and can support awareness campaigns [V–21, V–22].

V–8. Ideally, information can also be provided to the public face to face. Visits to dwellings by local authority staff take staff time but can prove highly effective in encouraging owners to carry out corrective actions. Exhibitions or citizens' evenings staffed by local authority personnel and national experts can also help to reduce the risks due to radon by promoting corrective actions. Remote advice services such as telephone hotlines and websites are cost effective means of disseminating advice and guidance.

REFERENCES TO ANNEX V

[V–1] LEE, T.R., The public's perception of radon, Radiat. Prot. Dosim. **42** (1992) 257–262.

[V–2] ZHANG, W., CHOW, Y., MEARA, J., GREEN, M., Evaluation and equity audit of the domestic radon programme in England, Health Policy **102** (2011) 81–88.

[V–3] SCIVYER, S., Review of Radon Awareness Activities in Europe, Building Research Establishment, Garston (2005).

[V–4] SCIVYER, S., Compilation of Responses to Radon Public Awareness Raising Questionnaires 2002–2003, Building Research Establishment, Garston (2005).

[V–5] EUROPEAN COMMISSION, Radon Prevention and Remediation: Overview and Background (2014), http://web.jrc.ec.europa.eu/radpar/

[V–6] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon, US EPA (2012), http://www.epa.gov/radon/pubs/citguide.html

[V–7] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Home Buyer's and Seller's Guide to Radon (2013), http://www.epa.gov/radon/pubs/hmbyguid.html

[V–8] CANADA MORTGAGE AND HOUSING COMMISSION, HEALTH CANADA, Radon: A Guide for Canadian Homeowners, CMHC and Health Canada, Ottawa (1997).

[V–9] RADIOLOGICAL PROTECTION INSTITUTE OF IRELAND, Understanding Radon Remediation: A Householder's Guide, RPII, Dublin (1997).

[V–10] BUNDESAMT FÜR STRAHLENSCHUTZ, Radon — Hauptursache der natürlichen Strahlenexposition (2013),
http://www.bfs.de/de/bfs/publikationen/broschueren/ionisierende_strahlung/radon/
[V–11] BUNDESUMWELTMINISTERIUM (BMU), BUNDESAMT FÜR STRAHLENSCHUTZ (BfS), Das Radon-Handbuch Deutschland, BMU, Bonn (2001).
[V–12] HEALTH PROTECTION AGENY, Radon — Don't Live with the Risk, Health Protection Agency, Chilton, Didcot (2005),
http://www.doeni.gov.uk/niea/radon_at_home__at_work_booklet.pdf
[V–13] STATENSSTRALSKYDDS-INSTITUT (Swedish Radiation Safety Authority), Vågen till ett radonfritt boende (2009),
http://www.stralsakerhetsmyndigheten.se/Global/Publikationer/Broschyr/2009/Faktablad_Vagen_till_ett_radonfritt_boende2.pdf
[V–14] ASSOCIAZIONE NAZIONALE PROFESSIONALE ESPERTI QUALIFICATI, Rischio radon: cosa è, come si previene, come si misura, come si interviene — 13 quesiti sul problema Radon (2003),
http://www.anpeq.it/anpeq/download/libretto_radon.pdf
[V–15] UNITED KINGDOM HEALTH PROTECTION AGENCY, The Risks to Your Health from Radon (2009),
http://www.ukradon.org/article.php?key=risksradon
[V–16] CENTRE SCIENTIFIQUE ET TECHNIQUE DU BÂTIMENT, Le radon dans les bâtiments, Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves, CSTB, Paris (2008).
[V–17] SWISS FEDERAL OFFICE OF PUBLIC HEALTH, National Action Plan concerning Radon 2012–2020, Bern (2011),
http://www.bag.admin.ch/themen/strahlung/00046/11649/index.html?lang=en
[V–18] SWISS FEDERAL OFFICE OF PUBLIC HEALTH, Radon: Informations sur un Thème "Rayonnant" (2008),
http://www.bag.admin.ch/themen/strahlung/00046/index.html?lang=en
[V–19] POORTINGA, W., BRONSTERING, K., LANNON, S., Awareness and perceptions of the risks of exposure to indoor radon: a population-based approach to evaluate a radon awareness and testing campaign in England and Wales, Risk Anal. **31** (2011) 1800–1812.
[V–20] KENDALL, G.M., GREEN, B.M.R., MILES, J.C.H., DIXON, D.W., The development of the UK radon programme, J. Radiol. Prot. **25** 4 (2005) 475–492.
[V–21] POORTINGA, W., BRONSTERING, K., LANNON, S.C., Awareness and perceptions of the risks of exposure to indoor radon: A population-based approach to evaluate a radon awareness and testing campaign in England and Wales, Risk Anal. **31** (2011) 1800–1812.
[V–22] FOJTIKOVA, I., ROVENSKA, K., Radon programmes and health marketing, Radiat. Prot. Dosim. **145** (2011) 92–95.

Annex VI

APPLICATION OF THE COMPLIANCE ALGORITHMS FOR BUILDING MATERIALS

METHOD USED FOR THE ASSESSMENT OF DOSES FROM BUILDING MATERIALS

VI–1. A method is presented in this Annex for calculating dose due to external gamma radiation from building materials on the basis of the approach of Markkanen [VI–1]. The results are given in tabular form as specific dose rates. This allows the most typical dose assessments to be made without computer calculations. Five examples of such assessments are given in this Annex.

VI–2. The method is based on calculating the dose rate for a rectangular building constructed of building material of uniform density and containing radionuclides of uniform activity concentration. The dose rate indoors is calculated by summing the separately calculated dose rates due to radionuclides in the walls, floor and ceiling of a room as presented in Fig. VI–1. The effects of doors and windows will lower the dose rate by only a minor amount and so for simplicity doors and windows are not considered in the calculation. The calculation covers situations in which the radionuclides are distributed in two layers of separate building materials with different densities and activity concentrations; for example, concrete walls covered with a thin layer of another material such as tiles.

VI–3. In many cases, building materials themselves provide significant shielding against gamma radiation from the soil in the terrestrial background. In the case of massive concrete structures, the shielding is almost complete. The reference level of 1 mSv/a used for building materials is defined as due to the ‘excess exposure’ caused by these materials above the exposure due to normal background levels of radiation. The basic approach in determining the ‘excess exposure’ is as follows:

(a) First, the total exposure due to the building material and the background levels is calculated, after allowance for the shielding provided by the building material against gamma radiation in the terrestrial background.
(b) The exposure to gamma radiation in the terrestrial background is then subtracted.
(c) The result for comparison with the reference level is referred to as the ‘excess exposure’.

VI–4. In the example calculations presented below, a world population weighted average dose rate of 60 nGy/h is assumed for gamma radiation in the terrestrial background [VI–2]. The applicable level of gamma radiation in the terrestrial background is to be used for calculations carried out in States. The possible shielding effect of materials for cosmic radiation is considered to be small, and therefore exposure to cosmic radiation is not considered in the assessments.

VI–5. The gamma dose rate is calculated in the middle of the standard sized room shown in Fig. VI–1. The specific gamma dose rates contributed by the walls, floor and ceiling are given in Table VI–1. The total dose rate indoors is calculated by summing the separately calculated dose rates due to walls, floor and ceiling. Various dose assessments resulting from the use of the specific dose rates given in Table VI–1 are described in Examples 1–5. The dose assessments provide examples relating to massive concrete structures (e.g. apartment blocks) and for a smaller, simpler type of structure such as those widely found in the rural areas of developing countries.

VI–6. A conversion factor of 0.7 Sv/Gy is used for converting the absorbed dose in air to an effective dose [VI–3].

VI–7. Risica et al. have carried out a sensitivity analysis concerning the effects of changes in the parameters for the room on the dose in the room and found the following results [VI–4]:

(a) The variation in the dose rate in air in relation to the position in the room was found to be limited to approximately 10% at a distance of up to 1 m from the walls.
(b) The absorbed dose rate in air was calculated as a function of room dimensions for a fixed height of 2.8 m and various widths and lengths of the room ranging from 2 m to 10 m were used, in both rectangular and square shapes. The maximum variation in the dose rate obtained was 6% from the calculation for a room with a volume of 60 m^3.
(c) The absorbed dose rate in air in the room was calculated as a function of the wall, floor and ceiling thickness. It was found that up to a thickness of 0.4 m, increasing the thickness increases the radiation dose rate, whereas when the thickness is greater than 0.4 m, self-absorption in the material makes the effect of a further increase in thickness negligible.

It can therefore be concluded that the variation in the dose rate in the model room is not significantly affected for room sizes ranging from 12 m^2 to 100 m^2 for a fixed room height of 2.8 m, or for variations in the wall thickness.

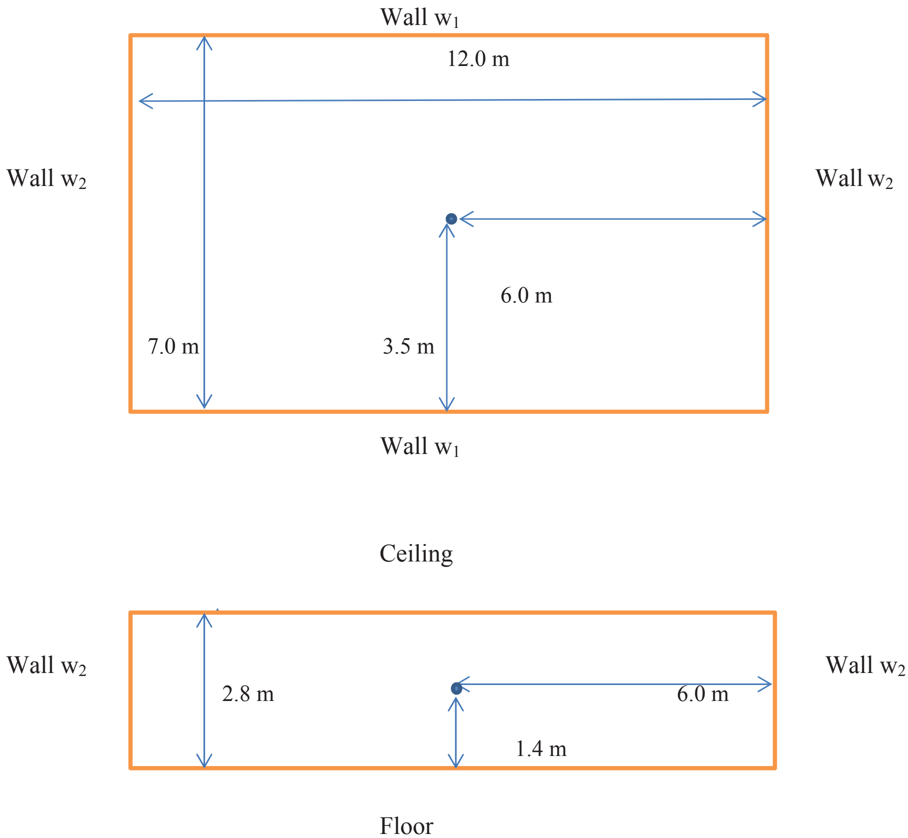

FIG. VI–1. The geometry used in the calculation of the gamma dose rate indoors due to building materials.[1]

[1] The dose rates are calculated for the centre point of the room. It can be shown that because of the 4π type exposure geometry, the dose rates at other points in the room do not vary by more than about 5–10% from that at the centre point. The dose rate at the centre point is therefore a good approximation for the dose rate within the whole room.

TABLE VI–1. SPECIFIC GAMMA DOSE RATE IN AIR DUE TO THE DIFFERENT STRUCTURES IN THE ROOM SHOWN IN FIG. VI–1

Mass per unit area of wall, ceiling or floor material[a] (kg/m^2)	Wall, ceiling or floor material (top layer)[b] (pGy/h per Bq/kg)			0.2 m thick concrete behind the wall, ceiling or floor material[c] (pGy/h per Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Wall w_1: Dimensions 12.0 m × 2.8 m, distance 3.5 m						
0	0	0	0	95	110	8.0
25	9	10	0.73	87	100	7.3
50	18	21	1.5	80	94	6.7
100	35	40	2.8	65	77	5.6
150	50	56	3.9	52	62	4.6
200	61	70	4.9	40	50	3.8
300	79	91	6.4	24	31	2.5
500	96	110	8.1	8	12	1.0
Wall w_2: Dimensions 7.0 m × 2.8 m, distance 6.0 m						
0	0	0	0	32	37	2.7
25	2.7	3.1	0.22	30	35	2.5
50	5.5	6.2	0.44	28	32	2.3
100	11	12	0.85	22	27	2.0
150	15	18	1.2	19	23	1.7
200	20	22	1.6	16	19	1.4
300	26	30	2.1	10	13	1.0
500	33	38	2.7	3.7	5.4	0.45
Floor or ceiling: Dimensions 12.0 m × 7.0 m, distance 1.4 m						
0	0	0	0	350	420	30
25	46	52	3.7	310	370	27
50	90	100	7.1	270	330	24
100	160	190	13	200	250	18

TABLE VI–1. SPECIFIC GAMMA DOSE RATE IN AIR DUE TO THE DIFFERENT STRUCTURES IN THE ROOM SHOWN IN FIG. VI–1 (cont.)

Mass per unit area of wall, ceiling or floor material[a] (kg/m^2)	Wall, ceiling or floor material (top layer)[b] (pGy/h per Bq/kg)			0.2 m thick concrete behind the wall, ceiling or floor material[c] (pGy/h per Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
150	220	250	18	150	180	14
200	260	300	21	110	140	11
300	310	360	26	56	78	6.3
500	350	420	30	15	27	2.2

[a] Mass per unit area of the wall, floor or ceiling is the product of the thickness and the density of the structure. For example, in the case of a 0.15 m thick wall made of building blocks whose density is 2000 kg/m^3, the mass per unit area of the wall is 0.15 m × 2000 kg/m^3 = 300 kg/m^2.

[b] This is the dose rate due to the wall, w_1 or w_2, or floor or ceiling, which have a certain mass per unit area. For example, if the wall w_1 has a mass per unit area of 300 kg/m^2 and its activity concentration of ^{226}Ra is 100 Bq/kg, the dose rate due to the ^{226}Ra in the wall w_1 is (79 pGy/h per Bq/kg) × (100 Bq/kg) = 7900 pGy/h = 7.9 nGy/h = 0.0079 μGv/h. The 'top layer' in brackets refers to the case where the wall, ceiling or floor structure comprises two different material layers; for example, a tile on top and a concrete structure behind it. In such a case, the specific dose rates given in this column can be used for the 'top layer' material, such as the tiles.

[c] In the case of a two layer structure (see footnote b), this column gives the dose rate for a 20 cm thick concrete structure behind the top layer. The shielding effect of the top layer is considered and the dose rate from this second material layer therefore becomes smaller as the mass per unit area of the top layer increases.

EXAMPLES OF DOSE ASSESSMENTS

Example 1: Exposure to gamma radiation in a concrete room where the concentrations of ^{226}Ra and ^{232}Th are slightly above average

VI–8. The walls, floor and ceiling of a room are constructed of concrete, as shown in Fig. VI–1. The concrete is assumed to have slightly elevated levels of radionuclides of natural origin. The room is assumed to have the specifications shown in Table VI–2.

TABLE VI–2. EXAMPLE 1: SPECIFICATIONS OF THE ROOM SHOWN IN FIG. VI–1

Radionuclide	Floors, ceiling, walls (concrete)
	Activity concentration
^{226}Ra	80 Bq/kg
^{232}Th	80 Bq/kg
^{40}K	800 Bq/kg
Other parameters	
Density of concrete	2350 kg/m^3
Thickness of concrete	0.20 m

VI–9. The mass per unit area of the walls, floor and ceiling is 2350 kg/m^3 × 0.20 m = 470 kg/m^2, thus the specific dose rates for a mass per unit area of 500 kg/m^2 in Table VI–1 are used. The dose rate in the room is calculated as shown in Table VI–3.

TABLE VI–3. EXAMPLE 1: THE DOSE RATE IN THE ROOM AS SHOWN IN FIG. VI–1

Source	Calculation	Dose rate
w_1 (concrete)	2 × (96 × 80 + 110 × 80 + 8.1 × 800)	0.045 9 μGy/h
w_2 (concrete)	2 × (33 × 80 + 38 × 80 + 2.7 × 800)	0.015 7 μGy/h
Floor and ceiling (concrete)	2 × (350 × 80 + 420 × 80 + 30 × 800)	0.171 2 μGy/h
Total dose rate in a room (cosmic radiation excluded)		0.232 8 μGy/h
Terrestrial gamma radiation outdoors: the concrete structures of the building shield against this radiation		–0.06 μGy/h
Excess dose rate caused by building materials		0.172 8 μGy/h
Excess effective dose	0.7 Sv/Gy × 0.172 8 μGy/h	0.121 μSv/h

VI–10. The annual excess effective dose to an occupant depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.121 μSv/h = 1060 μSv/a = 1.1 mSv/a
80% occupancy: 7008 h/a × 0.121 μSv/h = 848 μSv/a = 0.85 mSv/a
60% occupancy: 5256 h/a × 0.121 μSv/h = 636 μSv/a = 0.64 mSv/a

Example 2. Exposure to gamma radiation in a room where the walls are made of material with elevated concentrations of ^{226}Ra and ^{232}Th and the floor and ceiling are made of typical concrete

VI–11. The floor and ceiling of the room in Fig. VI–1 are constructed of concrete that contains the world population weighted average concentrations of radium, thorium and potassium in soil [VI–2] of 33 Bq/kg, 45 Bq/kg and 420 Bq/kg for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The walls are made of brick with elevated levels of radionuclides of natural origin. The material specifications are as shown in Table VI–4.

TABLE VI–4. EXAMPLE 2: SPECIFICATIONS OF THE ROOM AS SHOWN IN FIG. VI–1

Radionuclide	Floor, ceiling (concrete)	Walls (brick)
	Activity concentration	Activity concentration
^{226}Ra	33 Bq/kg	200 Bq/kg
^{232}Th	45 Bq/kg	300 Bq/kg
^{40}K	420 Bq/kg	1500 Bq/kg
Other parameters		
Density of concrete	2350 kg/m^3	2000 kg/m^3
Thickness of concrete	0.20 m	0.15 m

VI–12. The mass per unit area of the walls is 2000 kg/m^3 × 0.15 m = 300 kg/m^2 and the mass per unit area of the floor and ceiling is 2350 kg/m^3 × 0.20 m = 470 kg/m^2, thus the specific dose rates for a mass per unit area of 300 kg/m^2 for the walls and 500 kg/m^2 for the floor and ceiling in Table VI–1 are used. The dose rate in the room is calculated as shown in Table VI–5.

TABLE VI–5. EXAMPLE 2: THE DOSE RATE IN THE ROOM AS SHOWN IN FIG. VI–1

Source	Calculation	Dose rate
w_1 (brick)	2 × (79 × 200 + 91 × 300 + 6.4 × 1500)	0.1054 μGy/h
w_2 (brick)	2 × (26 × 200 + 30 × 300 + 2.1 × 1500)	0.0347 μGy/h
Floor and ceiling (concrete)	2 × (350 × 33 + 420 × 45 + 30 × 420)	0.0861 μGy/h
Total dose rate in a room (dose rate due to cosmic radiation excluded)		0.2262 μGy/h
Terrestrial gamma radiation outdoors: the concrete structures of the building shield against this source		–0.06 μGy/h
Excess dose rate caused by building materials		0.1662 μGy/h
Excess effective dose	0.7 Sv/Gy × 0.1662 μGy/h	0.116 μSv/h

VI–13. The annual excess effective dose to an occupant depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.116 μSv/h = 1016 μSv/a = 1.0 mSv/a
80% occupancy: 7008 h/a × 0.116 μSv/h = 813 μSv/a = 0.81 mSv/a
60% occupancy: 5256 h/a × 0.116 μSv/h = 610 μSv/a = 0.61 mSv/a

Example 3. Exposure to gamma radiation in a concrete room with tiles on the walls

VI–14. The walls, floor and ceiling of the room in Fig. VI–1 are constructed of concrete and all walls are covered with tiles with elevated levels of radionuclides of natural origin. The material specifications are as shown in Table VI–6.

TABLE VI–6. EXAMPLE 3: SPECIFICATIONS OF THE ROOM AS SHOWN IN FIG. VI–1

Radionuclide	Floor, ceiling, walls (concrete)	Walls (covered with tiles)
	Activity concentration	Activity concentration
^{226}Ra	33 Bq/kg	1200 Bq/kg
^{232}Th	45 Bq/kg	1500 Bq/kg
^{40}K	420 Bq/kg	1200 Bq/kg
Other parameters		
Density of concrete	2350 kg/m^3	2500 kg/m^3
Thickness of concrete	0.20 m	0.01 m

VI–15. The mass per unit area of the tiles is 2500 kg/m^3 × 0.01 m = 25 kg/m^2, so the corresponding values for specific dose rates in Table VI–I are used as shown in Table VI–7.

TABLE VI–7. EXAMPLE 3: THE DOSE RATE IN THE ROOM AS SHOWN IN FIG. VI–1

Source	Calculation	Dose rate
w_1 (tiles)	2 × (9 × 1200 + 10 × 1500 + 0.73 × 1200)	0.0534 μGy/h
w_1(concrete behind the tiles)	2 × (87 × 33 + 100 × 45 + 7.3 × 420)	0.0209 μGy/h
w_2 (tiles)	2 × (2.7 × 1200 + 3.1 × 1500 + 0.22 × 1200)	0.0163 μGy/h
w_2 (concrete behind the tiles)	2 × (30 × 33 + 35 × 45 + 2.5 × 420)	0.0072 μGy/h
Floor and ceiling (concrete)	2 × (350 × 33 + 420 × 45 + 30 × 420)	0.0861 μGy/h
Total dose rate in a room (dose rate due to cosmic radiation excluded)		0.1839 μGy/h
Terrestrial gamma radiation outdoors: the concrete structures of the building shield against this source		–0.06 μGy/h
Excess dose rate caused by building materials		0.1239 μGy/h
Excess effective dose	0.7 Sv/Gy × 0.1239 μGy/h	0.0867 μSv/h

VI–16. The annual excess effective dose to an occupant depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.0867 μSv/h =760 μSv/a = 0.76 mSv/a
80% occupancy: 7008 h/a × 0.0867 μSv/h =608 μSv/a = 0.61 mSv/a
60% occupancy: 5256 h/a × 0.0867 μSv/h =456 μSv/a = 0.46 mSv/a

In this example, it is interesting to further analyse the origin of the dose due to gamma radiation and especially the amount of the excess dose caused by the tiles. The dose rate due to the tiles is 0.0534 μGy/h + 0.0163 μGy/h = 0.0697 μGy/h; however, the excess dose rate due to the tiles is less than 0.0697 μGy/h because the tiles reduce the dose rate that is due to gamma radiation from the concrete behind them. The excess dose rate due to the tiles can therefore be obtained by calculating the dose rate in a room without tiles and by subtracting this from the total dose rate calculated above. The dose rate for the room without tiles is calculated as in Example 1, giving a value of 0.117 μGy/h. The excess dose rate due to the tiles is then 0.1839 − 0.117 μGy/h = 0.0669 μGy/h and to an occupant the excess effective dose due to the tiles is 0.7 Sv/Gy × 0.0669 μGy/h = 0.0468 μSv/h. The annual excess effective dose to an occupant due to the tiles depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.0468 μSv/h =410 μSv/a = 0.41 mSv/a
80% occupancy: 7008 h/a × 0.0468 μSv/h =328 μSv/a = 0.33 mSv/a
60% occupancy: 5256 h/a × 0.0468 μSv/h =256 μSv/a = 0.26 mSv/a

Example 4: Exposure to gamma radiation in a room where lightweight walls are made of materials with an elevated concentration of ^{226}Ra

VI–17. This model examines a form of construction that is common in rural areas of developing countries. The floor and ceiling of the room in Fig. VI–1 are made of wood, thatch or similar material and therefore make no contribution to the dose from exposure to gamma radiation indoors. The dose from exposure to gamma radiation indoors arises from the underlying soil and the walls of the room. The walls are constructed from hollow, light building blocks with elevated levels of ^{226}Ra. The material specifications are as shown in Table VI–8.

TABLE VI–8. EXAMPLE 4: SPECIFICATIONS OF THE ROOM AS SHOWN IN FIG. VI–1

Radionuclide	Walls (building blocks)
	Activity concentration
^{226}Ra	1200 Bq/kg
^{232}Th	45 Bq/kg
^{40}K	420 Bq/kg
Other parameters	
Density of concrete	1000 kg/m^3
Thickness of concrete	0.15 m

VI–18. The mass per unit area of the walls is 1000 kg/m^3 × 0.15 m = 150 kg/m^2. For the ceiling or floor there is no contribution to the dose. The walls do not provide much shielding against terrestrial background radiation and therefore no background is subtracted. The dose rate in the room is calculated as shown in Table VI–9.

TABLE VI–9. EXAMPLE 4: THE DOSE RATE IN THE ROOM AS SHOWN IN FIG. VI–1

Source	Calculation	Dose rate
w_1 (building block)	2 × (50 × 1200 + 56 × 45 + 3.9 × 420)	0.1283 µGy/h
w_2 (building block)	2 × (15 × 1200 + 18 × 45 + 1.2 × 420)	0.0386 µGy/h
Total dose rate in a room (dose rate due to cosmic radiation excluded)		0.1669 µGy/h
Terrestrial gamma radiation outdoors: because there is no floor, building materials provide very little shielding against this radiation; for simplicity the reduction in dose rate due to shielding is assumed to be zero.		0.00 µGy/h
Excess dose rate caused by building materials		0.1669 µGy/h
Excess effective dose	0.7 Sv/Gy × 0.1669 µGy/h	0.1168 µSv/h

VI–19. The annual excess effective dose to an occupant depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.117 μSv/h = 1025 μSv/a = 1.0 mSv/a
80% occupancy: 7008 h/a × 0.117 μSv/h = 820 μSv/a = 0.82 mSv/a
60% occupancy: 5256 h/a × 0.117 μSv/h = 615 μSv/a = 0.62 mSv/a

Example 5: Exposure to gamma radiation in a room where the concrete walls are made of material with an elevated concentration of ^{226}Ra

VI–20. This is the same as Example 4, except that here the walls are of 20 cm concrete. The material specifications are as shown in Table VI–10.

TABLE VI–10. EXAMPLE 5: SPECIFICATIONS OF THE ROOM AS SHOWN IN FIG. VI–1

Radionuclide	Walls (concrete)
	Activity concentration
^{226}Ra	1200 Bq/kg
^{232}Th	45 Bq/kg
^{40}K	420 Bq/kg
Other parameters	
Density of concrete	2350 kg/m^3
Thickness of concrete	0.20 m

VI–21. The mass per unit area of the walls is 2350 kg/m^3 × 0.2 m = 470 kg/m^2, thus the specific dose rates for a mass per unit area of 500 kg/m^2 in Table VI–1 are used. The dose rate in the room is calculated as shown in Table VI–11.

TABLE VI–11. EXAMPLE 5: THE DOSE RATE IN THE ROOM AS SHOWN IN FIG. VI–1

Source	Calculation	Dose rate
w_1 (building block)	2 × (96 × 1200 + 110 × 45 + 8.1 × 420)	0.2471 μGy/h
w_2 (building block)	2 × (33 × 1200 + 38 × 45 + 2.7 × 420)	0.0849 μGy/h
Total dose rate in a room (dose rate due to cosmic radiation excluded)		0.332 μGy/h
Terrestrial gamma radiation outdoors: because there is no floor, building materials provide very little shielding against this source; for simplicity the reduction in dose rate due to shielding is assumed to be zero.		0.00 μGy/h
Excess dose rate caused by building materials		0.332 μGy/h
Excess effective dose	0.7 Sv/Gy × 0.332 μGy/h	0.232 μGy/h

VI–22. The annual excess effective dose to an occupant depends on the annual occupancy time:

100% occupancy: 8760 h/a × 0.232 μSv/h = 2032 μSv/a = 2.0 mSv/a
80% occupancy: 7008 h/a × 0.232 μSv/h = 1626 μSv/a = 1.6 mSv/a
60% occupancy: 5256 h/a × 0.232 μSv/h = 1219 μSv/a = 1.2 mSv/a

REFERENCES TO ANNEX VI

[VI–1] MARKKANEN, M., Radiation Dose Assessments for Materials with Elevated Natural Radioactivity, Publication STUK-B-STO 32, Finnish Centre for Radiation and Nuclear Safety, Helsinki (1995).

[VI–2] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), Annex B: Exposures from Natural Radiation Sources, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

[VI–3] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1993).

[VI–4] RISICA, S., BOLZAN, C., NUCCETELLI, C., Radioactivity in building materials: Room model analysis and experimental methods, Sci. Total Environ. **272** (2001) 119–126.

CONTRIBUTORS TO DRAFTING AND REVIEW

Arvela, H.	Radiation and Nuclear Safety Authority, Finland
Boal, T.J.	International Atomic Energy Agency
Bradley, J.	Health Protection Agency, United Kingdom
Colgan, T.	International Atomic Energy Agency
Fojtíkova, I.	National Radiation Protection Institute, Czech Republic
Froňka, A.	National Radiation Protection Institute, Czech Republic
Hůlka, J.	National Radiation Protection Institute, Czech Republic
Jiranek, M.	Czech Technical University in Prague, Czech Republic
Markkanen, M.	Radiation and Nuclear Safety Authority, Finland
Miles, J.	Health Protection Agency, United Kingdom
Murith, C.	Federal Office of Public Health, Switzerland
Neznal, M.	Radon v.o.s., Czech Republic
Pierre, M.J.R.	Department of National Defence, Canada
Pravdova, E.	State Office for Nuclear Safety, Czech Republic
Rovenska, K.	National Radiation Protection Institute, Czech Republic
Shannoun, F.	World Health Organization
Thomas, J.	National Institute for Radiation Protection, Czech Republic
van der Steen, J.	Private consultant, Netherlands
van Deventer, T.E.	World Health Organization

Vlček, J.	National Radiation Protection Institute, Czech Republic
Webster, S.	Saskatchewan Labour, Canada
Zeeb, H.	World Health Organization

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