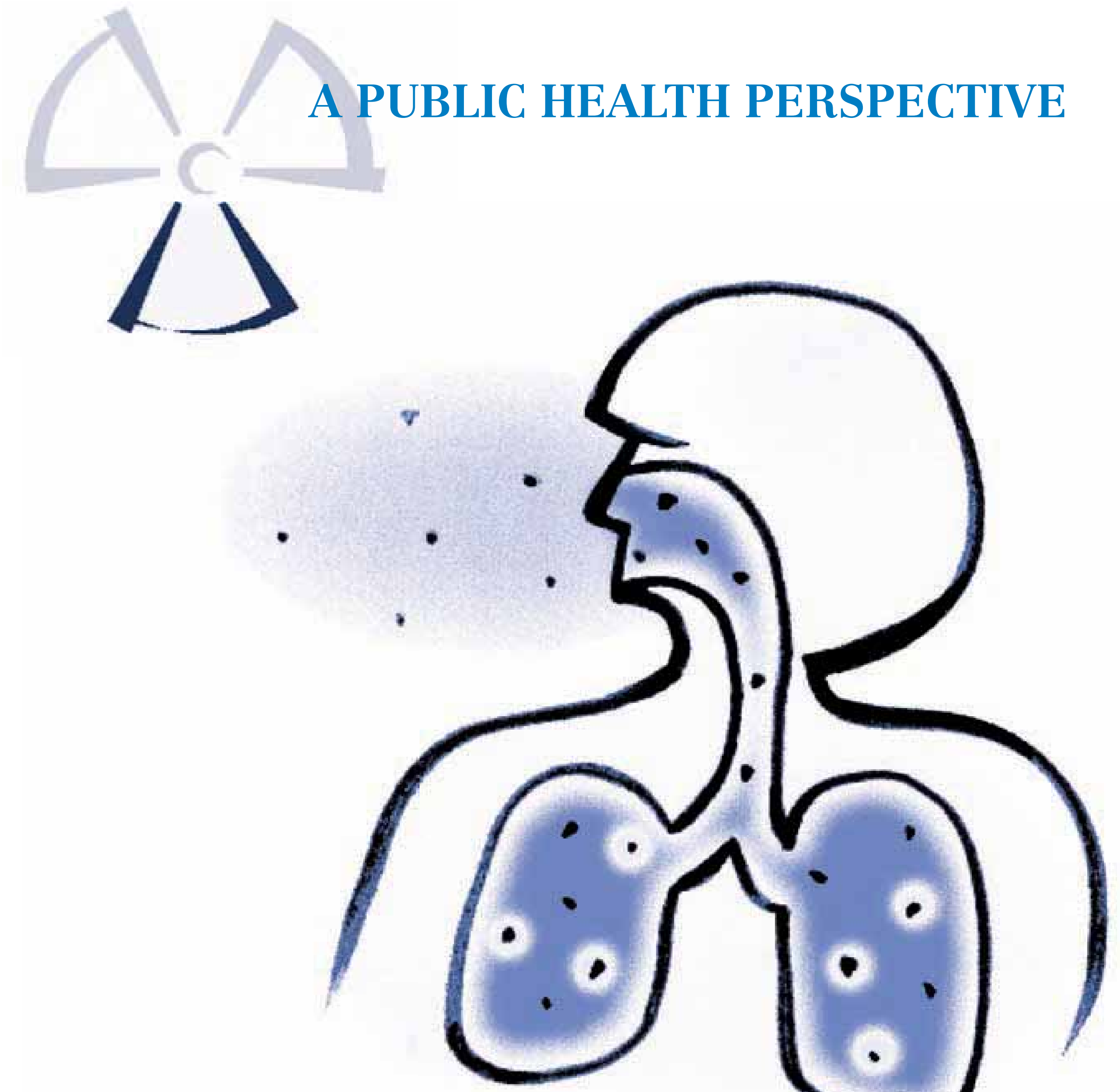
WHO HANDBOOK ON INDOOR RADON

A PUBLIC HEALTH PERSPECTIVE



World Health Organization

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WHO Library Cataloguing-in-Publication Data

WHO handbook on indoor radon: a public health perspective / edited by Hajo Zeeb, and Ferid Shannoun.

1.Radon - adverse effects. 2.Air pollutants, Radioactive. 3.Air pollution, Indoor. 4.Carcinogens, Environmental. 5.Radiation, Ionizing. 6.Lung neoplasms. 7.Environmental exposure. I.Zeeb, Hajo. II.Shannoun, Ferid. III.World Health Organization.

ISBN 978 92 4 154767 3 (NLM classification: WN 615)

Printed in France

Photo cover: © Swiss Federal Office of Public Health
Design and layout: Patrick Tissot/WHO

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Declaration of interests statement

All the individuals who participated in the meetings of the International Radon Project were asked to inform WHO if at any time a conflict of interest, whether actual or potential, could be perceived in their work and they were required to sign a conflict of interest statement. There was no conflict of interest for any participants contributed to the preparation of this document.

Acknowledgements

This Handbook was developed by the Department of Public Health and Environment within the framework of the WHO International Radon Project. It is based on the contribution of more than 100 scientists and radon experts, who participated in several consultation meetings to develop this document. Special thanks are given to all the participants and contributors.

The Handbook has been organized in six main chapters, each drafted by a respective working group of the WHO International Radon Project. In addition, an editorial group was part of the production and reviewing process. WHO is particularly grateful to this group for their assistance and efforts:

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WHO also acknowledges the participation of representatives from the International Atomic Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the International Commission on Radiological Protection and the European Commission as observers.

WHO thanks Derek Christie, Kelli Donnelly and Florence Samkange-Zeeb for their valuable contributions in reviewing and editing the manuscript.

WHO gratefully acknowledges the US Environmental Protection Agency (USA), the Department of Health (United Kingdom) and the Department of Environment, Heritage and Local Government (Ireland) for providing the main funding for the WHO International Radon Project. It is also indebted to the Federal Office of Radiation Protection (Germany) for its support in organizing meetings in Munich, Bonn and Mainz, as well as to the Federal Office of Public Health (Switzerland) for taking over the printing costs of the handbook.

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Preface

Radon is the second cause of lung cancer in the general population, after smoking. Epidemiological studies have provided convincing evidence of an association between indoor radon exposure and lung cancer, even at the relatively low radon levels commonly found in residential buildings. However, efforts to act on this information and to reduce the number of lung cancers related to radon exposures have so far only been successful in very few countries.

The World Health Organization first drew attention to the health effects from residential radon exposures in 1979, through a European working group on indoor air quality. Further, radon was classified as a human carcinogen in 1988 by IARC, the WHO specialized cancer research agency. In 1993, a WHO international workshop on indoor radon, organized in Eilat, and involving scientists and radon experts from Europe, North America and Asia, was a first step towards a unified approach to controlling radon exposures and advising on the communication of associated health risks.

In 2005, WHO established the International Radon Project to identify effective strategies for reducing the health impact of radon and to raise public and political awareness about the consequences of long term exposure to radon. Participants and contributors from more than 30 countries worked together towards a global understanding of a wide range of issues associated with indoor radon.

A key product of the WHO International Radon Project is this handbook, which focuses on residential radon exposure, emphasizing its impact from a public health point of view. It includes detailed recommendations on radon health risk reduction and sound policy options for prevention and mitigation of radon. The handbook is intended for countries that plan to develop national programmes or extend their activities regarding radon, as well as for stakeholders involved in radon control such as the construction industry and building professionals.

WHO recommends that, where indicated, comprehensive radon programmes be developed, preferably in close linkage with indoor air quality and tobacco control programmes. This handbook reflects the long-standing experience of several countries with such radon programmes. WHO looks forward to continuing and enhancing the collaboration with countries to achieve the challenging goal of reducing the radon-associated health burden.

Dr Maria Neira, Director
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Executive summary

Radon is a radioactive gas that emanates from rocks and soils and tends to concentrate in enclosed spaces like underground mines or houses. Soil gas infiltration is recognized as the most important source of residential radon. Other sources, including building materials and water extracted from wells, are of less importance in most circumstances. Radon is a major contributor to the ionizing radiation dose received by the general population.

Recent studies on indoor radon and lung cancer in Europe, North America and Asia provide strong evidence that radon causes a substantial number of lung cancers in the general population. Current estimates of the proportion of lung cancers attributable to radon range from 3 to 14%, depending on the average radon concentration in the country concerned and the calculation methods. The analyses indicate that the lung cancer risk increases proportionally with increasing radon exposure. As many people are exposed to low and moderate radon concentrations, the majority of lung cancers related to radon are caused by these exposure levels rather than by higher concentrations. Radon is the second cause of lung cancer after smoking. Most of the radon-induced lung cancer cases occur among smokers due to a strong combined effect of smoking and radon.

Radon measurements are relatively simple to perform and are essential to assess radon concentration in homes. They need to be based on standardized protocols to ensure accurate and consistent measurements. Indoor radon concentration varies with the construction of buildings and ventilation habits. These concentrations not only vary substantially with the season but also from day to day and even from hour to hour. Because of these fluctuations, estimating the annual average concentration of radon in indoor air requires reliable measurements of mean radon concentrations for at least three months and preferably longer. Short-term measurements provide only a crude indication of the actual radon concentration. Quality assurance for radon measurement devices is highly recommended in order to ensure the quality of measurements.

Addressing radon is important both in construction of new buildings (prevention) and in existing buildings (mitigation or remediation). The primary radon prevention and mitigation strategies focus on sealing radon entry routes and on reversing the air pressure differences between the indoor occupied space and the outdoor soil through different soil depressurization techniques. In many cases, a combination of strategies provides the highest reduction of radon concentrations.

The choice of radon prevention and mitigation interventions can be based on an analysis of cost-effectiveness. In this approach, net health-care costs are set in relation to net health benefits for a variety of actions or policies, providing an index with which these actions can be prioritized.

Selected analyses indicate that preventive measures in all new buildings are cost-effective in areas where more than 5% of current dwellings have radon concentrations above 200 Bq/m^3. Prevention in new homes tends to be more cost-effective than mitigation of existing homes. In some low-risk areas the measurement costs may be higher than the mitigation costs (for existing dwellings) due to the high number of homes that will have to be tested compared to the proportion of homes mitigated. Even if analyses indicate that remediation programmes are not cost-effective on a nationwide basis, indoor radon at high concentrations poses a considerable risk of lung cancer for individuals and requires mitigation.

Since the general public is often unaware of the risks associated with indoor radon, special risk communication is recommended. Radon risk communication needs to be focused on informing the different audiences and recommending appropriate action on reducing indoor radon. A cooperative effort is required, involving technical and communication experts, to develop a set of core messages. Radon risk messages should be kept as simple as possible and quantitative risk information must be expressed to the public in clearly understandable terms. It is useful, for example, to place the risk of lung cancer due to radon in comparison with other cancer risks, or with common risks in everyday life.

Public health programmes to reduce the radon risk should be ideally developed on national level. Such national radon programmes would be designed to reduce the overall population's risk from the national average radon concentration as well as the individual risk for people living with high radon concentrations.

A national radon policy should focus on identifying geographical areas where populations are most at risk from radon exposures and raising public awareness about the associated health risk. Key elements for a successful national programme include collaboration with other health promotion programmes (e.g. indoor air quality, tobacco control) and training of building professionals and other stakeholders involved in the implementation of radon prevention and mitigation. Appropriate building codes that require the installation of radon prevention measures in homes under construction should be enacted, and the measurement of radon during the purchase and sale of homes is useful to identify those with high radon concentrations.

A national reference level for radon represents the maximum accepted radon concentration in a residential dwelling and is an important component of a national programme. For homes with radon concentrations above these levels remedial actions may be recommended or required. When setting a reference level, various national factors such as the distribution of radon, the number of existing homes with high radon concentrations, the arithmetic mean indoor radon level and the prevalence of smoking should be taken into consideration. In view of the latest scientific data, WHO proposes a reference level of 100 Bq/m^3 to minimize health hazards due to indoor radon exposure. However, if this level cannot be reached under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq/m^3 which represents approximately 10 mSv per year according to recent calculations by the International Commission on Radiation Protection.

The overall goal of this handbook is to provide a current overview of the major aspects of radon and health. It does not aim to replace existing radiation protection standards, rather it puts emphasis on issues being relevant for the comprehensive planning, implementation and evaluation of national radon programmes.

Abbreviations

ACD	Activated charcoal detector
ASD	Active soil depressurization
ASTM	American Society for Testing and Materials
ATD	Alpha track detector
BEIR	Biological Effects of Ionizing Radiation
CBA	Cost benefit analysis
CRM	Continuous radon monitor
DALY	Disability adjusted life year
DEFRA	Department for Environment, Food and Rural Affairs
DIN	Deutsches Institut für Normung
DTD	Double alpha-track detector method
EC	European Commission
EIC	Electret ion chamber
EID	Electronic integrating device
ERR	Excess relative risk
ETS	Environmental tobacco smoke
GM	Geometric mean
GSD	Geometric standard deviation
HVAC	Heating ventilation and air conditioning
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
LSC	Liquid scintillation counting
MDC	Minimum detectable concentration
NCRP	National Council on Radiation Protection and Measurements
NRC	National Research Council
OECD	Organization for Economic Co-operation and Development
PAEC	Potential alpha energy concentration
PSD	Passive soil depressurization
PT	Proficiency test
QA	Quality assurance
QALY	Quality adjusted life year
QC	Quality control
RPD	Relative percent difference
RR	Relative risk
STAR	Systems for Test Atmospheres with Radon
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USDHHS	United States Department of Health and Human Services
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WL	Working level
WLM	Working level month

Glossary

Building professionals: this term describes all those involved in the design, construction, renovation and maintenance of buildings as well as those involved in the design and installation of radon prevention and mitigation systems.

Concentration: the activity of radon gas in terms of decays per time in a volume of air. The unit of radioactivity concentration is given in Becquerel per cubic metre (Bq/m^3).

Disability adjusted life year (DALY): a measure of health based on the length of a person's life adjusted by their level of disability. DALYs lost are commonly calculated with reference to a "gold standard" of full health in a country with long life expectancy: for example, a person in Southern Africa disabled by blindness who then dies aged 45 has lost several years of full health as a result of blindness, but also 35 years of life compared to the average life expectancy of 80 in Japan.

Equilibrium factor (F-factor): radon is constantly decaying and giving rise to radon progeny. These are short-lived and decay until reaching a long-lived isotope of lead. The F-factor is used to describe the ratio between radon and its progeny. An F-factor of 1 means equal amounts of radon and its progeny. An F-factor of 0.4 is taken as representative for homes.

Excess relative risk (ERR): the ERR is an epidemiological risk measure that quantifies how much the level of risk among persons with a given level of exposure exceeds the risk of non-exposed persons.

Exposure: the amount of time a person spends in any given radon concentration. It is determined by multiplying the radon concentration, measured in Bq/m^3 of each area by the amount of time spent in that area.

Geometric mean (GM): the GM represents the central tendency or typical value of a set of numbers which follow a log-normal distribution. The GM is calculated by finding the n-th root of the product of n numbers.

Homes or dwellings: these terms are interchangeable and refer to all detached and attached structures used for non-occupational human residency. The term "house" refers to a detached single-family dwelling.

Householders: this is a term of convenience used to collectively describe those living in a home or dwelling. It refers to occupants of the home, including owners of the property as well as tenants.

Long-term measurement: a measurement of radon concentrations that takes place over period of 3 months up to 1 year.

Membranes or barriers: both terms refer to a continuous plastic type sheet that is placed across the foundation of the house during construction, whose purpose is to prevent radon entering the house when construction is completed.

Mitigation or remediation: these terms are interchangeable and refer to steps taken in an existing building to reduce radon entry.

National radon programme: a series of measures, aimed at minimizing exposure of the population to radon, that are implemented by agencies designated by a national authority.

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

Prevention: in the context of this hanbook, measures installed during construction of new homes or dwellings aimed at preventing the entry of radon.

Quality adjusted life year (QALY): a year of life adjusted for its quality, value or utility. One year in full health is given the value of 1 QALY; the same period in moderate pain, for example, might be given a value of 0.7 QALY. The QALY aims to incorporate quality of life and quantity of life in one measure, and so is attractive to health economists as a general measure of health outcome.

Quality assurance: the set of planned and systematic actions put in place at specified stages of the radon measurement process to ensure confidence and accuracy of the measurement results.

Quality control: the quality checks carried out within the radon measurement laboratory as part of the overall quality assurance system.

Radon-prone area: an area where a significant proportion of homes exceed the reference level.

Reference level: this level does not define a rigid boundary between safety and danger but represents the annual mean radon concentration in a home above which it is strongly recommended or required to reduce the radon concentration.

Relative Risk (RR): the RR is a ratio of the probability of a disease occurring in the exposed group versus a non-exposed group.

Renovation: work that changes the structure, heating, cooling and or mechanical systems of the home that may open up new entry routes for radon, disrupt ventilation patterns or change air pressure patterns.

Short-term measurement: a measurement of radon concentrations that takes place over a period of not more than 3 months.

Social marketing: the application of marketing along with other ideas and techniques to achieve specific behavioral goals for a social good. It is applied in health promotion campaigns to change people’s behavior, for example in anti-smoking messages or in efforts aimed at preventing skin cancer by encouraging people to avoid excessive exposure to sunlight.

Working level month (WLM): working levels are defined as any combination of the short-lived progeny in one litre of air that results in the ultimate release of 1.3×10^5 MeV of potential alpha particle energy. The cumulative exposure to an individual exposed at this concentration over a “working month” of 170 hours (or at twice this concentration over half as long, etc.) is defined as a “working level month” (WLM).

Introduction

The risks to human health posed by ionizing radiation are well known. Radon gas is by far the most important source of ionizing radiation among those that are of natural origin. Radon (^{222}Rn) is a noble gas formed from radium (^{226}Ra), which is a decay product of Uranium (^{238}U). Uranium and radium occur naturally in soils and rocks. Other decay products of uranium include the isotopes thoron (^{220}Rn) and actinon (^{219}Rn). Radon gas, which has a half-life of 3.8 days, emanates from rocks and soils and tends to concentrate in enclosed spaces like underground mines or houses. It is a major contributor to the ionizing radiation dose received by the general population.

When radon gas is inhaled, densely ionizing alpha particles emitted by deposited short-lived decay products of radon (^{218}Po and ^{214}Po) can interact with biological tissue in the lungs leading to DNA damage. Cancer is generally thought to require the occurrence of at least one mutation, and proliferation of intermediate cells that have sustained some degree of DNA damage can greatly increase the pool of cells available for the development of cancer. Since even a single alpha particle can cause major genetic damage to a cell, it is possible that radon-related DNA damage can occur at any level of exposure. Therefore, it is unlikely that there is a threshold concentration below which radon does not have the potential to cause lung cancer.

Health effects of radon, most notably lung cancer, have been investigated for several decades. Initially, investigations focused on underground miners exposed to high concentrations of radon in their occupational environment. However, in the early 1980s, several surveys of radon concentrations in homes and other buildings were carried out, and the results of these surveys, together with risk estimates based on the studies of mine workers, provided indirect evidence that radon may be an important cause of lung cancer in the general population. Recently, efforts to directly investigate the association between indoor radon and lung cancer have provided convincing evidence of increased lung cancer risk causally associated with radon, even at levels commonly found in buildings. Risk assessment for radon both in mines and in residential settings have provided clear insights into the health risks due to radon. Radon is now recognized as the second most important cause of lung cancer after smoking in the general population.

The understanding of radon sources and radon transport mechanisms has evolved over several decades. In the 1950s, high concentrations of radon were observed in domestic and drinking water from drilled wells. Initially, concern about radon in water focused on health effects from ingesting the water. Later, it was determined that the primary health risk of radon in water was from the inhalation of radon released indoors. By the mid-1970s, emanation of radon from building materials was found to be a problem in some areas due to the use of alum shale[1] with enhanced levels of radium. By 1978, houses were identified where the indoor radon concentrations were not associated with well water transport or emanation from building materials. Soil gas infiltration became recognized as the most important source of indoor radon. Other sources, including building materials and well water, are of less importance in most circumstances.

[1] A variety of shale or clay slate used to produce a particular type of light concrete.

This handbook focuses on indoor radon exposure. Epidemiological evidence indicates that indoor radon is responsible for a substantial number of lung cancers in the general population. The distribution of indoor radon in most countries is best represented by a log normal distribution, with the majority of the radon concentrations occurring in the lower range. As a result, the vast majority of radon-induced lung cancers are thought to occur following exposure to low and moderate radon concentrations. UNSCEAR reported recently that there is now a remarkable coherence between the risk estimates developed from epidemiological studies of miners and residential case-control radon studies. While the miner studies provide a strong basis for evaluating risks from radon exposure and for investigating the effects of modifiers to the dose–response relation, the results of the recent pooled residential studies provide a direct method of estimating risks to people at home without the need for extrapolation from miner studies.

The handbook is organized in six chapters, each introduced by key messages to allow an effective orientation for the reader. Usually, terms or words are defined when first used. Some specific terms are further defined in the glossary of this document.

Chapter 1 discusses the current knowledge about health risks from radon and presents the most recent estimates of radon population exposures and associated risks for lung cancer. This chapter also deals with other potential health effects related to radon.

Chapter 2 provides a framework for the selection of radon measuring devices and the development of procedures for the reliable measurement of radon in both air and water. In addition, the chapter outlines guidance for various scenarios of radon measurements such as individual testing of single homes or diagnostic measurements of building materials.

Chapter 3 discusses radon control options during the construction of new dwellings (prevention) and radon reduction in existing dwellings (mitigation or remediation).

Chapter 4 considers the use of economic evaluation as a systematic way of assessing the costs and benefits of different preventive and remedial actions. The methodology of cost-effectiveness analysis, and the relevance of this approach to radon actions, are reviewed. A case study illustrates the approach and the interpretation of results.

Chapter 5 provides guidance on the development of radon risk communication strategies and proposes several core messages to communicate radon risk to different target groups.

Finally, chapter 6 presents components for the development of a national radon programme and the framework for the organization of such a programme. Radon reference levels and their importance in this context are also discussed in this chapter.

Thus, the different chapters of this handbook offer an international perspective on radon as an environmental health problem. The handbook focuses on residential radon exposures, emphasizing its impact from a public health point of view and it includes detailed recommendations on radon health risk reduction and sound policy options for prevention and mitigation of radon. Countries need to develop radon prevention and mitigation programmes reflecting elements that are unique to their regions (e.g. radon sources, transport mechanisms, building regulations, building codes and construction characteristics). The handbook does not aim to replace existing radiation protection standards but to enable countries to comprehensively plan, implement and evaluate national radon programmes. It is intended for countries that plan to develop national programmes or extend their radon activities, as well as for stakeholders involved in radon control such as the construction industry and building professionals.

1. Health effects of radon

KEY MESSAGES

- Epidemiological studies confirm that radon in homes increases the risk of lung cancer in the general population. Other health effects of radon have not consistently been demonstrated.
- The proportion of all lung cancers linked to radon is estimated to lie between 3% and 14%, depending on the average radon concentration in the country and on the method of calculation.
- Radon is the second most important cause of lung cancer after smoking in many countries. Radon is much more likely to cause lung cancer in people who smoke, or who have smoked in the past, than in lifelong non-smokers. However, it is the primary cause of lung cancer among people who have never smoked.
- There is no known threshold concentration below which radon exposure presents no risk. Even low concentrations of radon can result in a small increase in the risk of lung cancer.
- The majority of radon-induced lung cancers are caused by low and moderate radon concentrations rather than by high radon concentrations, because in general less people are exposed to high indoor radon concentrations.

This chapter discusses current knowledge on health risks from radon, including both lung cancer and other potential health effects. It also gives estimates of radon concentrations in various countries and summarizes recent estimates of the burden of radon-induced lung cancer. Radon is the largest natural source of human exposure to ionizing radiation in most countries. In the general population most exposure occurs indoors, especially in small buildings such as houses (UNSCEAR 2000), although there are some groups for whom occupational exposure presents a greater risk.

Evidence of increased mortality from respiratory disease among certain groups of underground miners in central Europe dates back to the sixteenth century, but it was not until the nineteenth century that it was appreciated that the disease was in fact lung cancer. Radon was first suspected as the primary cause of these cancers in radon-exposed miners in the twentieth century, and its causal role in lung cancer became firmly established in the 1950s. Further historical details are presented elsewhere (BEIR IV 1988). Studies of underground miners exposed occupationally to radon, usually at high concentrations, have consistently demonstrated an increased risk of lung cancer for both smokers and non-smokers. Based primarily on this evidence, radon was classified as a human carcinogen by the International Agency for Research on Cancer in 1988 (IARC 1988).

Since the 1980s, a large number of studies have directly examined the relationship between indoor radon and lung cancer in the general population. Individually, these studies are generally too small either to rule out a material risk, or to provide clear evidence that one existed. The investigators of the major studies in Europe, North America, and China have therefore brought their data together, and re-analyzed it centrally (Lubin et al. 2004, Krewski et al. 2005, 2006, Darby et al. 2005, 2006). These three pooled-analyses present very similar pictures of the risks of lung cancer from residential exposure to radon. Together, they provide overwhelming evidence that radon is causing a substantial number of lung cancers in the general population and they provide a direct estimate of the magnitude of the risk. They also suggest that an increased risk of lung cancer cannot be excluded even below 200 Bq/m^3, which is the radon concentration at which action is currently advocated in many countries.

1.1 Lung cancer risks in radon-exposed miners

Lung cancer rates in radon-exposed miners have generally been studied using a cohort design in which all men employed in a mine during a particular time period are identified. The men are then followed up over time, regardless of whether they remain employed in the mine, and the vital status of each man is established at the end of the follow-up period. For those who have died, the date and cause of death is ascertained, and the death rate from lung cancer calculated, both overall and after subdivision by factors such as age, calendar period and cumulative exposure to radon. In these studies, exposure to radon was usually estimated retrospectively and in many of the studies the quality of the exposure assessment was low, particularly in the early years of mining, when the exposures were highest and no radon measurements were performed. In studies of radon-exposed miners radon progeny concentrations are generally expressed in terms of “working levels” (WL). The working level is defined as any combination of the short-lived progeny in one litre of air that results in the ultimate release of 1.3×10^5 MeV of potential alpha particle energy. The cumulative exposure of an individual to this concentration over a “working month” of 170 hours (or twice this concentration over half as long, etc.) is defined as a “working level month” (WLM).

A review of the major studies of underground miners exposed to radon that were available in the 1990s was carried out by the Committee on the Biological Effects of Ionizing Radiation (BEIR VI 1999). Eleven cohort studies were considered, including a total of 60 000 miners in Europe, North America, Asia and Australia, among whom 2 600 deaths from lung cancer had occurred. Eight of these studies were of uranium miners, and the remainder were of miners of tin, fluorspar or iron. Lung cancer rates generally increased with increasing cumulative radon exposure, but in one study (Colorado cohort) the rate increased at moderate cumulative exposures and then decreased again at high cumulative exposures. After exclusion of cumulative exposures above 3 200 WLM in this study, the lung cancer rate increased approximately linear with increasing cumulative radon exposure in all 11 studies, although the size of the increase per unit increase in exposure varied by more than a factor of ten between the studies, and this variation was much greater than could be explained by chance. Despite the substantial variation in the magnitude of the risk that was suggested by the different studies, the BEIR VI committee carried out a number of analyses considering pooled data from all 11 studies, giving different weights to the different studies. One such analysis estimated that the average increase in the lung cancer death rate per WLM in the 11 studies combined was 0.44% (95% confidence interval 0.20-1.00%). The percentage increase in the lung cancer death rate per WLM varied with time since exposure, with the highest percentage increase in risk in the period 5-14 years after exposure. It also varied with the age that the person concerned had reached, with higher percentage increases in risk at younger ages. Another finding of the BEIR VI study was that miners exposed at relatively low radon concentrations had a larger percentage increase in lung cancer death rate per WLM than miners exposed at higher radon concentrations. In order to summarize the risks seen in the studies of radon-exposed miners and to make projections about the likely risks in other radon-exposed populations, the BEIR VI committee developed a number of models. For illustration, the exposure-age-concentration model is summarized in Table 1.

Table 1. Patterns of radon-related lung cancer in miners in the studies considered by the BEIR VI Committee and the study of German uranium miners

	BEIR VI[a] Committee	German[b] uranium miners
ERR/WLM in baseline category[c] (%)		
β	7.68	1.35
Time since exposure		
θ_{5-14}	1.00	1.00
θ_{15-24}	0.78	1.52
θ_{25+}	0.51	0.76
Attained age (years)		
$\phi_{<55}$	1.00	1.00
ϕ_{55-64}	0.57	0.80
ϕ_{65-74}	0.29	0.66
ϕ_{75+}	0.09	0.49
Radon concentration (WL)		
$\gamma_{<0.5}$	1.00	1.00
$\gamma_{0.5-1.0}$	0.49	0.52
$\gamma_{1.0-3.0}$	0.37	0.36
$\gamma_{3.0-5.0}$	0.32	0.31
$\gamma_{5.0-15.0}$	0.17	0.25
$\gamma_{15.0+}$	0.11	0.12

[a] Source: BEIR VI (1999)

[b] Source: Grosche et al. (2006)

[c] i.e. 5-14 years since exposure, attained age <55 years, and concentration <0.5 WL

In both studies the model relating radon exposure to risk of death from lung cancer is $R=\beta\omega^*\phi_{age}\gamma_z$, where R is the percentage increase in the death rate from lung cancer for a person of a certain age with a given history of exposure to radon; β is the parameter relating the increase in the lung cancer death rate to history of radon exposure; ω^* represents the radon exposure in WLM and takes the form of a weighted average, $\omega^* = (\omega_{5-14}+\phi1_{5-24}\omega_{15-24}+\phi_{25}+\omega_{25+})$, with ω_{5-14}, ω_{15-24}, and ω_{25}+ representing the exposure incurred during the periods 5-14, 15-24, and 25+ years prior to the current age. The coefficient of ω_{5-14} is equal to one, while θ_{15-24} and θ_{25+} represent the relative contributions from exposures received 15-24 years and 25+ years previously, compared to exposures received in the period 5-14 years previously. Exposures occurring less than 5 years previously were assumed not to incur any risk. The parameter φ_{age} represents the modifying effect of age, while the parameter γ_z represents the modifying effect of radon concentration.

Since the publication of the BEIR VI report, further follow-up has been conducted for the Czech study of radon-exposed miners (Tomasek et al. 2002, 2004) and for the French study (Rogel et al. 2002, Laurier et al. 2004). Several papers have been published giving further analyses of some other groups (Langholz et al. 1999, Stram et al. 1999, Hauptmann et al. 2001, Hornung et al. 2001, Duport et al. 2002, Archer et al. 2004, Hazelton et al. 2001, Heidenreich et al. 2004). In addition, cohorts of radon-exposed coal miners in Poland (Skowronek et al. 2003) and Brazil (Veiga et al. 2004) have been established, as well as a large cohort of uranium miners in the former German Democratic Republic (Kreuzer et al. 2002).

The German cohort includes a total of 59 001 men who had been employed by the Wismut Company in Eastern Germany (Grosche et al, 2006). By the time of the first mortality follow-up, a total of 2 388 lung cancer deaths had occurred. The German cohort is of particular interest, as it is nearly as large as all the 11 cohorts available to the BEIR VI Committee combined. In addition, the miners were all from the same geographical area and had the same social background, and the entire cohort was subject to the same follow-up procedure and the same system of exposure assessment. In this study, the average increase in lung cancer death rate per WLM was 0.21% (95% confidence interval 0.18-0.24%), just over half that seen in the BEIR VI analysis. When an exposure-age-concentration model similar to that used by the BEIR VI Committee was fitted to the German cohort, the highest percentage increase in the death rate per WLM was during the period 15 to 24 years after exposure, compared to 5 to 15 years in the BEIR VI model (cf. Table 1). The percentage increases were lower at older ages, as in the BEIR VI model, although the age-gradient was less steep. In both studies, the percentage increase in death rate per unit exposure decreased with increasing radon concentration, with exposures at 15.0+ WL carrying about one tenth the risk of those at <0.5 WL.

For some of the miner studies available to the BEIR VI Committee, information on smoking was available and in these studies the lung cancer death rate increased by 0.53% per WLM on average (95% confidence interval 0.20-1.38%), similar to the average percentage increase for all eleven studies considered by the BEIR VI Committee. When the analysis was carried out separately for never smokers (i.e. lifelong non-smokers) and for ever smokers (i.e. current and ex-smokers combined) the lung cancer death rate increased by 1.02% per WLM (95% confidence interval 0.15-7.18%) for the never smokers and 0.48% per WLM (95% confidence interval 0.18-1.27%) for the ever smokers. Thus, the percentage increase in lung cancer risk per WLM was larger in the never-smokers than in the ever-smokers, but the difference was not statistically significant (BEIR VI 1999).

Information on smoking habits is not generally available in the German cohort study. However, a case-control study of lung cancer among former employees of the German uranium mining company diagnosed at certain clinics during the 1990s has been carried out (Brueske-Hohlfeld et al. 2006). This study also found that the percentage increase in the lung cancer death rate per WLM was larger in never-smokers than in ex-smokers, and larger in ex-smokers than in current smokers (current smokers: 0.05% (95% confidence interval 0.001-0.14%); ex-smokers: 0.10% (95% confidence interval 0.03-0.23%); never-smokers: 0.20% (95% confidence interval 0.07-0.48%)).

Whether or not the true percentage increase in the lung cancer death rate per WLM differs between never-smokers and ever-smokers, it should be noted that the absolute increase in death rate per WLM will be much higher for current smokers than for never-smokers. This is due to the fact that for a given radon concentration, smokers have much higher lung cancer rates than never-smokers. For ex-smokers, the absolute increase per WLM will lie between those for current and for never-smokers, depending on factors such as the duration of smoking and the number of cigarettes per day smoked before quitting, and also the time since smoking cessation.

1.2 Lung cancer risks in the general population from indoor radon

Background

The magnitude of lung cancer risk seen in underground miners exposed to radon strongly suggests that radon may be a cause of lung cancer in the general population due to the exposure that occurs inside houses and other buildings. The conditions of exposure in mines and indoors differ appreciably (NRC 1991), and the smoking-related risks in the miners that have been studied differ from the smoking-related risks in the general populations of today. Other determinants of lung cancer risk differ between exposure in mines and indoors. For example, many of the miners were exposed to other lung carcinogens, such as arsenic, in addition to radon. All these differences mean that there is substantial uncertainty in extrapolating from the miner studies to obtain a quantitative assessment of the risk of lung cancer from radon in the home.

Much of the uncertainty associated with quantitative extrapolation from the studies of miners can be avoided by directly studying the association between indoor radon and risk of lung cancer. In such studies, radon exposures are usually expressed as the average concentration of radon gas per cubic metre of air to which an individual has been exposed at home over the previous few decades, and the unit is Becquerel per cubic metre (Bq/m^3), where 1 Bq corresponds to one disintegration per second. Indoor radon concentrations in an individual house are usually subject to systematic diurnal and seasonal variation and the annual average radon concentration is also usually subject to substantial random year-to-year variation related to numerous factors (e.g. weather patterns and occupant behaviour such as window opening).

Initial attempts to study the risk of lung cancer from indoor radon included a number of geographical correlation studies (sometimes known as “ecological studies”), which examined the correlation between average radon concentrations and average lung cancer rates in different geographical areas. However, the usefulness of such studies is severely limited since they cannot control adequately for other determinants of lung cancer risk, such as cigarette smoking, which causes a much larger number of lung cancers than radon in most populations. Therefore, ecological studies often provide biased and misleading estimates of the radon-related risk. Further details and some illustrations of the biases that can occur are presented elsewhere (Puskin 2003).

A more appropriate way to examine the association between lung cancer and residential radon exposure is a case-control study, in which a predetermined number of individuals who have developed lung cancer are identified, together with a predetermined number of control individuals who have not developed the disease, but who are otherwise representative of the population from which the cases of lung cancer were drawn. In these studies, the controls are usually matched to the cases by age and sex. Detailed residential histories then need to be obtained for each individual in the study, as well as detailed information on smoking histories and other factors that determine each person’s risk of developing lung cancer. In order to estimate the average radon concentration to which each individual in the study has been exposed over the previous few decades, measurements of the radon concentration need to be made both in his or her present home and, if the individual has moved in the last few decades, in other homes where the individual has lived. Once this is done, the radon concentrations can be compared between individuals who have developed lung cancer and the control individuals. Special statistical methods have been developed to account for variations in the other factors that influence the risk of developing lung cancer so that, in effect, comparisons are made only between individuals who have similar smoking histories and also similar values for other factors that determine the risk of lung cancer. Using such methods, the relationship between the risk of lung cancer and the average indoor radon concentration over the previous few decades can be estimated.

At least 40 case-control studies of indoor radon and lung cancer have now been conducted. Individually, most of these studies have not been large enough either to rule out an increased risk or to provide clear evidence that an increased risk existed. Therefore, in order to combine the information from more than one study, a number of authors have considered the published results from several studies to obtain a pooled estimate (Lubin and Boice 1997, Lubin 1999, Pavia et al. 2003). These systematic reviews of published papers have all concluded that the radon-related risk of lung cancer, as published in the individual studies, varies appreciably from one study to another. However, the methodology used to analyze the various studies differs considerably from study to study, notably in the extent to which the differing smoking-related risks of lung cancer for different individuals have been taken into account and in the quantification of the radon exposure histories of each individual. Such divergences may well lead to differences between the risk estimates in the individual studies and cannot be eliminated without access to basic data for each individual involved in the studies (Field et al. 2002).

In order to compare the findings of the different case-control studies of radon and lung cancer appropriately, and to ensure that the different smoking-related risks for different individuals are fully taken into account, it is necessary to assemble the component data on radon concentration, smoking history and other relevant factors for each individual in each of the original studies and to collate the data in a uniform way. When this has been done, parallel analyses of the different studies can be carried out, and the findings from the individual studies can be compared. Then, if the data from the different studies are consistent, they can be combined and an estimate of the risk of radon-related lung cancer can be derived based on all the studies included. Three analyses collating and comparing the individual information from a number of component studies have now been carried out, including 13 European studies (Darby et al. 2005, 2006), 7 North American studies (Krewski et al. 2005, 2006), and 2 Chinese studies (Lubin et al. 2004), respectively. All three analyses concluded that it was appropriate to derive a pooled estimate of the risk of lung cancer from radon in the home from the component studies. A summary of the findings of these pooled analyses appears in Table 2 and further details are presented below.

The European pooling study

The European pooling study (Darby et al. 2005, 2006) included data from all thirteen European studies of residential radon and lung cancer that satisfied selected inclusion criteria. These criteria required that studies had to be of a certain size (minimum 150 people with lung cancer and 150 control individuals without lung cancer, drawn from the same population) and that detailed smoking histories for each individual were available. In terms of exposure, radon measurements in homes where the individual had lived during the past 15 years or more were required. In total, over 7 000 lung cancer cases and more than 14 000 controls were entered into the pooled analysis. The study considered the effect on lung cancer risk of exposures to radon during the 30 year period ending 5 years prior to the diagnosis of lung cancer, or prior to a comparable reference date for control individuals. The available radon measurements covered a mean of 23 years and, where necessary, were adjusted for seasonal variation so that each measurement was representative of the radon concentration in a home over an entire year. For homes where no radon measurements could be obtained (e.g. the house had been demolished) the concentration was estimated indirectly as the mean of all the radon measurements

Table 2. Summary of risks of lung cancer from indoor radon based on international pooling studies that have combined individual data from a number of case-control studies and on studies of radon exposed miners

	Nbr. of studies included	Nbr. of lung cancers	Nbr. of controls	Exposure Window (years)[a]	Percentage increase in risk of lung cancer per 100 Bq/m^3 increase in radon concentration	
					Based on measured radon	Based on long-term average radon[b]
Pooled analyses of studies of indoor radon in the home						
European (Darby et al. 2005, 2006)	13	7 148	14 208	5-35	8 (3, 16)	16 (5, 31)
North American (Krewski et al. 2005, 2006)	7	3 662	4 966	5-30	11 (0, 28)	-
Chinese (Lubin et al. 2004)	2	1 050	1 995	5-30	13 (1, 36)	-
Weighted average of above results of pooling studies					10	~20[c]
Studies of radon exposed miners[d, e]						
BEIR VI analysis (BEIR VI 1999; Lubin et al. 1997)	11	2 787		5-35	All miners: 5 Miners exposed to <50 WLM only: 14 Miners exposed to <50 WLM and at <0.5 WL only: 30	
German uranium miners study (Grosche et al. 2006)	1	2 388		5-35	All miners: 3 Miners with low exposures incurred at low dose rates: 18[f]	
French and Czech uranium miners (Tomasek et al. 2008)	2	574		5+ 5-35	All miners (mean exposure rate 4.5 WLM/year): 32	

[a] i.e. considering radon concentrations during the period starting 35 years before and ending 5 years before the date of diagnosis for cases of lung cancer, or a comparable date for controls.

[b] i.e. adjusting for year-to-year random variability in indoor radon concentration

[c] Informal estimate, indicating the likely effect of removing the bias induced by random year-to-year variation in radon concentration.

[d] Risks per WLM have been converted to risks per 100 Bq/m^3 by assuming that 1 Bq/m^3 at equilibrium is equivalent to 0.00027 WL, that the "equilibrium factor" in dwellings is 0.40, that subjects spend 70% of the time at home, that there are 365.25 x 24 / 170 = 51.6 'Working Months' in one year, and that the ratio of the dose to lung cells for exposures in homes to that for similar exposures in mines (sometimes referred to as the K-factor) is unity.

[e] Only one study has specifically addressed the effect of measurement error in the estimates of radon-related lung cancer risk in miners (Stram et al. 1999). This concluded that for miners exposed at concentrations below 15 WL measurement error was of little consequence.

[f] Informal estimate, obtained by multiplying the estimate for all miners in the German cohort by 6, i.e. the ratio of the estimates for all miners and for miners exposed to <50 WLM and <0.5 WL from the BEIR VI analysis.

in the residences of control group members in the relevant study area. To obtain the "measured radon concentration" for each individual, a time-weighted average of the radon concentrations in all the homes occupied over the past 5 to 34 years was calculated, with weights proportional to the length of time that the individual had lived in each of them.

After detailed allowance for the different lung cancer risks due to the varying smoking histories for individuals, the variation between the proportionate increase in risk per unit increase in radon concentration in the European studies was no larger than expected from random variation. It was therefore appropriate to pool the data. When this was done, a clear positive association between radon and lung cancer emerged. The risk of lung cancer increased by 8% per 100 Bq/m^3 increase in measured radon concentration (95% confidence interval 3-16%). The estimated percentage increase in lung cancer rate for each unit increase in residential radon concentration did not vary according to the age or sex of the individual more than would be expected by chance, nor did it vary (on this proportionate scale) more than would be expected by chance according to his or her smoking history (cf. Table 3).

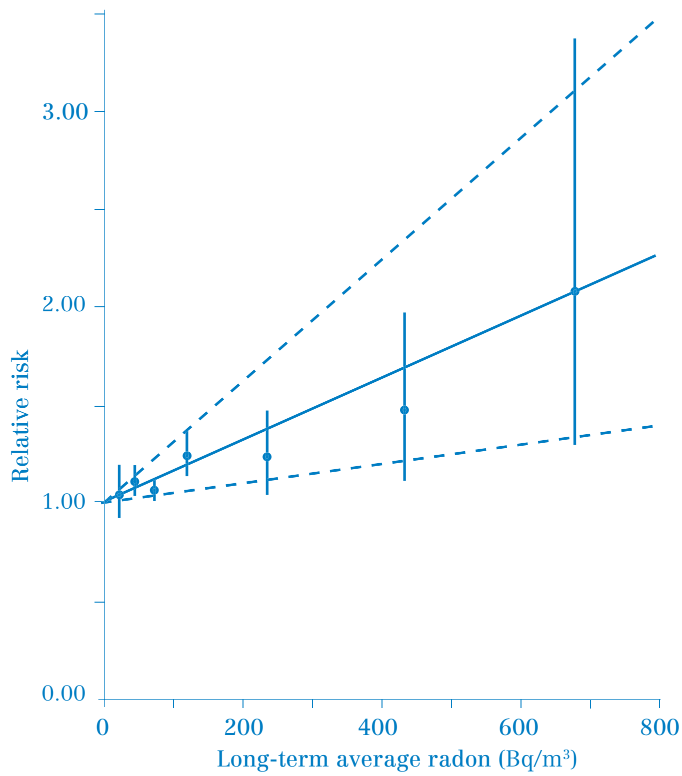
Table 3. Risk increase of radon-related lung cancer per 100 Bq/m^3 of measured indoor radon concentration based on the results of the European and North American pooling studies

	European pooling study[a]		North American pooling study[b]	
		% risk increase (95% CI)		% risk increase (95% CI)
Sex				
	Men	11 (4,21)	Men	3 (-4, 24)
	Women	3 (-4,14)	Women	19 (2, 46)
	p for heterogeneity	*0.19*		
Age at disease occurrence (years)				
	<55	<0 (<0, 20)	<60	2 (<0, 35)
	55-64	14 (3, 31)	60-64	80 (13, 257)
	65+	7 (1, 16)	65-69	2 (-5, 28)
			70-74	33 (1, 102)
			75+	-2 (-10, 30)
	p for trend	*0.98*		
Smoking status				
	Current cigarette smoker	7 (-1, 22)	Never smoked	
	Ex-smoker	8 (0, 21)	cigarettes	10 (-9, 42)
	Lifelong non-smoker	11 (0, 28)	Current or ex-cigarette	
	Other	8 (-3, 56)	smoker	10 (-2, 33)
	p for heterogeneity	*0.92*		
Overall				
	Based on measured radon	8 (3, 16)	Based on measured radon	11 (0, 28)

Sources: [a]Darby et al. (2005, 2006), [b]Krewski et al. (2005, 2006).
CI = confidence interval, p-values less than 0.05 denote statistical significance.

In the European pooling study, the exposure-response relationship appeared to be approximately linear with no evidence for a threshold below which there was no risk. In particular, the results were incompatible with a threshold above 150 Bq/m^3 (i.e. 150 Bq/m^3 was the 95% upper confidence limit for any threshold). Furthermore, the investigators found a statistically significant association between radon concentration and lung cancer, even when the analysis was restricted to people in homes with measured radon concentrations below 200 Bq/m^3. The risk of lung cancer was 20% higher (95% confidence interval 3-30%) for those individuals with measured radon concentrations 100-199 Bq/m^3 (mean: 136 Bq/m^3) when compared to those with measured radon concentrations under 100 Bq/m^3 (mean: 52 Bq/m^3).

As mentioned above, there is substantial year-to-year random variation in the average annual radon concentration in a home, depending, for example, on variation in the weather (Zhang et al. 2007). Therefore, if the risk of lung cancer due to radon from the case-control studies is estimated based only on the measured radon concentrations and without taking this variation into account, then the risk is likely to be underestimated. Therefore, in the European pooling study, the analysis was repeated using "long-term average radon concentration" (i.e. taking into account the random year-to-year variability in measured radon concentration). The final estimated risk coefficient, based on the long-term average radon concentration, was 16% per 100 Bq/m³ (95% confidence interval 5-31%). Once again, on this proportionate scale, the risk did not vary more than would be expected by chance with age or sex or according to the smoking status of the individual, and the dose-response relationship was approximately linear, as demonstrated in Figure 1.



Source: Darby et al. 2005
Relative risks and 95% confidence intervals are shown for categorical analyses and also best fitting straight line. Risks are relative to that at 0 Bq/m³.

Figure 1. Relative risk of lung cancer versus long-term average residential radon concentration in the European pooling study

The North American pooling study

The North American Pooling study (Krewski et al. 2005, 2006) involved 3 662 cases and 4 966 controls from seven studies in the USA and Canada. The methodology was similar to that used for the European study. As with the European study, the radon-related risk in the component studies was found to be consistent, once the data for individual subjects had been collated. When data from all seven studies were combined, the risk of lung cancer increased by 11% per 100 Bq/m^3 increase in measured radon concentration (95% confidence interval 0-28%). When the analyses were restricted to the subsets of data with greater exposure accuracy, the lung cancer risk estimates increased. For example, for individuals who lived in only one or two houses in the period 5 to 30 years prior to recruitment, with at least 20 years covered by dosimetry, the investigators reported a percentage increase of 18% (95% confidence interval 2-43%) per 100 Bq/m^3. The estimated percentage increase in lung cancer rate for each unit increase in measured residential radon concentration did not vary according to the age or sex of the individual more than would be expected by chance, nor did it vary more than would be expected by chance according to his or her smoking history (cf. Table 3).

As with the European pooling study, the results of the North American pooling were consistent with a linear dose-response relationship with no threshold. However, unlike the European Pooling study, no formal adjustments for variations in yearly residential radon concentrations have been performed so far. When further analyses become available, a direct comparison between the findings of the North American and European pooled studies after accounting for year-to-year variations in indoor radon concentration will be feasible.

The Chinese pooling study

Lubin and colleagues (2004) analysed 1 050 cases and 1 996 controls from two studies in two areas: Gansu and Shenyang. For the pooled data, the risk per 100 Bq/m^3 measured radon concentration increased by 13% (95% confidence interval 1-36%). This effect was chiefly due to the data from the much larger Gansu study, although the results of the two component studies were compatible with each other. As with the European and North American pooling studies, the results were consistent with a linear dose-response relationship with no threshold.

Overall evidence on the risk of lung cancer from residential radon

The three pooling studies present a very similar picture of the risk of lung cancer from residential exposure to radon (cf. Table 2). There is overwhelming evidence that radon is acting as a cause of lung cancer in the general population at concentrations found in ordinary homes. In particular, in all three pooling studies there was no evidence that the proportionate increase in risk per unit increase in radon concentration varied with the age, sex or smoking habits of the study subjects more than would be expected by chance. In addition, the dose-response relationship appeared to be linear, with no evidence of a threshold, and there was substantial evidence of a risk increase even below 200 Bq/m^3, the concentration at which action is currently advocated in many countries.

The three major pooling studies reported increased risks of lung cancer based on a measured radon concentration of 8% (95% confidence interval 3-16%), 11% (0-28%) and 13% (1-36%) per 100 Bq/m^3 increase in measured radon concentration (Table 2). As these three estimates are statistically compatible with each other, a weighted average, with weights proportional to their variances, can be calculated. This gives a joint estimate from the three pooling studies, based on measured radon concentrations, of 10% per 100 Bq/m^3.

As described above, estimates based on measured radon concentration are likely to under estimate the true risks associated with residential radon, due to the year-to-year random variation in radon concentrations in a home. The only pooling study to date that has carried out a detailed analysis of the risks of residential radon based on a long-term average, as opposed to measured radon concentrations, is the European pooling. In this study, the risk estimate based on long-term average concentrations was twice the risk estimate based on measured radon concentrations. Data from repeated radon measurements made in separate years in the same home in China show a similar year-to-year variation as in the European studies (Lubin et al. 2005), while data from the United States also suggest considerable year-to-year random variation (Zhang et al. 2007). If it is assumed that the effect of adjusting for year-to-year random variation in the three pooling studies combined is the same as in the European study, then a joint risk estimate from the three pooling studies, based on long-term radon concentrations, would be around 20% per 100 Bq/m^3 (cf. Table 2).

Other potential sources of radon exposure misclassification include detector measurement error, spatial radon variations within a home, missing data from previously occupied homes that are currently inaccessible, failure to link radon concentrations with subject mobility, and measuring radon gas concentration as a surrogate for radon progeny exposure (Field et al. 2002). It is generally difficult to assess the impact of these potential exposure measurement errors. However, if the misclassification does not differ systematically between cases and controls, the observed results tend to be biased towards zero (i.e. the true effect is underestimated). In fact, empiric models with improved retrospective radon exposure estimates were more likely to detect an association between residential radon exposure and lung cancer (Field et al. 2002).

A number of other factors have not been included in the formal analyses for the majority of indoor radon studies. In particular, there are frequently errors in the assignment of individuals to smoking categories and, in some countries, there may have been systematic changes in the radon concentrations over the last few decades, due to increased energy efficiency and the introduction of air conditioning. The overall effect of these factors, as described above, may indicate that the true effect of radon may be somewhat higher than the estimated risk in the residential radon studies, even after correction for year-to-year random variation in measured radon concentrations.

Direct comparison of the risks of lung cancer in studies of indoor radon with risks based on studies of radon-exposed miners is complicated. The generally higher exposures and also the inverse exposure-rate effect in the miners' data (cf. Table 1) contribute to this. Summary risk estimates from miners' studies are somewhat lower than from residential radon studies. For example, when all the miners included in the BEIR VI analysis are considered, the estimated risk is approximately 5% per 100 Bq/m^3, with somewhat lower estimates for the large German study. For the BEIR VI study, an additional analysis including only miners with cumulative exposures below 50 WLM (i.e. the exposure that would be received from living in a house with a radon concentration of around 400 Bq/m^3 for 30 years) has been carried out (Lubin et al. 1997) and suggests an increase of 14% per 100 Bq/m^3, while a further analysis considering only miners with cumulative exposures below 50 WLM and exposed only at <0.5 WL (i.e. $<\sim 2\,000$ Bq/m^3) suggests an increase in risk of 30% per 100 Bq/m^3. Similarly, results from an analysis of French and Czech cohorts that are restricted to workers with low exposure rates, an exposure window of 5 to 34 years and a comparatively high precision of exposure assessment indicate a risk increase in the order of 32% per 100 Bq/m^3 as shown in Table 2 (Tomasek et al. 2008).

In summary, there is good agreement between the estimates of radon-related risk based on the studies of indoor radon and the studies of underground miners with relatively low cumulative exposures accumulated at low concentrations.

1.3 Radon and diseases other than lung cancer

When an individual spends time in an atmosphere that contains radon and its decay products, the part of the body that receives the highest dose of ionizing radiation is the bronchial epithelium, although the extra thoracic airways and the skin may also receive appreciable doses. In addition, other organs, including the kidney and the bone marrow, may receive low doses (Kendall et al 2002). If an individual drinks water in which radon is dissolved, the stomach will also be exposed.

The evidence for radon-related increases in mortality from cancers other than lung cancer has been examined in the same studies of radon-exposed miners that were included in the BEIR VI analyses (Darby et al. 1995), and no strong evidence was found that radon was causing cancers other than lung cancer. However, further investigations are focusing on this issue. For example, a recent case-cohort study evaluating the incidence of leukaemia, lymphoma, and multiple myeloma in Czech uranium miners (Rericha et al. 2007) found a positive association between radon exposure and leukemia, including chronic lymphocytic leukemia. The relationship between radon exposure and cardiovascular disease has been examined in a number of cohorts of radon-exposed miners, but none has found evidence that radon is causing heart disease (Villeneuve et al. 1997, 2007, Xuan et al. 1993, Tomasek et al. 1994, Kreuzer et al. 2006). A case-control study of stomach cancer in an area where there were high concentrations of natural uranium and other radionuclides in drinking water gave no indication of an increased risk (Auvinen et al. 2005).

About 20 ecological studies of exposure to radon in the general population and leukaemia either in children or in adults have been carried out. Several of these, including a recent methodologically advanced study by Smith et al. (2007), have found associations between indoor radon concentration and the risk of leukaemia (including chronic lymphocytic leukaemia in the Smith et al. study) at the geographic level (for a review see: Laurier et al. 2001). An ecological study performed in Norway showed an association between multiple sclerosis and indoor radon concentration (Bolviken 2003). Generally, these associations has been confirmed in a high-quality case-control or cohort study, either in radon-exposed miners or in the general population, although several such studies have been carried out (Laurier et al. 2001, Möhner et al. 2006). As with the studies of radon exposure and lung cancer, these ecological studies are prone to a number of biases. They are therefore likely to give misleading answers and should not be taken as evidence that radon is acting as a cause of these diseases.

1.4 Burden of lung cancer caused by indoor radon

From the evidence presented above, it is clear that exposure to radon is a well established cause of lung cancer in the general population. In any particular country, the proportion of lung cancers occurring each year which are radon-induced will be determined chiefly by the indoor radon concentrations in that country. Surveys have been carried out to determine the distribution of residential radon concentrations in most of the 30 member countries of the Organization for Economic Co-operation and Development (OECD). The worldwide average indoor radon concentration has been estimated at 39 Bq/m^3 (Table 4).

Table 4. Indoor radon concentrations in OECD countries

	Indoor Radon Levels [Bq/m³]		
Country	Arithmetic mean	Geometric mean	Geometric standard deviation
OECD countries			
Australia	11	8	2.1
Austria	99	15	NA
Belgium	48	38	2
Canada	28	11	3.9
Czech Republic	140	44	2.1
Denmark	59	39	2.2
Finland	120	84	2.1
France	89	53	2.0
Germany	49	37	2.0
Greece	55	44	2.4
Hungary	82	62	2.1
Iceland	10	NA	NA
Ireland	89	57	2.4
Italy	70	52	2.1
Japan	16	13	1.8
Luxembourg	110	70	2
Mexico	140	90	NA
Netherlands	23	18	1.6
New Zealand	22	20	NA
Norway	89	40	NA
Poland	49	31	2.3
Portugal	62	45	2.2
Republic of Korea	53	43	1.8
Slovakia	87	NA	NA
Spain	90	46	2.9
Sweden	108	56	NA
Switzerland	78	51	1.8
United Kingdom	20	14	3.2
USA	46	25	3.1
Worldwide average	39		

Sources: WHO (2007), UNSCEAR (2000), Billon et al. (2005) and Menzler et al. (2008).

Detailed calculations of the numbers of radon-induced lung cancers attributable to radon exposure have previously been published for a number of countries. The calculations are based on the estimated concentrations of indoor radon from the surveys together with the indirect estimates of risk provided either by the studies of miners in the BEIR VI analysis or by the direct evidence provided by the European pooling studies (Table 5).

In most populations, lung cancer rates are much higher in current cigarette smokers than in lifelong non-smokers. The proportionate increase in the risk of lung cancer per unit increase in indoor radon concentration is similar in lifelong non-smokers and cigarette smokers in studies of residential radon (Table 3). Furthermore, in the miner studies for which smoking information is available, the proportionate increase in the risk of lung cancer per unit increase in indoor radon concentration is also

Table 5. Estimates of the proportion of lung cancer attributable to radon in selected countries

Country	Mean indoor radon [Bq/m³]	Risk estimate used in calculation	Percentage of lung cancer attributed to radon [%]	Estimated no. of deaths due to radon-induced lung cancer each year
Canada (Brand et al. 2005)	28	BEIR VI	7.8	1 400
Germany (Menzler et al. 2008)	49	European pooling study[a]	5	1 896
Switzerland (Menzler et al. 2008)	78	European pooling study[a]	8.3	231
United Kingdom (AGIR 2009)	21	European pooling study[a]	3.3	1 089
		BEIR VI	6	2 005
France (Catelinois et al. 2006)	89	European pooling study	5	1 234
		BEIR VI	12	2 913
United States (BEIR VI, 1999)	46	BEIR VI	10-14	15 400 - 21 800

[a] with adjustment for year-to-year variation in indoor radon concentrations.

similar. It follows that the majority of radon-induced lung cancers are caused jointly by radon and by smoking, in the sense that lung cancer would not have occurred if either the individual had not smoked cigarettes or had not been exposed to radon.

At an individual level, the risk of radon-induced lung cancer following exposure to a given radon concentration is much higher among current cigarette smokers than among lifelong non-smokers. This has been illustrated by the pooled analysis of European residential radon studies (Darby et al. 2005). For lifelong non-smokers, it was estimated that living in a home with an indoor radon concentration of 0, 100 or 800 Bq/m³ was associated with a risk of lung cancer death (at the age of 75) of 4, 5 or 10 in a 1 000, respectively. However, for a cigarette smoker, each of these risks would be substantially greater, namely 100, 120 and 220 in 1 000. For those having stopped smoking, the radon-related risks are substantially lower than for those who continue to smoke, but they remain considerably higher than the risks for lifelong non-smokers.

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2. Radon measurements

KEY MESSAGES

- Radon measurements in homes are easy to perform, but need to be based on standardized (e.g. national) protocols to ensure accurate and consistent measurements.
- Long-term integrated radon measurements are preferred for assessing the annual average radon concentration within a house or other dwelling.
- High temporal variation of indoor radon makes short-term measurements unreliable for most applications.
- The type of detector should be carefully selected since it influences the cost of measurement per dwelling and therefore the cost of a radon programme on a national level.
- Quality assurance and quality control measures are strongly recommended to assure the reliability of radon measurements.

This chapter provides a framework for the selection of devices for the measurement of radon and its decay products and also for the development of procedures and policies to assure the reliability of radon measurements in both air and water. The chapter also gives guidelines for various scenarios of radon measurements, including protocols ranging from individual testing of a single home to diagnostic measurements to assess radon exhalation from building materials; these guidelines may serve to enhance national guidance for radon measurement or provide the basis for the development of new guidelines. Quality assurance and quality control guidelines are also presented. The main sources of detailed guidance on radon devices and measurements are publications from OECD (1985), NCRP (1988), SSK (2002) and USEPA (1992, 1993, 1997).

Although radon decay products, primarily polonium (^{218}Po and ^{214}Po), are responsible for most of the radiation dose delivered by radon (^{222}Rn), radon gas concentration is generally considered a good surrogate for the radon decay product concentration. In addition, radon gas measurements are usually preferred to decay product measurements because of their relative simplicity and cost effectiveness. Radon measurements are often discussed in terms of either a short-term or long-term test (Quindos et al. 1991). A short-term test for radon, using an activated charcoal detector or another type of detector such as an electret ion chamber, can provide a first indication of the mean long-term radon concentration in a home. However, diurnal and seasonal radon variations should be taken into account when performing short-term radon measurements. Since high radon concentrations commonly occur during periods when homes are "closed up" (i.e. windows closed), a short-term measurement performed during this period, or season, can overestimate the yearly mean radon concentration. Alternatively, a short-term radon measurement performed during a period when the house has increased ventilation (e.g. windows open) can substantially underestimate the mean annual radon concentration. Therefore, in order to assess the annual average radon concentration within a home, devices that provide a long-term integrated radon measurement are preferred. However, it should be noted that even yearly radon concentrations in the same home can vary (Zhang et al. 2007). In addition, situations may arise where decay product measurements are necessary in order to improve the estimate of the overall radon dose to the individual.

Table 6. Radon gas measurement devices and their characteristics

Detector Type (Abbreviation)	Passive/Active	Typical Uncertainty[a] [%]	Typical Sampling Period	Cost
Alpha-track Detector (ATD)	Passive	10 - 25	1 - 12 months	low
Activated Charcoal Detector (ACD)	Passive	10 - 30	2 - 7 days	low
Electret Ion Chamber (EIC)	Passive	8 - 15	5 days - 1 year	medium
Electronic Integrating Device (EID)	Active	~ 25	2 days - year(s)	medium
Continuous Radon Monitor (CRM)	Active	~ 10	1 hour - year(s)	high

[a] Uncertainty expressed for optimal exposure durations and for exposures ~ 200 Bq/m^3 .

The most popular radon measuring devices (Table 6) used by countries surveyed within the WHO International Radon Project (WHO 2007) were alpha-track detectors (ATDs), electret ion chambers (EICs), and activated charcoal detectors (ACDs). Active devices in use by many countries included electronic integrating devices (EIDs) and continuous radon monitors (CRMs). Passive devices do not require electrical power or a pump to work in the sampling setting, whereas active devices require electricity and include the ability to chart the concentration and fluctuations of radon gas during the measurement period. For homes, ATDs are a popular choice to obtain a long-term radon measurement and are often deployed for a one-year period, while EICs are often used for short (e.g. several days) to intermediate (e.g. weeks to months) measurement periods. EICs also have the ability to integrate the radon concentration over time (e.g. 8-hour home occupancy period), using an open-and-close feature of the detector. The use of CRMs has become more prevalent as the price of these detectors has slowly declined. CRMs can automatically provide time-resolved information.

Table 7 provides a general guide for the selection of measurement methods and detectors for various measurement scenarios. The use of grab samples was not included in the list of recommended detectors and was not listed as a popular method

Table 7. Primary methods and devices for residential radon measurements

Method	Measurement Type	Device
Preliminary Test for Radon	Short-term Sampling	CRM, EIC, ACD
Assessment of Exposure	Time Integrating	ATD, EIC, CRM, EID
Remediation Testing	Continuous Monitoring	CRM

to assess radon concentrations (WHO 2007). Grab samples are air samples collected, using various devices like scintillation cells, over time intervals as short as minutes and then taken to the laboratory for analysis. These types of measurements do not capture the fluctuations in radon or radon decay product concentration over time. Grab samples are not included within the guidelines as they are not recommended for assessment of radon exposure or for making decisions regarding the need for mitigation. Additional details on measurement devices can be found in George (1996) and in reports from OECD (1985), NCRP (1988), SSK (2002) and USEPA (1992, 1993).

2.1 Measurement devices

This section summarizes the main measurement devices of radon and its decay products, reflecting current practice in some countries with established radon programmes.

2.1.1 Radon gas detectors

a. Alpha-track detectors

An ATD is a small piece of specially produced plastic substrate enclosed within a filter-covered diffusion chamber that excludes the entry of radon decay products as shown in Figure 2. The plastic is generally a polyallyl diglycol carbonate (PADC or CR-39), cellulose nitrate (LR-115), or polycarbonate (Makrofol) material. When alpha particles are generated by radon or radon decay products in proximity to the detecting material, they can strike the detecting material, producing microscopic areas of damage called latent alpha tracks. Chemical or electro-chemical etching of the plastic detector material enlarges the size of the alpha tracks, making them observable by light microscopy so that they can be counted either manually or by an automated counting device. The number of tracks per unit surface area, after subtracting background counts, is directly proportional to the integrated radon concentration in Bqh/m^3. A conversion factor obtained by controlled exposures at a calibration facility allows conversion from track density to radon concentration. Alpha-track detectors are generally deployed for an exposure period ranging from 1 month to 1 year. Alpha-track detectors are insensitive to humidity, temperature, and background beta and gamma radiation, but measurements performed at very high altitudes (e.g. above 2 000 m) may require slight adjustments due to differences

Figure 2. Examples of radon detectors

in air density that can affect the distance alpha particles can travel (Vasudevan et al. 1994). Cross-sensitivity to thoron can be avoided by using a diffusion chamber with a large diffusion resistance to gas entering the chamber. A minimum detectable concentration (MDC) of 30 Bq/m^3, calculated by methods discussed elsewhere (Currie 1968, Alshuler and Pasternack 1963, Strom and MacLellan 2001), for a 1 month exposure is generally achievable for ATDs. Even lower MDCs can be obtained as prescribed by Durrani and Ilic (1997) and Field et al. (1998).

b. Activated charcoal adsorption detectors

ACDs are passive devices deployed for 1-7 days to measure indoor radon. The principle of detection is radon adsorption on the active sites of the activated carbon. After sampling, the detector is sealed and the radon decay products equilibrate with the collected radon. After a 3-hour waiting period, the collectors can be directly gamma counted, or analytically prepared for liquid scintillation counting techniques. In the gamma counting method, the charcoal canisters or bags contain 25-90 g of activated carbon. In the alpha counting method, 20 ml liquid scintillation vials containing 2-3 g of activated carbon are used. The canisters can be open-faced or equipped with a diffusion barrier to extend the measurement period to 7 days. Because the response of ACD devices is affected by humidity, they must be calibrated under various levels of humidity. The devices should also be calibrated over the range of exposure durations and temperatures likely to be encountered in the field. If different types of carbon are mixed, the calibration may not remain constant. Because charcoal allows continuous adsorption and desorption of radon, the method only provides a good estimate of the average radon concentration over the exposure time if changes in radon concentration are small. The use of a diffusion barrier reduces the effects of drafts and high humidity. Since radon decays with a half-life of 3.8 days, detectors must be returned for analysis as soon as possible after the exposure period. For example, some laboratories require that detectors be returned to the laboratory within 8 days. An MDC of 20 Bq/m^3, calculated by methods described by Altshuler and Pasternack (1963), for a 2 to 7 day exposure period, is generally achievable for standard ACDs. Further details are given by George (1984) and USEPA (1987).

c. Electret ion chambers

EICs are passive devices that function as integrating detectors for measuring the average radon gas concentration during the measurement period. The electret serves both as the source of an electric field and as a sensor in the ion chamber. Radon gas, but not decay products, enters the chamber by passive diffusion through a filtered inlet. Radiation emitted by radon and its decay products formed inside the chamber ionizes the air within the chamber volume. The negative ions are collected by the positive electret located at the bottom of the chamber. The discharge of the electret over a known time interval is a measure of time-integrated ionization during the interval. This in turn is related to the radon concentration. The electret discharge in volts is measured using a noncontact battery-operated electret reader. This value, in conjunction with a duration and calibration factor, yields the radon concentration in desired units. Typical short-term EICs are designed to measure radon for 2 to 15 days at a concentration of 150 Bq/m^3. The long-term EICs measure radon over 3 to 12 months at a concentration of 150 Bq/m^3. EICs have been described previously (Kotrappa et al. 1990). These devices have been used in various countries and have displayed excellent accuracy and precision if standard operating procedures (routine correction for background gamma radiation, assuring the electrets are free of dust, etc.) are followed (Sun et al. 2006).

d. Electronic integrating devices

Most EIDs use a solid-state silicon detector within a diffusion chamber for counting the alpha particles emitted by the radon decay products. Due to the small dimensions of the diffusion chamber, long integration times (> 2 days) are often necessary for a statistically stable reading at moderate radon concentrations. Higher sensitivities can be achieved by applying high voltage to collect the charged radon decay products electrostatically by direct contact to the detector. High air humidity may affect the measurement. An MDC of 20 Bq/m^3 is typical for a 7-day exposure period. For several popular EIDs, the ability to routinely calibrate these detectors is lacking.

e. Continuous radon monitors

There are several types of commercially available CRMs using various types of sensors including scintillation cells, current or pulse ionization chambers, and solid-state silicon detectors. CRMs either collect air for analysis using a small pump or by allowing air to diffuse into a sensor chamber. All CRMs have electrical circuitry that provide a summary report, and often a time-resolved recording, which allows the calculation of the integrated radon concentration for specified periods. The different types have their specific advantages. For example, when using solid-state silicon detectors, alpha spectrometry is possible (Tokonami et al. 1996, Iimoto et al. 1998a), allowing discrimination between radon and thoron. Some devices eliminate the cross-sensitivity to air humidity by drying the incoming air. Generally, the MDC of these devices is about 5 Bq/m^3 calculated using standard methods. CRMs require routine calibrations to assure proper functioning and reliable results. Figure 3 shows an example of an electronic radon measure device.

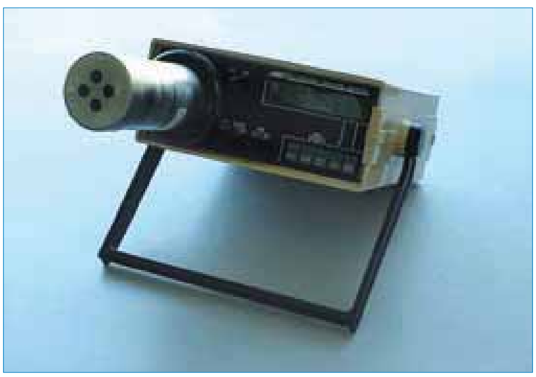

Figure 3. An example of an electronic radon measurement device

2.1.2 Specialized gas and radon decay product detectors

a. Thoron measurement devices

The indoor concentration of thoron (^{220}Rn) has been found to be high in some dwellings, contributing 50% or more to the total potential alpha energy concentration (PAEC) (Shang et al. 2005). Thoron originates, in general, from the walls of a structure and due to its short half-life develops a decreasing concentration gradient towards the centre of the room. To minimize measurement errors due to thoron, it is important to place the detectors at least 20 cm away from the wall. In order to measure the combined radon and thoron concentration, or to assess the influence of thoron on radon measurement, a separate determination of thoron can be performed.

Several methods are available for measuring thoron. With the double alpha-track detector method (DTD), both radon and thoron can be measured separately. This method uses two diffusion chambers with ATDs and the different half-lives of thoron (56 s) and radon (3.8 d) for differentiating the two isotopes. One diffusion chamber with a high diffusion resistance detects only radon; a second one with a low diffusion resistance detects both radon and thoron. It is possible to calculate the thoron concentration at the detectors, knowing the sensitivities of the ATD substrates to radon and thoron. Because the thoron value results from the difference between two readings, the detection limit and uncertainty are higher than for single ATD measurements (Table 8). More information on DTD can be found in Doi et al. (1992), Zhuo et al. (2002), and Tokonami et al. (2005a). In the two-filter method, air passes a first filter (retaining aerosols, thoron and radon decay products), crosses a chamber and exits through a second filter. The exit filter collects all the radon decay products formed within the chamber. In order to minimize losses at the chamber walls, the flow rate should be set to allow adequate radon decay product formation inside an optimally sized chamber. Activity analysis can be performed after sampling (grab sampling) or during filtration by scintillation measurement or semiconductor alpha spectrometry (continuous measurement).

Other continuous thoron monitors (CTM) work with the technique already described for CRMs: electrostatic collection of charged radon decay products on a silicon solid-state detector and subsequent detection by alpha spectrometry. However, considerable measurement uncertainty can result from the inability to adequately calibrate the detector for the short-lived thoron gas (Table 8). It should be mentioned here that the alpha decay of the thoron decay product ^{212}Bi may affect radon measurements because it has the same alpha emitting energy of 6.0 MeV as the radon decay product ^{218}Po. Further, the thoron progeny ^{212}Po, which emits an alpha particle with an energy of 8.8 MeV, may affect radon measurements that employ gross-alpha counting techniques. Radon gas monitors used in a mixed radon/thoron atmosphere should adjust for this effect. Because the thoron concentration in a room is not homogeneous, the representativeness of any measurement is difficult to ascertain. This makes the direct determination of thoron decay products even more important than for radon. Due to the longer half-life of the decay product ^{212}Pb (10.6 h) as compared to thoron gas (56 s), the indoor thoron decay product concentration is less heterogeneous. Radon and thoron discriminative measurements can be made by using a single scintillation cell, by estimating alpha counting efficiencies for radionuclides associated with radon and thoron using Monte-Carlo techniques (Tokonami et al. 2002).

Table 8. Thoron gas measurement devices and their characteristics

Detector Type (Abbreviation)	Passive/Active	Typical Uncertainty [%]	Typical Sampling Period	Cost
Double Track Detector (DTD)	Passive	25	3 - 12 months	low
Two-Filter Method (TFM)	Active	10	10 hours	high
Continuous Thoron Monitor (CTM)	Active	25	2 hours - 1 year	high

b. Radon and thoron decay product measurement devices

In situations where a more precise assessment of the radiation exposure is needed (e.g. in a situation where the equilibrium factor F between radon and its decay products differs significantly from the usually assumed value of F = 0.4), the direct determination of the radon decay products can be performed in terms of the equilibrium equivalent radon concentration, the total PAEC, or the activities of each single decay product. All available methods are based on the collection of the radon decay products on filters and a subsequent activity measurement on the filter. Depending on the analyzing technique, different filter material is used, e.g. for alpha measurement, membrane filters on which the sample is deposited at the surface (Iimoto et al. 1998b). Examples of radon and thoron decay product measurement devices include gross alpha counters, integrating alpha-track decay product detectors, alpha-spectrometric devices with surface barrier detectors, and attached-unattached samplers (NCRP 1988, Cheng et al. 1992).

2.1.3 Radon in water measurement devices

The presence of radon in groundwater is predominantly due to the decay of radium (^{226}Ra) found in rock and soils and does not mainly originate from the radium dissolved in water. Radon can also be generated within water distribution systems with high radium concentrations from radium adsorbed iron pipe scales (Field et al. 1995, Fisher et al. 1998a). Radon exposure from waterborne radon sources may occur either from ingestion or from inhalation of radon released from water. The cancer risk resulting from the release of waterborne radon (showering, dish washing, etc.) is generally considered much greater than the risk from drinking water containing radon (NRC 1998). A commonly used estimate for the transfer coefficient of radon between water and air for homes in North America is 1.0×10^{-4} (Nazaroff et al. 1987). In most parts of the world, radon released into the indoor air from waterborne sources is much less than the radon emanating from ground sources beneath the home. Several well-established methods exist for the collection (Field and Kross 1996) and measurement (Vitz 1991) of radon in water. Techniques for measuring radon in water include direct gamma counting (Galli et al. 1999), electret ion chambers (Kotrappa and Jester 1993), and gas transfer by membranes (Surbeck 1996, Freyer et al. 2003). Liquid scintillation counting and the de-emanation radon measurement techniques are the most prevalent methods for measuring radon concentrations in water (Prichard et al. 1991, Prichard and Gesell 1977, Lucas 1957, 1964) and will be discussed in detail.

a. Liquid scintillation counting

Liquid scintillation counting (LSC) is the most sensitive and widely used method to measure radon in water. The popularity of liquid scintillation for radon analysis is due to several factors including the excellent accuracy and precision of the method, the low level of detection, the limited need for sample preparation, the ability to rapidly measure a large number of samples, and the ability of the counter to change samples while unattended. Because of the high solubility of radon in organic solvents, properly collected water samples (Field and Kross 1996) can be added directly to the scintillation cocktail (e.g. toluene, xylene, or mineral oil) to form a two-phase aqueous/organic system. The radon will be partitioned between the water/scintillation cocktail and the air space in the vial and will become available for measurement by LSC methods. The LSC technique quantifies the activity of radon and decay products from the rate of photons emitted from the scintillation fluid (Prichard and Gesell 1977, Prichard et al. 1991). Limitations of the LSC technique include the initial start-up cost to purchase the counter and the need to perform the analyses in a laboratory.

b. De-emanation counting

Measurement of radon in water by de-emanation involves extracting the dissolved radon from water into a radon-free gas that is subsequently transferred to a radon measuring device, such as a scintillation cell. For water to be analysed, a water sample is transferred to a bubbler. By bubbling the water sample with a radon-free gas (e.g. nitrogen), whose volume is five-to tenfold greater than the volume of the liquid, de-emanation of water at normal temperatures can be achieved. In this example, an evacuated scintillation cell is refilled by the gas enriched with the extracted radon. The cell is counted after a delay of about 3 hours to establish radioactive equilibrium between radon and its decay products. Depending on the counting time, a detection limit below 1 Bq/l can be achieved.

Besides EIC, two other techniques for measuring radon in water are direct gamma counting and gas transfer by membranes (Galli et al. 1999, Surbeck 1996, Freyer et al. 2003).

2.2 Measurement protocols

This section provides general guidance for some typical radon measurement purposes and locations. In this discussion, “short-term” refers to measurements that average radon concentrations over days or weeks, while “long-term” measurements generally cover a season or more (several months to one year). As previously mentioned, long-term radon measurements are preferred because temporal variations of a factor of two or more commonly occur in repeated short-term measurements. Since radon measurements serve various purposes in different settings, appropriate measurement strategies and protocols need to reflect these differences. It is important to seek input on these protocols from stakeholders including researchers, radon measurement providers, builders, and officials who are responsible for implementing regional and national health guidance. In determining the best approach for each situation, consideration should be given to measurement variability and the predictive value of the results, given the uncertainties that arise from spatial, temporal and instrument variations. For example, the variable could be typical personal exposure, or average radon concentrations at a location, or even worst-case radon concentrations.

It is vital to determine the predictive performance of the measurements in a representative sample of building stock, so that sound decision protocols lead to appropriate action. The radon measurement uncertainty, reference level, and decision protocol all affect the reliability of the decision to act in a given region. Several countries have published detailed guidelines for measuring radon in various situations and for making decisions in a given situation (RPII 2002, Synnott and Fenton 2005, SSK 2002, USEPA 1993). Some of these guidelines were established prior to studies of regional behaviour of radon in buildings and may not be directly applicable to new, as yet unsurveyed regions. Special measurement strategies and protocols may be required in radon-prone areas, as described in chapter 6, in order to maximize detector efficiency and reliability in countries with diverse climates, geologies, and building practices.

2.2.1 Measurements in homes

Radon measurements performed in private homes should strive to produce reliable estimates of an individual’s exposure at a modest cost. High temporal variation of indoor radon in many regions makes short-term measurements unreliable for this application, except in cases where extremely high radon concentrations are expected. In some countries, measurements made in various seasons are adjusted to estimate an annual-average radon concentration based on “typical” seasonal variations (Baysson et al. 2003, RPII 2002). In addition, a single measurement in one room where radon is expected to reach its highest concentration is sometimes used to estimate the “whole house” radon concentration. This measurement should be made in a frequently occupied room, either on the level with the most ground contact if soil gas radon is the main source, or a frequently occupied space with the least airflow if building material is the main source of radon. The uncertainty introduced by these practices should be included in the decision-making protocol. Of particular importance is a clear and unambiguous definition for the term “frequently occupied.” This definition differs among countries, especially if the number of hours is used in the definition, given that the total percent of time spent inside a home varies by country. The measurement protocol should minimize the potential for technical failure of the detectors, whose results may be affected by drafts, moisture, temperature, strong light, gamma rays or thoron.

In some countries, radon measurements are part of a standard home safety assessment which is carried out before a sale. Although real-estate transactions provide a window of opportunity to assess hazards associated with a property, the pressure to conclude a sale often interferes with accurate assessment of the potential radon hazard. In countries such as the USA, where radon testing during real-estate transactions is a common practice, side-by-side (collocated) short-term measurements at a single location are usually applied. These diagnostic tests frequently fail in radon-prone areas with strong seasonal radon variation. Current short-term radon measurement technologies are unable to produce accurate estimates of annual-average radon concentrations (Steck 1990, Steck 1992, White 1994, White et al. 1994). In some cases, short-term measurements may be used if they are interpreted using a wide confidence interval to identify homes with elevated radon concentrations. However, this practice may lead to misclassifying homes as having either high or low long-term radon concentrations. Long-term measurements can be started simultaneously with short-term measurements, to allow the transaction to proceed while an accurate assessment takes place. Examples of measurement practice in some countries are given in Box 1. In some countries, detailed instructions on the deployment of detectors are also given, for example the installation at breathing height and at a specific distance from doors and windows (DIN 1994).

Box 1: Examples of measurement practice in some countries

> Finland and Sweden recommend measurements during the heating season (October to April) as during this period higher indoors radon concentrations are expected. Ireland and the United Kingdom carry out radon measurements over any three-month period throughout the year and apply seasonal correction factors. In Italy, one-year measurements are generally performed to avoid uncertainties related to seasonal variations. In the USA, the majority of measurements are made in connection with real-estate transactions, so short-term measurements are more commonly performed.

2.2.2 Measurements in large buildings

Radon exposure patterns in large buildings such as schools, commercial buildings and multiunit residential structures may differ from exposure in detached houses due to differences in building structure, occupancy and heating, ventilation and air conditioning (HVAC) operation. Measurement protocols should reflect these differences by defining multiple sampling locations in highly occupied locations for buildings with large floor areas, multiple floors, and multiple compartments with separate HVAC systems. Generally, lower floors should be sampled at a higher rate, because of the potential for increased radon concentrations on ground-contact floors, when radon from soil gas is the main source (Fisher 1998b, Synnott 2004, 2006). Room-to-room radon variations in some buildings suggest that a significant fraction of rooms need to be measured in most buildings. Many buildings show diurnal radon variations. This effect can be enhanced in buildings with mechanical HVAC or strong diurnal use patterns. Buildings that have high average radon concentrations, but are only occupied for part of the day, may need to be measured during occupied periods to determine if there is significant diurnal radon variation.

2.2.3 Diagnostic measurements for mitigation and post-mitigation

The decision to mitigate a dwelling should be based on long-term average radon concentrations in frequently occupied spaces. If a short-term screening test shows a very high radon concentration, the decision to mitigate can be made without a confirmation from a long-term test. Short-term and long-term measurements should be started simultaneously at the location of the original measurement(s), a few days after a mitigation system is installed. Long-term tests should be repeated every few years to ensure sustained effectiveness of the mitigation system.

2.2.4 Diagnostic measurements to assess radon emanation from building materials

Radon flux - or exhalation - from building materials can be measured either in the laboratory or in a field setting. If a sample of the building material is easily obtainable, the radon exhalation rate can be determined by placing it in a closed chamber and subsequently sampling the air (Ingersoll et al. 1983, Folkerts et al. 1984). Field assessments of radon flux use various techniques including an accumulation method, a flow method, and an adsorption method. In addition to measuring the exhalation rates, high-resolution gamma ray spectrometry is often used to determine the activity of natural radionuclides in the building material. Details describing these methods and others are found elsewhere (De Jong et al. 2005, Stoulos et al. 2003, Petropoulos et al. 2001, Keller et al. 2001, NCRP 1988, Collé et al. 1981).

2.2.5 Exposure assessment in epidemiologic studies

Radon exposure assessments for epidemiological studies can be seriously compromised by several factors including intrinsic radon detector measurement error, failure to account for temporal and spatial radon variations within a home, missing measurement data from previously occupied homes, failure to link radon concentrations with an individual's mobility, measuring radon gas as a surrogate for radon decay product exposure (Steck and Field 2006, Field et al. 1996) and potential cross-sensitivity to thoron (Zhuo et al. 2002). The use of year-long radon gas measurements using ATDs is recommended with linkage to the individual's mobility patterns within the home (Field et al. 2000, Field et al. 2002). In order to minimize missing data from the inability to measure the radon in previously occupied homes, inclusion criteria for cases and controls can include the requirement for long residency in the current home. Alternatively, some case-control studies have used glass-based retrospective radon detectors to measure the implanted radon progeny. Additional details regarding retrospective radon detectors are discussed by Steck and Field (2006).

2.3 Quality assurance for radon measurements

Quality assurance (QA) is a broad concept that includes all matters that individually or collectively influence the quality of a measurement. WHO strongly recommends the implementation of QA standards and guidelines to ensure confidence in the measurement results. Several aspects are discussed here, including the quality control of measurements. In addition, general guidance is provided on elements of a QA programme that are common to all types of measurement devices. However, since recommendations for quality control (QC) measurements vary depending on the type of device, the remainder of the discussion on QA is divided into continuous, integrating and equilibrating methods.

2.3.1 Quality assurance plan

All entities (individuals, businesses, government agencies, etc.) providing measurement services should establish and maintain quality assurance programmes. At the heart of a quality assurance programme is the QA plan, which includes written standard operating procedures, written procedures for attaining quality assurance objectives and a system for recording and monitoring the results of QC measurements. Guidance on preparing QA plans is available, for example from USEPA (1984, 1997).

2.3.2 Minimum detectable concentration

Any entity performing radon measurements should calculate and include the minimum detectable concentration (MDC) for its measurement system in its QA plan and report it with the radon measurement results. Methods for determining the detection limit and MDC are discussed elsewhere (Altshuler and Pasternack 1963, ANSI 1989, Currie 1968, Strom and MacLellan 2001).

2.3.3 Intercomparison exercises

As far as possible, entities performing radon measurements should participate periodically in inter-laboratory comparison exercises. Such exercises are typically carried out in one of two ways. A continuous radon monitor may be chosen as a "transfer standard" and sent to several reference laboratories for exposure in Systems for Test Atmospheres with Radon (STAR). STAR is an acronym used to designate the equipment needed for the creation and the use of an atmosphere containing a reference concentration of radon.[2] Once the CRM has been received at the laboratory, the operator of each STAR compares the values generated by the transfer standard with the values generated by the system that is used to monitor the STAR. This method can only be used between facilities that have STAR. Radon measurements from STAR must be traceable to a primary national reference standard by an acceptable inter-comparisons method.

The other method requires a radon reference facility that has a STAR to "host" the exercise. Entities that perform radon measurements then send devices to that facility for exposure in the STAR. The devices are returned, but the concentration of radon to which they were subjected is not disclosed. Each entity then reports its results to the host facility, which then issues a report comparing all the participants' results with the conventionally true value(s). As part of the inter-comparison exercises, cross-checks for detector sensitivity to thoron should be considered. Examples of inter-laboratory comparisons can be found elsewhere (e.g. Butterweck et al. 2002, Tokonami et al. 2005b, Röttger et al. 2006, Beck et al. 2007).

2.3.4 Performance tests and "Blind Spikes"

Certifying or licensing agencies often require entities that perform radon measurements to participate in a performance test or proficiency test (PT). The participant collaborates with a recognized reference facility which has a STAR to expose devices to a controlled radon concentration; it then returns them without disclosing the value of the radon concentration to which they were exposed. The participant then assesses the performance of the devices and reports the results to the facility. The results are compared to the conventionally true value(s) and a report is issued, informing the participant whether the PT was passed, based on the criteria established by the certifying or licensing agency. This is similar to an inter-comparison exercise, except that only one radon measuring participant at a time may be involved with the STAR facility; whereas, during an inter-comparison exercise, several entities are typically involved at the same time. If the participant is not required to perform a PT by some certifying or licensing agency, but merely wishes to accomplish the same exercise for its QA programme, this is called a "blind spike".

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[2] A current reference list of STAR facilities as well as laboratories that provide traceable reference sources is maintained at the website www.radonweb.org.

2.3.5 Blind tests

Certifying or licensing agencies may wish to carry out performance tests on radon measuring entities without their knowledge. This is called a “blind test”, as the entities do not know the conventionally true value, or even that they are being tested. This is relatively easy to do for entities that analyze devices that are marketed to the general public or radon-testing firms. The agency can merely purchase devices and arrange for them to be exposed to a controlled radon concentration in a STAR, after which they are sent to the entity for analysis with fictitious exposure location information. For entities that do not market devices, such as users of continuous monitors, blind testing is more difficult and costly.

2.3.6 Continuous device methods

a. Calibration

Continuous monitors are calibrated individually by the manufacturer or by a reference laboratory, authorized and trained by the manufacturer. The calibration process consists of a number of steps appropriate for the specific type of monitor, including some or all of the following: 1) check of voltage, current and/or wave patterns at critical points in the circuitry, followed by adjustments as necessary; 2) check of batteries and recharging, with replacement if needed; 3) determination of proper discriminator settings and high-voltage settings on a photomultiplier tube; 4) determination of the background by exposure to a radon-free environment of nitrogen or aged air, and checks of the calibration factor by exposure to a reference atmosphere in a STAR. If more than one continuous monitor using scintillation cells are used by one entity, each scintillation cell should be matched to a given photomultiplier tube and not used with other photomultiplier tubes. Otherwise, the calibration factor should be determined for each combination of scintillation cell and photomultiplier tube.

A statement, or certificate, of calibration should be issued containing information such as: 1) the condition of the monitor “as received” including any physical damage and settings of discriminator, voltage, background and calibration factor as necessary; 2) the measured background; 3) the measured response to the reference atmosphere; 4) the settings of the discriminator, voltage, background and calibration factor, “as calibrated”; 5) the date the calibration was performed, and 6) the name and signature of the person responsible for the calibration.

A calibration sticker should be affixed to the monitor containing: 1) the name of the facility performing the calibration; 2) the initials of the person performing the calibration; 3) the date of the calibration; 4) the expiry date of the calibration; 5) the values of the background and of the calibration factor, and 6) the serial number of the monitor. The monitor should be calibrated at regular intervals, typically annually or semiannually, depending on the recommendation of the manufacturer and the requirements of licensing or certifying agencies.

b. Background

Assessing the background of a continuous monitor at least annually is essential and usually performed as part of the calibration process. Over time, a long-lived decay product of radon, ^{210}Pb, accumulates in the detector. The remaining two radionuclides in the uranium decay series, ^{210}Bi and ^{210}Po, come into some degree of equilibrium with the ^{210}Pb. It is usually the build-up of the alpha-particle emitter ^{210}Po that causes the background to increase with time.

The background of a continuous monitor that uses a scintillation cell may need to be measured more often, depending on the amount of use and the concentration of radon to which the scintillation cell is exposed. A common protocol is to start by measuring the background every 1 000 hours of operation. If the change in background is less than the equivalent of ~ 30 Bq/m^3, then the number of hours between background measurements can be increased, as long as the system is not subjected to a large concentration of radon. If more than one continuous monitor is used, the background should be determined for each combination of scintillation cell and photomultiplier tube.

c. Internal checks

Some continuous monitors provide internal checks that can be made by the user between calibrations, such as a check of batteries, a standard source for checking the performance of the detector, and an electronic check of the performance of the detector. If such internal checks are available, they should be performed prior to each measurement. For some types of monitors, an internal check occurs automatically every time a measurement is initiated.

d. Duplicates

Measurements should be duplicated at a rate specified in the QA plan such as 10% (USEPA 1993) by collocating two monitors of the same type and performing the measurement simultaneously with both monitors. The relative percent difference (RPD) of the two measurements can then be calculated as a measure of precision of the monitor. Such measurements of RPD should be tabulated and plotted on control charts as explained below. If duplicate measurements do not coincide, this could be an indication that one or both of the monitors are no longer correctly calibrated and this should prompt further investigation.

e. Informal intercomparisons

If two monitors of the same type are not available for a duplicate measurement, a device of a different type, such as a charcoal device, can be used side-by-side with a monitor. Such measurements are called “informal inter-comparisons” rather than “duplicates” as they cannot produce an estimate of precision for either type of device. However, such measurements can provide useful information insofar as a disagreement between the two measurements may indicate a problem with one or both measurement types. The RPD should be calculated and evaluated as discussed below.

f. Cross-checks

With an interval of about six months, or halfway between calibrations, radon monitors should be used for “duplicate” measurements with another monitor of the same type that has recently been calibrated. This is called a “cross-check” measurement. Because it can be assumed that the recently calibrated monitor provides a better estimate of the radon concentration, the relative error should be calculated with the assumption that this monitor provides the conventionally true value. Correction factors can then be applied.

2.3.7 Integrating and equilibrating device methods

a. Calibration

Integrating and equilibrating devices, such as alpha-track devices, electret ion chambers and charcoal devices, are not calibrated individually. Rather, batches of devices representative of those used in the field are subjected to exposure in a STAR under varying parameters such as radon concentration, duration of exposure, relative humidity and temperature. The manufacturer or the laboratory that checks the device develops sets of calibration curves or algorithms, based on data from exposures in a STAR. Descriptions of such procedures for charcoal canister devices are given by George (1984) and USEPA (1987). The curves or algorithms produce values of the calibration factor for the device, as a function of operational factors (e.g. duration of exposure, electrical potential on electrets) and environmental factors (e.g. ambient gamma background, relative humidity, temperature, altitude). Periodic spiked samples as described later are used by manufacturers or laboratories to demonstrate that the calibration continues to produce results that are reliable "In Control". The calibration process must be repeated every time that the device is modified physically including, for charcoal devices, the use of a different lot of charcoal, or every time that periodic quality control data indicate the results are no longer reliable.

b. Duplicates or collocated measurements

Side-by-side or "collocated" measurements provide an estimate of the precision of the measurements and of the overall precision of the device and laboratory process. The rate at which collocated measurements are made should be specified in the QA Plan. Making collocated measurements at a specified rate, such as every tenth measurement, should help ensure that they occur over the range of radon concentrations encountered in the field (USEPA 1993). For each set of collocated measurements, the appropriate statistic should be calculated and tabulated in quality control records and plotted on a control chart. If only two collocated measurements "duplicates" are consistently made, then the RPD statistic may be used; otherwise, a coefficient of variation must be used. Performance goals for precision, such as a range that is "In Control" a "Warning Level" and a "Control Limit" as well as the actions that will be taken if limits are exceeded, should be specified in the QA Plan. Information on control charts, setting limits and determining when corrective action should be taken is given by Goldin (1984) and USEPA (1984, 1993).

c. Laboratory background measurements

Laboratory equipment that is used to analyze devices, such as charcoal canisters and alpha-track detectors, has an inherent background that must be measured and subtracted from the response of detectors used in the field. Background measurements are also used in establishing the detection limit and MDC of the analysis system as explained earlier. The QA Plan of the analysis laboratory should include criteria that establish the minimum number of detectors from each batch that require testing, or the frequency of measurement of a representative blank device, to establish the laboratory background for the measurement system.

d. Field background control measurements

Field background control measurements, or "field blanks", are used to ensure that handling, shipping or storage do not cause the devices to respond more strongly than the MDC established by the analysis laboratory. Users of devices in the field should set aside a specific percentage of devices, for example 5% (USEPA 1993) for submission to the laboratory as blanks. The blank devices should be handled in the same manner as those used for field measurements. When the field devices are deployed, the blank devices should be stored in a low-radon environment, such as a sealed box containing activated charcoal. The blank detectors should be shipped to the laboratory, along with field detectors, with fictitious location information so that the blanks do not receive special handling or processing. The QA Plan should contain instructions for action to be taken if a reported measurement for a blank exceeds the laboratory's MDC, and should include alerting the laboratory of the problem. This could be an indication of a problem with the user's handling or storage, but could also be an indication of a problem with the laboratory. The blank measurement value should not necessarily be subtracted from the values of the field measurements. Any such use of the blank measurement results should be done only at the discretion of the analytical laboratory.

e. Spikes

A percentage of devices should be sent to a reference laboratory where they are exposed to a known radon concentration for a specified period of time and under controlled environmental conditions in a STAR. These are called "spiked samples" or "spiked measurements". Spiked measurements provide an estimate of the overall precision of the device and laboratory process. The rate at which spiked measurements are made should be specified in the QA Plan. For each individual measurement, the relative error should be calculated, assuming the value provided by the operator of the STAR is the conventionally true value, tabulated in quality control records and plotted on a control chart. As previously described, performance goals for precision, such as a range that is "In Control", a "Warning Level" and a "Control Limit", as well as the actions that will be undertaken if limits are exceeded, should be specified in the QA Plan. Information on control charts, setting limits and determining when corrective action should be taken is available elsewhere (Goldin 1984, USEPA 1984, 1993).

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3. Radon prevention and mitigation

KEY MESSAGES

- Strategies both for radon prevention (new dwellings) and mitigation (existing dwellings) are needed to achieve an overall risk reduction.
- Radon sources, radon concentrations and radon transport mechanisms influence the choice of prevention and mitigation strategies.
- Radon measurements should always be made to determine the effectiveness of any radon prevention or mitigation effort.
- Professionals in the building sector are key players for radon prevention and mitigation. Strategies are needed to train them and to ensure their competence in this area.
- Research-based guidelines and/or standards for radon prevention and mitigation should be established at national level.

This chapter focuses on radon control options during the construction of new dwellings (including extensions to existing buildings or renovation work), which is referred to as prevention as well as on radon reduction in existing dwellings, which is referred to as mitigation or remediation. In the framework of radon prevention and mitigation guidelines, training and technical criteria for radon control systems are also discussed. The most common source of indoor radon is the soil and geology under the building. However, radon sources may also include domestic and drinking water from drilled wells (groundwater supplies) and emanation of radon from building materials, including concrete, bricks, natural building stones, natural gypsum, and materials using industrial byproducts such as phosphogypsum, blast furnace slag, and coal fly ash (EC 1999, Somlai et al. 2005). Radon sources and radon transport mechanisms may have a considerable influence on the cost-effectiveness of various prevention and mitigation strategies.

3.1 Organization of radon prevention and mitigation actions

In this section, several specific points related to prevention and mitigation action in the context of an organized radon programme are discussed. General aspects of the organization of national radon programmes are outlined in detail in chapter 6.

Radon control should aim for an overall risk reduction in the population. This may not be achievable if there are only goals for mitigation in existing buildings. Therefore, prevention goals should also be established to reduce radon concentrations in new dwellings. Without such goal-setting the total number of dwellings with elevated indoor radon will increase when:

1. new dwellings with elevated indoor radon are added to the housing stock;
2. the number of new dwellings with elevated indoor radon exceed the number of existing houses that are mitigated.

The key elements for successful prevention and mitigation actions within the framework of a national radon programme are the following:

1. Radon control actions should consider a combination of building types:
   - new and existing homes, since the greatest amount of radon exposure is generally in homes;
   - buildings where the public is likely to be exposed for long periods such as schools, preschool facilities, state-owned or leased buildings, and lodging facilities.

2. Research on buildings should be used to identify the most cost-effective radon control strategies for prevention and mitigation. Structural, foundation, and ventilation systems as well as construction practices vary from region to region. Specifically, this research should be used to develop:
   - radon prevention standards and regulations such as building codes for new dwelling construction;
   - radon mitigation standards and requirements for remediation of existing dwellings (cf. Section 3.1.2).

3. The contribution of different radon sources varies between countries and even regions. The following mechanisms may be considered:
   - pressure-driven soil gas infiltration;
   - emanation of radon from building materials;
   - water transport of radon.

4. Appropriate training and certification of building professionals should be implemented to ensure the efficiency of prevention and mitigation actions.

Some of the common aspects for radon prevention and mitigation actions are discussed in the following sections.

3.1.1 Design criteria for radon control systems

Radon systems for prevention as well as mitigation require the following design criteria:

- able to reduce radon concentrations considerably below the reference level;
- safe and not creating back-drafting;

- durable and functional for the expected life of the building;
- easy monitoring of the performance;
- quiet and unobtrusive;
- low costs for installation, operation and maintenance;
- easy to install an additional fan when passive soil depression systems (PSD) are used.

Table 9 shows a comparison of different radon control systems for new construction that takes these design criteria into consideration.

Table 9. Radon control options for new construction

Option	Radon reduction potential	Long-term performance	Monitoring ease	Quiet and unobtrusive	Cost to	
					Install	Operate
Sealing soil contacted surfaces	None to low - moderate	Usually poor to fair	Repeated radon testing required	Usually very good	Moderate	Very low
Soil gas barriers	Highly variable	Stable but often limited Rn reduction	Repeated radon testing required	Very good	Depends on care and quality	None
Passive ventilation unoccupied lower space	Moderate to good	Very good	Repeated radon testing required	Very good	Low	Low
Active ventilation unoccupied lower space	Good	Very good	Repeated radon testing required	Good	Moderate	Moderate
Active soil de-pressurization[a]	Moderate to greatest	Very good	Pressure &/or radon testing needed	Usually very good	Low	Moderate
Passive soil de-pressurization[a]	Low to moderate	Good if sealing is maintained	Repeated radon testing required	Usually very good	Low	Very low
Balanced ventilation[b]	Low to moderate	Good if operated and maintained	Repeated radon testing required	Usually very good	Low to high	Moderate to high

Source: USEPA (1993).

[a] Active and passive soil depressurization are highlighted since they are the most common radon control strategies.

[b] Balanced ventilation refers to ventilation that is balanced between the exhaust from and the supply to the space.

3.1.2 Research-based guidelines and/or standards

Radon prevention and mitigation guidelines and/or standards should be developed or adapted to serve as a minimum requirement for good practice. The guidelines or standards should be based upon building science research. Furthermore, the guidelines and standards should be based on defined design criteria, since they cannot address every possible situation.

When developing these guidelines and standards, it is important to consult radon mitigation contractors, building researchers as well as other building and construction professionals. Flater and Spencer (1994) have shown that if these guidelines and standards become part of building codes, inspection procedures are needed to insure compliance. Countries with mitigation or prevention guidance documents or standards include Austria, Belgium, China, the Czech Republic, Finland, France, Ireland, Latvia, Norway, Russia, Sweden, Switzerland, the United Kingdom, and the United States of America (WHO 2007). Examples for some guidance documents are given in Box 2.

Box 2: Examples for radon guidance documents

China: Standard Guide for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings (GB/T 17785-1999); Indoor Air Quality Standard (GB/T 18883-2002).

United Kingdom: Guide to Radon Remedial Measures in Existing Dwellings (BRE 1998).

USA: Active Soil Depressurization Radon Mitigation Standards for Low Rise Residential Buildings (AARST 2006); Standard Practice for Installing Radon Mitigation in Existing Low-Rise Residential Buildings (ASTM 2007).

3.1.3 Radon professionals training and proficiency test

To design and install cost-effective radon control systems, a strategy should be developed to train radon mitigation professionals, building contractors and other relevant professionals. In addition, public health officials may be trained in general radon prevention strategies. If radon preventive regulatory requirements are implemented, building authorities should also be trained.

At a minimum, this strategy should include initial training, although it could also include further education courses. The training programme should be developed in consultation with building researchers, building contractors and construction workers. Universities, government and/or nongovernmental agencies may be included in the training.

In addition, it is recommended to develop strategies to ensure the proficiency of the trained professionals by certifying or licensing them and by making increased use of such professionals.

3.2 Radon prevention strategies in new constructions

As mentioned before, the most important radon transport mechanism is pressure-driven airflow (i.e. advection) from the soil to the occupied space. Other driving forces include diffusion. Since air pressure differences between the soil and the occupied space are the primary driving force for radon entry, radon prevention strategies usually focus on reversing this pressure difference. This is commonly accomplished through the use of active (fan powered) or passive (no fan) soil depressurization. Membranes between the soil and the indoors may be used in combination with air pressure control strategies. The use of membranes as a stand-alone control technique is addressed in section 3.2.3.

3.2.1 Assessing the effectiveness of radon prevention strategies

Radon control strategies in new buildings are not always successful in achieving and maintaining low indoor radon concentrations (Synnott 2003, Saum 1993). Therefore, it is desirable to test new buildings for radon:

- prior to occupancy: Indoor radon concentrations in an unoccupied building may vary from those in an occupied building because of differences in heating and ventilation. However, testing prior to occupancy can identify problems and it may be easier to correct problems at this stage rather than during occupancy;
- during occupancy: radon measurements once a new building is occupied will demonstrate whether the indoor radon concentrations are below the reference level. Since performance of radon control systems can vary over time, radon testing should be done periodically over the life of the structure (Gammage and Wilson 1990).

These measurements should be conducted according to recognized measurement protocols, as described in chapter 2.

3.2.2 Preconstruction site assessment

A number of approaches are used worldwide to assess the potential for elevated indoor radon concentrations across geographic areas of various dimensions. One approach involves mapping regions, counties, municipalities or other geographic areas. Another approach used in some countries, such as the Czech Republic (Neznal et al. 2004), involves testing individual building sites prior to construction to establish a radon index for the site. The index is then used to define the degree of radon protection needed for building on that site. However, in countries including Finland, Ireland, Norway, Sweden, Switzerland, the United Kingdom, and the United States of America, the most cost-effective approach appears to be the use of radon control options in all new homes (WHO 2007). Sometimes this approach is restricted to radon-prone areas (cf. Chapter 6).

3.2.3 Radon prevention strategies

Most prevention strategies address steps to limit soil gas infiltration due to air pressure differences between the soil and the indoor occupied space. Radon prevention strategies should consider the specific mix of construction practices, radon sources, and transport mechanisms in the region or country, in order to be cost-effective. Under certain conditions a combination of strategies may be necessary such as in buildings with multiple types of foundations. Several prevention strategies are summarized and listed here:

a. Active soil depressurization (ASD)

Figure 4 shows an ASD, which is simple to install and provides greater radon reduction compared to PSD systems (USEPA 1993). Thus, ASD may be a favoured option for home builders. It has a rich history, beginning with its initial experimental applications in Canada (Scott 1979, Gessall and Lowder 1980, DSMA ATCON 1982). Commonly, ASD systems include the following basic components:

- suction point(s) located below the ground-contacted floor or slab of the home and connected to a continuous and uniform permeable aggregate layer, ground water control system, or a sump;
- a discharge point located in a manner that minimizes the opportunity for human exposure, for example above the highest roof. There is evidence that ASD discharges at ground level create a risk of radon re-entering the house (Henschel and Scott 1991, Yull 1994, Henschel 1995). Therefore, even if the risk appears to be small, ASD systems should be installed in a way that minimizes this risk;
- a continuously operating inline fan is located outside and above the conditioned space of the home. An important distinction between ASD in existing homes and new construction is that, in the latter, the use of a permeable layer and sealing provide the opportunity to use smaller, more energy-efficient fans;
- a U-tube manometer may be used as a system indicator to monitor performance such as pressure differences in the vent pipe below the fan;
- systems should be labeled at every accessible level to avoid confusion with the plumbing system (similar to PSD).

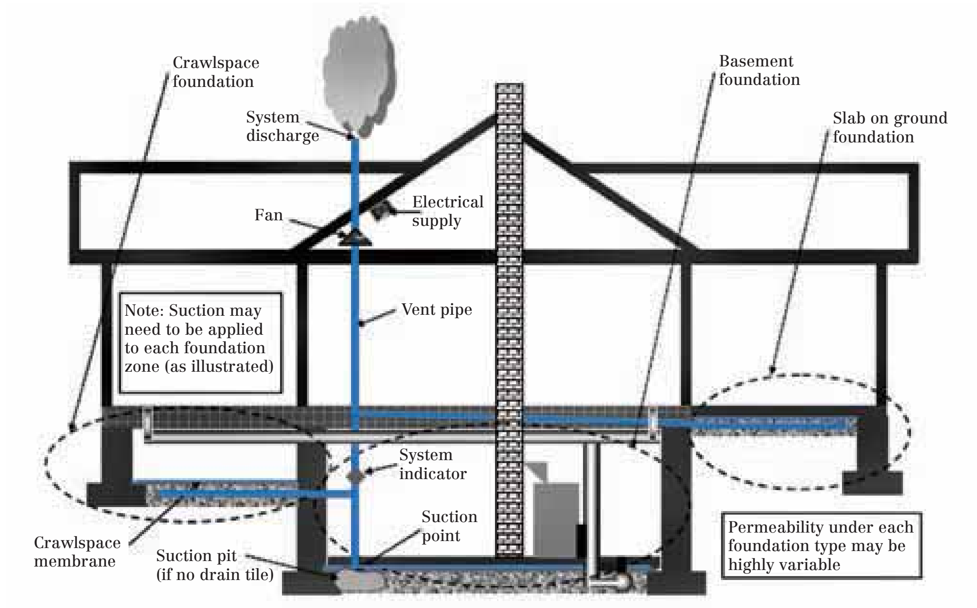

Figure 4. Active soil depressurization for radon control in new constructions

b. Passive soil depressurization (PSD)

PSD (cf. Figure 5) is used in new construction. It is similar to active soil depressurization (ASD), with the following exceptions:

- the effectiveness of PSD depends on the thermal buoyancy of airin the vent pipe and its ability to slightly depressurize the soil under the dwelling. To make it effective the following should be considered:
  - o the system must have a uniform permeable layer under all elements with direct contact to the ground (e.g. concrete slabs, crawlspace membranes);
  - o the vent pipe must be routed mainly through the heated portion of the building and any sections of the vent pipe in unheated areas must be insulated;
  - o the vent pipe routing must allow the easy installation of a fan if the PSD system fails to achieve sufficient radon reduction;
  - o the exhaust duct must discharge above the highest roof;
  - o the systems should be labeled at every accessible level to avoid confusion with the plumbing system;
- the elements of the building that are in contact with the soil must be sealed to prevent soil gas infiltration (see the sections on sealing and barriers);
- since air pressure differences are so small between the vent pipe and the occupied area, the only way to monitor system performance is via periodic or continuous radon monitoring.

In new construction, PSD appears to reduce radon by about 50% (Dewey and Nowak 1994). If the PSD system is properly designed and installed, small fans (e.g. 75 W

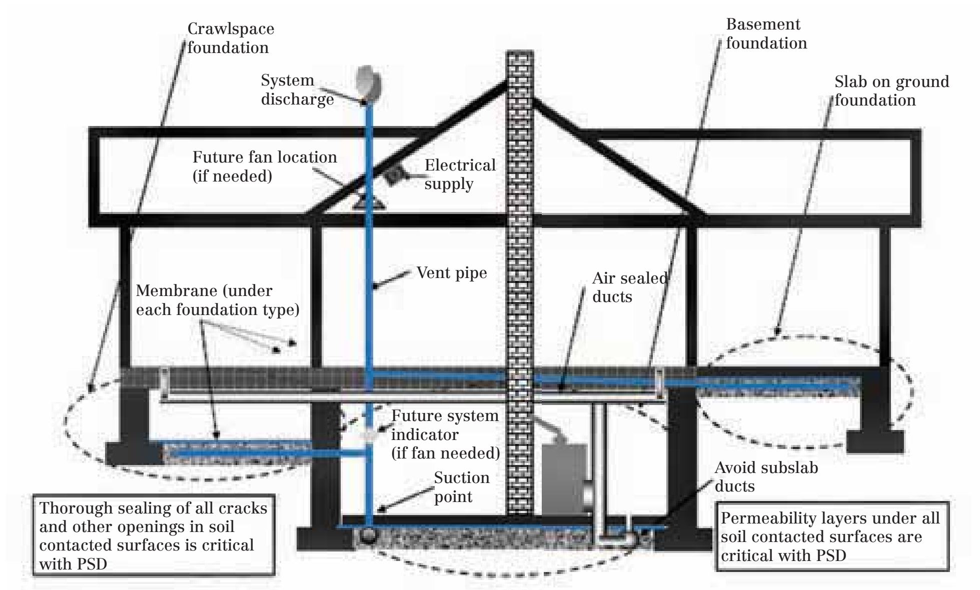

Figure 5. Passive soil depressurization for radon control in new constructions

or less) may be used to activate the system (Saum 1991, ASTM 2007). The use of a smaller fan saves energy-related operating costs.

c. Sealing of surfaces

The sealing of the surfaces which separate the indoor occupied space from the soil can improve the performance of other prevention strategies such as PSD or ASD. In these cases, sealing reduces the loss of conditioned air from indoors, which may be substantial (Henschel 1993), and increases the reversal of air pressure from the soil to the indoors.

As a stand-alone prevention strategy, sealing has limited potential for radon reduction (Brennan et al. 1990, Scott 1993), especially over time. Sealing does not address the major reason why radon moves from the soil to the indoors, i.e. pressure-driven airflow.

d. Barriers and membranes

Barriers or membranes between the soil and the indoors may be used as a stand-alone radon prevention strategy or in combination with other techniques such as passive or active soil depressurization. Membranes may also help limit moisture migration to the indoors. Consideration should be given to using barriers with independent third-party approval for characteristics such as air tightness, diffusion, strength and durability properties (SINTEF 2007).

While barriers may be useful to reduce radon transport from the soil to the indoors, opinions vary about their effectiveness:

- advocates note that there is little that can go wrong after they are installed, while acknowledging that the barrier must be air-tight. Scivyer and Noonan (2001) found in their study that there were no significant changes in radon concentrations in homes with full radon membranes over a ten-year period. However, there was no indication concerning the initial effectiveness of the membranes;

- critics of membranes note that it is very difficult to make membranes air-tight under common construction conditions. A punctured membrane would potentially act as a trap to collect soil gas and funnel it into the building through any available openings. In addition, barriers do not address air pressure differences (Scott 1993). Barriers might be more effective in moderate climates where pressure differences due to temperature are small. Examples of poor and good radon barrier installations are shown in Figure 6.

Barriers may be used in combination with other prevention techniques such as soil depressurization. When used with soil depressurization, the barrier does not need to be continuous. For example, in Finland, when soil depressurization piping is installed, reinforced bitumen felt is installed below the floor-foundation wall.

Poor Good

Figure 6. Examples of barrier installations

e. Ventilation of unoccupied spaces

Ventilation of unoccupied spaces between the soil and the occupied space (e.g. vented crawlspaces) can reduce indoor radon concentrations by separating the indoors from the soil and reducing the concentration of radon below the occupied space. The effectiveness of this strategy depends upon a number of factors. These include the air-tightness of the floor system above the vented unoccupied space, and, with passive ventilation, the distribution of vents around the perimeter of unoccupied space. A variation of this approach involves the use of a fan to either pressurize or depressurize the unoccupied space. However, fan-driven depressurization of crawlspaces may pose problems such as back-drafting of combustion appliances and energy loss (ASTM 2003a). Subslab and submembrane depressurization (SSD and SMD) may be either active or passive and are recommended for radon control in buildings with crawlspace foundations. SSD and SMD offer greater radon reduction than crawlspace ventilation.

f. Ventilation of occupied spaces

For overall indoor air quality, an exchange between indoor and outdoor air is desirable. For radon prevention, ventilation has varied results and may lead to energy losses, especially in extreme climates. If the major radon source is building material, ventilation will be needed. However, it is better to avoid the use of building materials that are sources of radon in the first place (EC 1999).

g. Water treatment

Water treatment is not commonly carried out in new constructions, except in areas where high radon concentrations in water are known to be a problem. For more information about water treatment techniques to reduce indoor air concentrations, see the radon mitigation paragraph at the end of section 3.3.2.

3.3. Radon mitigation strategies in existing buildings

Some aspects of radon mitigation are similar to radon prevention, although there are subtle but important differences. The cost-effectiveness of radon mitigation varies according to the type of system installed and the quality of the installation. There is evidence that active soil depressurization most effectively reduces radon concentrations, if installed by an experienced contractor, as compared to others including householders themselves (Naismith et al. 1998).

To decide on mitigation or to determine the effectiveness of any mitigation action, radon measurements must be carried out in a manner that is consistent with recognized measurement protocols and the applicable reference level (cf. Chapters 2 and 6).

The scope and urgency of mitigation recommendations may be based upon the radon concentrations, as determined by measurements. For example, if the measurement indicates slightly elevated indoor radon and there is no time-sensitivity for radon reduction, limited or phased mitigation steps may be suggested. Then, if needed, upgrades can be carried out.

In some countries, such as the United States of America, mitigation efforts focus on more robust remediation, such as active soil depressurization. This approach maximizes radon reduction with a small incremental cost difference compared to other, more limited approaches. Furthermore, more forceful approaches give greater confidence in achieving radon reduction targets. The robust approach to mitigation is appropriate when there is time sensitivity in reducing radon, for example during the buying and selling of a house.

As discussed in chapter 2, post mitigation measurements should always be made to determine the effectiveness of the radon reduction efforts. Furthermore, mitigated homes should be periodically retested since the performance of radon mitigation systems can change (Gammage and Wilson 1993).

3.3.1 Building investigations and diagnostic tests prior to mitigation

The following steps are important to match the most cost-effective radon reduction system to the unique characteristics of the building being mitigated. Generally, the diagnostic process should be more thorough in complex buildings and more difficult mitigation situations. Investigation and diagnostics may occur in various ways, each with its advantages and disadvantages. In most countries, the premitigation examination is carried out by a private contractor who does the mitigation. In Switzerland, a governmental employee conducts this inquiry and then advises the property owner on mitigation options. In Norway, the diagnostic model is to have an independent assessment by a private contractor who only does diagnostics and who is, ideally, independent from the mitigation contractor. In Finland, Ireland, Sweden, the United Kingdom and the USA, diagnostics are usually performed by the mitigation contractor. Diagnostic tests should take into consideration the following essential elements:

- a visual inspection of the building is almost always necessary to determine radon entry dynamics and potential mitigation strategies such as:
  - o radon entry points;
  - o ASD suction point options;
  - o routing options for ASD ducts;
  - o major sources of house depressurization;
  - o history of the construction and alteration of the building;
  - o combustion appliances that vent combustion pollutants to the outdoors;

- when pressure-driven soil gas infiltration is suspected, it is often helpful to use chemical smoke, a powder ampoule or a micromanometer to determine:
  - o pressure differences, for example between the soil and the indoors or between the outdoors and the indoors;
  - o pressure field extension in the soil under the occupied space, when depressurized with a vacuum cleaner or temporary fan (Henschel 1993).

The non-thermal smoke ampoule gives a qualitative indication of pressure differences, while a micromanometer produces quantitative data reflecting the strength of the pressure difference. Also, a micromanometer to measure indoor-outdoor pressure differences may be used with the exhaust ventilation on and off to understand potential radon entry dynamics:

- when considering mechanical ventilation, either to pressurize indoor spaces or to dilute radon after it enters, it may be necessary to determine the air-tightness of the building shell. Often, a fan door (also known as a blower door) is used for this purpose (ASTM 2003b). The fan door can also be useful to determine how much ventilation may be needed to achieve the desired amount of indoor radon reduction. Measuring the air flow rate will give information about the original ventilation rate, and thus the potential effect of a ventilation system on the indoor radon concentration;

- in mechanically ventilated buildings, it may be helpful to use a continuous radon monitor to determine if the operation of the mechanical ventilation system has an effect on indoor radon concentrations. If radon entry is associated with the operation of a mechanical ventilation system, the radon mitigation strategy may involve adjustments in the mechanical system before other radon mitigation strategies are considered. Any adjustments in ventilation should not create other problems and should be carried out by a mechanical contractor knowledgeable about ventilation systems and familiar with regulations and standards;

- when emanation from building materials is suspected, measurement needs to be performed as described under section 2.2.4;

- when water originating from a private or nonpublic well is suspected, water samples should be taken and analyzed in a laboratory.

3.3.2 Radon mitigation strategies

Radon mitigation strategies need to be adapted to the specific mix of housing and building characteristics, climate zones, radon sources, and transport mechanisms in order to be cost-effective. A summary of radon mitigation techniques is presented in Table 10. The installation costs reflect those of experienced radon mitigation contractors. Combination techniques may be used in mitigation, as in prevention, for complicated buildings or when one approach does not produce sufficient results (BRE 1998, Henschel 1993, Pye 1993, Roserens et al. 2000, Welsh et al. 1994). In general, radon mitigation systems may be categorized as follows:

Table 10. Common radon mitigation techniques, performance and costs[a,b]

Technique	Typical Radon Reduction in [%]	Typical Contractor Installation Costs [€][c]	Typical Annual Operating Costs [€][d]	Notes
ASD[e]: High to Low Porosity Subslab	50 to 99	850 to 2 700	50 to 275	Subslab suction is placed in porous stone subslab fill, ground-water control components, and/or a perforated sump
ASD[e]: Very Low Porosity Subslab	50 to 99	850 to 2 700	50 to 275	Also known as subslab depressurization
ASD[e]: Submembrane Depressurization	50 to 99	1 100 to 2 700	50 to 275	In accessible crawlspaces, a membrane is placed over exposed soil and suction is applied under the membrane
Under Floor Active Ventilation	50 to 99	550 to 1 600	50 to 275	Uses a fan to pressurize or depressurize inaccessible spaces separating the soil and the occupied space (caution: if plumbing exposed to freezing conditions)
Under Floor Passive Ventilation	0 to 50	0 to 550 if additional vents added	Variable	Not effective in heating dominated regions and in homes with non-air tight floors (caution: plumbing freeze up)
Radon Wells	60 to 95	2 150 to 4 300	Variable	Most effective in very porous soils (such as eskers). May be used to reduce radon entry into multiple homes
Soil Pressurization	50 to 99	550 to 1 600	50 to 275	Most effective in very porous soils with moderately elevated soil radon and a very air-tight soil contacted concrete slab
Soil Contacted Crawlspace Pressurization	50 to 99	550 to 1 600	150 to 550	Most effective when the soil contacted space is relatively air-tight and isolated from outdoors and other indoor spaces
Passive Ventilation of Occupied Space	Variable/ temporary	None	100 to 750	Significant loss of heated or cooled air; not a permanent mitigation strategy, especially in more severe climates
Active Ventilation of Occupied Space	30 to 70	225 to 2 700	7 to 550	Ranges from a very small supply fan[f] to a balanced heat recovery ventilator (both operating continuously)

[a] The data have been reported by USEPA (2003) and have been modified to be similar to those from Finland and the United Kingdom.

[b] The two primary water mitigation techniques are aeration and activated charcoal filtration, which are not listed in this table.

[c] Installation costs may be higher when cosmetic treatments to the house are necessary, when local demand for mitigation is high and/or if there is a shortage of mitigation professionals.

[d] Fan electricity and house heating/cooling loss costs based on assumptions regarding climate (moderate), house size and the local cost of electricity and heating fuel (Bohac et al. 1992).

[e] ASD refers to active soil depressurization. It is highlighted in this table since ASD is the most common radon mitigation technique.

[f] The small supply fan would be used to slightly pressurize spaces in ground contact.

a. Active soil depressurization

As described before, ASD is the most common form of radon mitigation in existing houses. Due to its high reliability in radon reduction in a wide variety of houses and other buildings, ASD should be one of the first approaches considered. According to a WHO survey (WHO 2007), active soil depressurization represented the majority of radon mitigation reported by the following countries: Austria, Belgium, Finland, Germany, Norway, Slovenia, Sweden, United Kingdom and the USA. The specific configurations of these systems depend on foundation characteristics (e.g. basement, slab-on-grade and crawlspace foundations).

The main difficulties of applying ASD to existing buildings compared with new construction are the following:

- the material underneath the lowest floor of the building may have very limited permeability and thus, it may be necessary to install a sump or a suction pit (to increase the sub-slab surface area upon which suction is applied) or the ASD fan may need to be resized;
- it may be difficult to seal openings between the soil and the occupied space;
- it may be difficult to route the vent piping.

b. Ventilation of occupied spaces

The ventilation of occupied spaces may be done actively by using a fan or passively by operating windows or vents manually. There is limited evidence concerning the effectiveness of passive or natural ventilation for radon control (Cavallo et al. 1991, 1996). However, in moderate climates such as in Ireland, ventilation is used as an effective radon mitigation method (Synnott 2004, 2007). Ventilation approaches to radon reduction are more common in mechanically ventilated schools and other large buildings than in small houses (WHO 2007). Fan-powered ventilation can reduce pressure differences between the soil and the occupied space, as well as dilute indoor radon after it enters. These systems are especially useful when one or more of the following factors are implicated:

- a major radon source is from building materials;
- the building is located in a non-heating or non-cooling dominated climate, thus ventilation has lower energy penalties;
- there are multiple indoor air quality problems;
- ASD is not feasible or does not sufficiently reduce radon concentrations.

Mechanical ventilation may be done in one of the three following ways, taking into account its advantages and disadvantages:

1. Exhaust ventilation, which depressurizes the indoors in relation to the soil and the outdoors, is almost never used for radon control, and especially not in heating or cooling dominated climates;

2. Supply ventilation (or positive ventilation) tends to pressurize the indoors in relation to the soil and the outdoors as well as dilute the radon after it has entered. An example with a cost-estimate is given in Box 3. Supply ventilation carries possible risks such as, in hot climates, condensation damage to the building envelope. However, small supply fans have been used successfully in the United Kingdom and Switzerland to reduce indoor radon. Critics argue that filters must be maintained by residents to be

effective and that all windows and doors must be kept closed (Clarkin et al. 1992). In colder climates, the fans need to be equipped with heating elements;

3. Balanced exhaust ventilation neither pressurizes nor depressurizes the indoors in relation to the soil and the outdoors. This form of ventilation dilutes radon after it has entered the building. In heating and/or cooling climatic conditions, balanced ventilation is often done with a heat or energy recovery ventilator to reduce energy consumption.

Box 3: An example of a supply ventilation with some cost-estimates

Fans reduce radon by slightly pressurizing the indoors in relation to the soil or reducing the negative indoor air pressure. Fans with a maximum output of 52 l/s have been used in houses in the United Kingdom with radon concentrations up to 750 Bq/m^3 to reduce concentrations to below the reference level of 200 Bq/m^3. These systems cost about 500-750$ to install and 10-15$ to operate annually.

c. Sealing of surfaces

Sealing off openings in surfaces between the indoors and the soil is a controversial stand-alone mitigation technique with, at best, limited effectiveness. For example, success with sealing alone has been reported in only one out of 1500 cases and therefore sealing is not recommended (Turk et al. 1991, USEPA 1993). In Finland, sealing alone reduces indoor radon concentrations by 10 to 30% (Arvela and Hoving 1993). Norway recommends sealing as an initial step followed by, if needed, additional mitigation (SINTEF 2007). When used with active soil depressurization, sealing improves system performance. But as a stand-alone strategy, it is very difficult to seal off soil contacted surfaces enough to prevent pressure-driven radon entry.

d. Water treatment

In the relatively rare cases where significant amounts of radon are transported indoors by water from a private drilled well, radon is released into the indoor air. In such cases, water treatment may be used to reduce the indoor air concentration of radon. The health risk associated with radon in water is primarily via inhalation as opposed to ingestion. The primary strategies to reduce indoor radon from well water at the point of entry into the home are:

- aeration: in a sealed tank, air is bubbled through the water or the water is sprayed into the air or is cascaded over objects while radon is extracted from the water to the outdoors;
- filtration with granular activated carbon is generally less expensive but results in less radon reduction.

Dembek et al. (1993) and the WHO Guidelines for drinking water (WHO 2005) give further information on radon mitigation in water.

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4. Cost-effectiveness of radon control

KEY MESSAGES

- The cost-effectiveness of preventive measures improves as the average radon concentration in an area increases. However, in many cases it would be cost-effective to install radon prevention measures such as a radon barrier in all new buildings.
- The cost-effectiveness of remediating existing buildings is strongly influenced by the costs of identifying affected homes and by the remediation costs themselves.
- Even if cost-effectiveness analyses indicate that remediation programmes are not cost-efficient on a nationwide basis, in areas of high radon concentration remediation should still be undertaken.
- Cost-effectiveness analyses are helpful tools for evaluating current policies and can lead to new and more cost-effective ways of reducing radon risk.
- Cost-effectiveness analyses provide useful information for policy makers when evaluating policies and alternatives, but are subject to uncertainties and limitations. The results of such analyses should therefore be interpreted and communicated carefully.

This chapter considers the use of economic evaluation as a systematic way of assessing the costs and benefits of different preventive and remedial actions. The chapter begins by setting out the main elements of economic evaluation, in particular the methodology of cost-effectiveness analysis, and the relevance of this approach to radon actions. It then briefly considers previous applications of economic evaluation to the issue of radon reduction. A case-study illustrates the kind of data required to perform a cost-effectiveness analysis, methods for presenting results, and how these results can be interpreted. The chapter ends with some recommendations concerning the use of cost-effectiveness analysis in the formulation and evaluation of radon policies.

4.1 The framework of cost-effectiveness analysis

Economics begins with the premise that we live in a world of scarcity, where choices have to be made by individuals, organizations and governments about the allocation of scarce resources. Allocative decisions can be influenced by many factors, and can be inconsistent or wasteful unless some form of decision rule is used. One approach that has been advocated to assist policy in a number of countries is cost-benefit analysis (CBA), in which analysts attempt to attach a monetary value to all the costs and benefits associated with a particular policy or action. The decision to recommend proceeding or not depends on whether the estimated costs exceed the value of the benefits. The first explicit use of this approach was in the USA in the 1930s, to try to improve federal spending decisions concerning New Deal[3] investments such as flood control measures (Porter 1995). CBA has subsequently been used to evaluate major investment decisions such as underground railway extensions, the location of international airports and motorways, and the adoption of road safety and environmental measures.

However, the difficulty of assigning agreed monetary values to things such as landscape views, species diversity, and human lives has prevented widespread acceptance or adoption of the CBA approach. In health care in particular, analysts have for some time advocated a more limited evaluative technique known as cost-effectiveness analysis, which avoids some of the difficulties associated with CBA. Cost-effectiveness was first applied to health care decision-making in the 1960s, and its key features were set out in a seminal article in 1977 (Weinstein and Stason 1977). The recommended methodology for cost-effectiveness analysis is still evolving, but a reasonable degree of international consensus has been reached on the main elements (Gold et al. 1996, Drummond et al. 2005).

The cost-effectiveness approach also starts from the premise that scarce resources require resource-allocation decisions to be guided by considerations of costs in relation to expected benefits. However, in cost-effectiveness analysis, no attempt is made to place a monetary valuation on these benefits. Instead, the ratio of net health care costs to net health benefits (that is, beneficial effects minus any adverse consequences such as side effects) is calculated for a variety of actions or policies, providing an index with which these actions can be ordered and prioritized.

4.1.1 Using the quality-adjusted life-year as an outcome measure

In principle, cost-effectiveness analysis can use any relevant measure of outcome or benefit, such as cases detected, deaths averted, symptom-free days, or percentage reduction in radon. However, comparisons can only be made between actions using the same measure of outcome: it is not possible to compare directly the cost-effectiveness of one action measured as cost per cancer case averted with the cost-effectiveness of another action measured as cost per day free of symptoms of heart disease. Consequently, researchers working in this area have advocated the use of a composite measure of outcome which includes quantity of life - a measure of survival, expressed in life-years - but also quality of life. The resulting measure is the quality-adjusted life-year (QALY), which in principle should permit comparisons across most actions on policies that are intended to improve health.

As an illustration of the use of QALY, consider a 70-year old woman with an "average" quality of life. If full health-related quality of life is 1 and death is 0, her quality of life might be judged to be 0.85: that is, each calendar year is equivalent to 0.85 quality-adjusted life-years. If she then has a stroke which leaves her disabled and reduces

[3] The New Deal was a package of measures introduced by the USA government in the 1930s to help the economy move out of recession (The Great Depression).

her life expectancy from 15 to 8 years, and if the disability is judged to be equal to 0.6, then her quality-adjusted life expectancy will have fallen from (15 x 0.85) 12.75 QALYs to (8 x 0.6) 4.8 QALYs, a loss of (12.75 - 4.8) 7.95 QALYs that can be attributed to both shorter life expectancy and reduced quality of life.

An alternative composite outcome measure, the disability adjusted life year (DALY), was developed in the early 1990s in response to a World Bank commission to provide a global burden of disease study to inform research and policy priorities and to recommend intervention packages for countries at different stages of development (Murray et al. 1994, World Bank 1993). However, DALYs have been less widely used for the evaluation of specific interventions.

The advantage of either QALYs or DALYs as outcome measures when allocating resources is that they capture the two main dimensions on which an intervention for the prevention or treatment of any disease can be assessed – mortality and morbidity – and therefore allow comparisons to be made across many alternative uses of resources intended to improve health. By comparing cost-effectiveness ratios and systematically selecting those with more favourable ratios, the total health gained from a specified budget can be maximized. The approach is similar whether QALYs or DALYs are used; the main difference being that within the QALY framework, the cost-effectiveness ratio would be the cost per quality-adjusted life-year gained, whereas in the DALY framework the ratio would be the cost per disability adjusted life year averted. In the example below, the QALY is used but the overall approach is not dependent on this choice. Cost-effectiveness analysis can therefore help promote efficiency when allocating health resources, and provides a useful framework within which to evaluate the likely costs and benefits of new interventions or policies.

The following simplified example demonstrates how the cost-effectiveness approach could be used in radon prevention and mitigation to obtain a maximum health benefit within a given budget. Suppose that a new radon prevention measure has been shown to be effective in a pilot study, and that the radiation protection agency is instructed to introduce this measure into all previously unprotected school buildings. However, it is given no additional budget to implement this policy. It begins by evaluating the total costs and effects for all existing programmes. In total, ten separate and independent programmes are identified, each with different costs and effects, and from these it is possible to calculate the cost-effectiveness ratio for each programme, by dividing the programme cost by its effectiveness (in each case, the added or incremental cost compared to the next best alternative and the added or incremental effectiveness). Table 11 presents the results of ten hypothetical interventions in different types of houses, workplaces, and schools. In such an example, it is evident that cost-effectiveness varies widely, from around €6 700 (programme 3) to €62 500 per QALY gained (programme 7).

Reordering the interventions in Table 11 by cost-effectiveness, and calculating the cumulative costs and effects, gives the results reported in Table 12. Providing all the programmes has a total cost of €9.7 million, and yields a total of 681 QALYs in comparison with no programme activities. Figure 7 shows the information as a diagram with cumulative QALYs gained on the x-axis and cumulative cost on the y-axis. Starting at the origin, each programme is added in order of cost-effectiveness, with each point representing cumulative costs and effects. The slope between any two points is the same as the cost-effectiveness ratio for that programme. The resulting curve can be viewed as the cost-effectiveness frontier, as it shows the maximum health gain obtainable from any given level of resources using existing programmes. Any point below and to the right of this curve is not reachable with existing programmes, while any point above and to the left is an inefficient use of resources as more benefit could be obtained at the same or lower cost.

Table 11. Costs, effects and cost-effectiveness of 10 hypothetical interventions

Programme	Total cost (€k) (QALYs)	Incremental effectiveness (Cost per QALY gained)	Cost-effectiveness
1	1 200	140	8 571
2	700	27	25 926
3	800	120	06 667
4	800	18	44 444
5	2 000	85	23 529
6	500	64	7 813
7	1 000	16	62 500
8	1 100	85	12 941
9	1 400	102	13 725
10	200	24	8 333
Total	**9 700**	**681**	

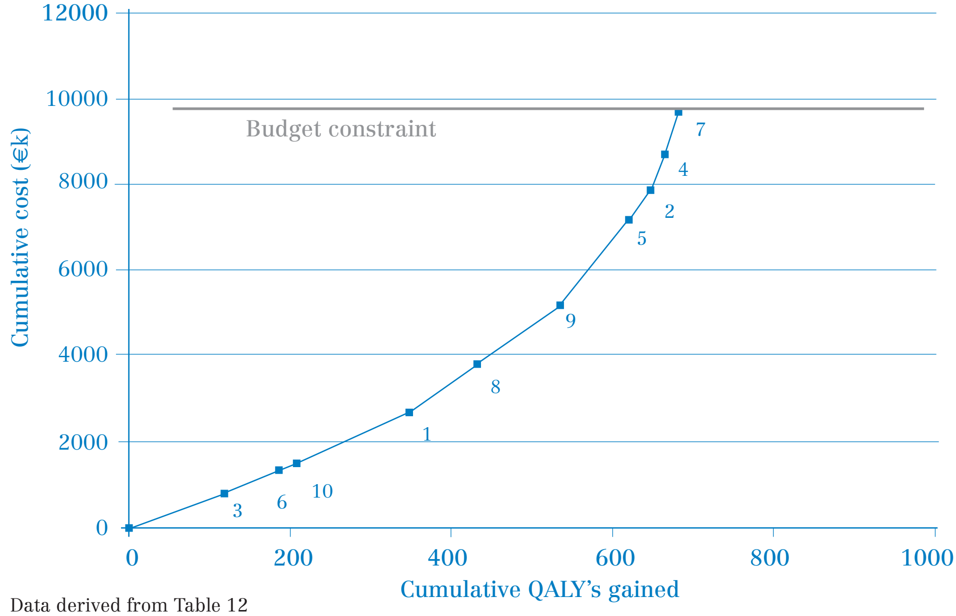
Table 12. Ten hypothetical interventions rank-ordered by cost-effectiveness

Programme	Total cost (€k)	Cumulative cost (€k)	Effectiveness (QALYs)	Cumulative effectiveness (QALYs)	Cost-effectiveness (Cost per QALY gained)
3	800	800	120	120	6 667
6	500	1 300	64	324	7 813
10	200	1 500	24	348	8 333
1	1 200	2 700	140	260	8 571
8	1 100	3 800	85	433	12 941
9	1 400	5 200	102	535	13 725
5	2 000	7 200	85	620	23 529
2	700	7 900	27	647	25 926
4	800	8 700	18	665	44 444
7	1 000	9 700	16	681	62 500
Total		**9 700**		**681**	

Table 13. Costs, effects and cost-effectiveness after introduction of a new programme

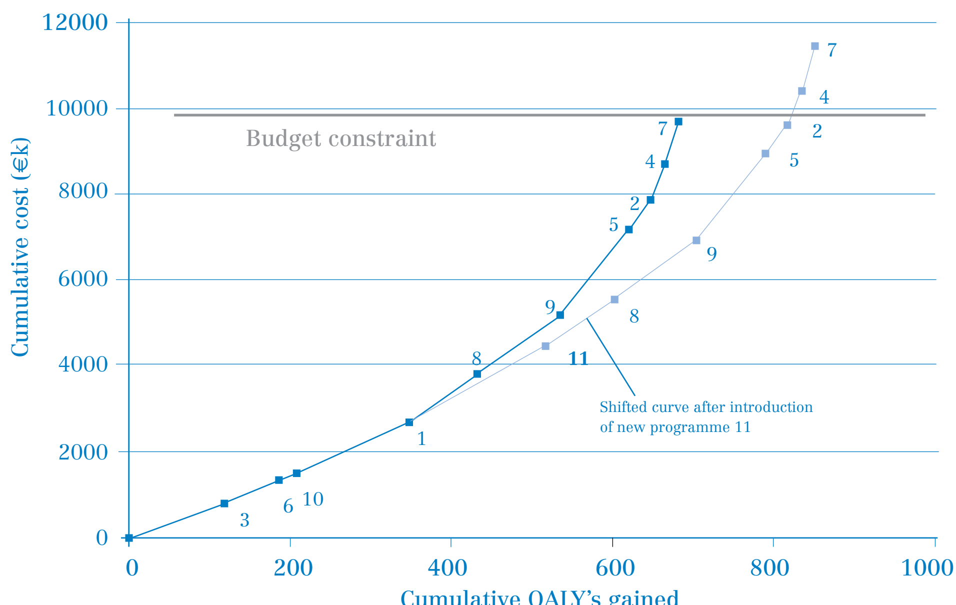
Programme	Total cost (€k)	Cumulative cost (€k)	Incremental effectiveness (QALYs)	Cumulative effectiveness (QALYs)	Cost-effectiveness (Cost per QALY gained)
3	800	800	120	120	6 667
6	500	1 300	64	324	7 813
10	200	1 500	24	348	8 333
1	1 200	2 700	140	260	8 571
11	1 800	4 500	170	518	10 588
8	1 100	5 600	85	603	12 941
9	1 400	7 000	102	705	13 725
5	2 000	9 000	85	790	23 529
2	700	9 700	27	817	25 926
4	800	10 500	18	835	44 444
7	1 000	11 500	16	851	62 500
Total		**9 700**		**817**	

Programme 11 is newly introduced. Programmes 4 and 7 have to be dropped in order not to exceed total budget.



Data derived from Table 12

Figure 7. Cost-effectiveness frontiers



Data combined from Figure 7 and Table 13

Figure 8. Shift in cost-effectiveness frontier after introduction of new programme

The new prevention measure (programme 11) can now be introduced into this example. It has a total cost of €1.8 million annually, and when implemented will yield a gain of 170 QALYs, giving an incremental cost-effectiveness of €10 600 per QALY gained. This is better than several existing programmes, as shown in Table 13: the new programme 11 is ranked after programmes 3, 6, 10 and 1, while programmes 4 and 7, which were the least cost-effective, are pushed above the budget constraint and dropped. However, despite dropping these, total QALYs gained have risen from 681 in Table 11 to 817 in Table 13, while expenditure remains within the €10 million budget. Figure 8 again shows this information in the form of a cost-effectiveness frontier, which has now been extended so that more health gain is obtained with the same resources. The area between the two curves represents the gain in health.

The example above illustrates how the cost-effectiveness approach can be used to help decide what priority to give to a new policy: first by assessing whether it is cost-effective compared to alternative policies for achieving the same objective, and second by helping identify less cost-effective activities that could be dropped to make way for the new policy.

4.2 Previous economic evaluations of radon prevention and mitigation

Several economic analyses or evaluations of radon reduction programmes, including both remediation of existing buildings and prevention for new buildings, have been reported over the last two decades. Only a few of these analyses have been published in peer-reviewed journals or in proceedings of international conferences, while some are not readily available since they have been published only as parts of national reports, mostly not in English. Others are more or less qualified judgements rather than comprehensive cost-effectiveness analyses since they are based on simplified assumptions and calculations as well as on limited data on costs of remedial and/or preventive measures. Differences in assumptions and analytic design make a comparison of these analyses difficult. Therefore, only some of the most comprehensive and recent analyses which have been published in international peer-reviewed journals will be discussed here (Castren 1994, Colgan and Gutierrez 1996, Coskeran et al. 2005, 2006, Denman et al. 2005, USEPA 1992, Field et al. 1996, Ford et al. 1999, Kennedy et al. 1999, 2001, 2002, Letourneau et al. 1992, Maecinoewski and Napolitano 1993, Maringer et al. 2001, Moeller and Fujimoto 1988, Mossman and Sollito 1991, Stigum et al. 2003, 2004)[4].

The cost-effectiveness of preventive and remedial measures against radon is measured both as the cost of preventing a lung cancer death and as the cost per life-year gained. In some of these analyses, the cost-effectiveness has been quantified as the cost per quality adjusted life-year (QALY) gained by further considering the impact of radon remediation on the quality of an individual's life as well as its duration. For most of the studies, the results are in the range of €15 000 and €55 000 per QALY gained – generally with lowest values for preventive measures in future dwellings compared to remedial measures in existing homes.

The cost of prevention and mitigation varies between countries due to differences in house type and construction – as well as differing mitigation experience and availability of standard descriptions of cost-effective measures. Some countries have developed comprehensive radon programmes where measurement and mitigation services are offered at a reasonable cost – thereby reducing the costs per QALY gained. The mean radon concentration and the distribution of radon varies from country to country and between regions within countries which also have an impact on the analysis. Generally, the cost per QALY gained is lowest in the areas with the highest radon concentrations.

The variation of lung cancer incidence and smoking habits between countries, and the use of different risk models/data in the analysis also influence the economic evaluations. None of the previous analyses have used updated risk data from the most recent collaborative analyses in Europe, North America and China (Darby et al. 2005, Krewski et al. 2005, Lubin et al. 2004). Most of the studies discussed here have concluded that preventive measures in all new buildings are cost-effective in areas where more than 5% of the present housing stock is above 200 Bq/m^3. In some areas

[4] In the framework of the WHO International Radon Project a comprehensive literature research of published and unpublished economic evaluation of radon reduction programmes was realized.

with low average radon concentrations, the measurement costs may be higher than the mitigation costs in existing dwellings, due to the high number of homes that have to be tested compared to the proportion requiring mitigation. In some countries, less than 20% of measured homes above the Reference Level are mitigated and if less than 5% of the housing stock in these areas is affected, more than 100 homes will have to be tested per home mitigated. In these areas, the measurement costs will be much higher than the mean mitigation costs.

4.3 Example of a cost-effectiveness analysis

In this section, the use of cost-effectiveness analysis is demonstrated by an example from the United Kingdom. The numbers and results reported are real, but the objective is to draw attention to the methods rather than the results, which are likely to vary in different settings and countries. The necessary steps of such an analysis and the influence of data input, risk factors and exposure levels as well as main results are presented and discussed below.

4.3.1 Steps in conducting a cost-effectiveness analysis

Step 1: Define the programme being evaluated and its alternative

Cost-effectiveness is a comparative method which compares the costs and effects of a particular policy or course of action against some alternative. The alternative may be an existing or new policy, or a do-nothing policy. In this example, we consider two main types of programme:
1) the cost-effectiveness of installing radon prevention measures in new homes in areas where at least 3% of homes could be expected to have measured radon concentrations above 200 Bq/m^3, compared with not carrying out such measures.
2) the cost-effectiveness of approaching householders in areas where 5% or more of existing homes are expected to have radon levels above 200 Bq/m^3, and inviting them to test their homes for radon and to take remedial action if their homes are found to have radon levels in excess of 200 Bq/m^3, compared with taking no action.

These particular policies assume that there are sufficient survey data to enable informed estimates of radon levels on a regional basis. If such data are not available, it will be necessary either to evaluate alternative programmes, or to incorporate the costs of obtaining such data into the cost-effectiveness analysis.

Step 2: State the perspective of the study

A wide range of different costs can be included in a cost-effectiveness analysis, including costs incurred by different government agencies, private expenditures, and other costs such as losses of earnings as a result of morbidity or premature mortality. The results of an analysis may vary depending on the perspective adopted. Comprehensive analyses adopt a "societal" perspective in which all costs are included, but agencies such as health departments may be mainly interested in the costs or savings falling directly on them. In the example discussed here, we include direct costs incurred or saved by local and central government agencies in offering and providing tests; costs of house-holders paying for preventive or remedial measures; and costs to the health service in caring for people with lung cancer and in caring for people living longer if lung cancer is prevented. Items such as social security payments and benefits are typically not included in cost-effectiveness analyses.

Step 3: State the time horizon, discount future costs and benefits

A cost-effectiveness analysis should adopt an analytic horizon that is long enough to capture all the main costs and benefits of the programme being evaluated. For radon prevention and remediation this is likely to be a lifetime, as radon exposure affects the lifetime risk of lung cancer and hence life expectancy; the costs of maintaining and running active prevention and remediation measures will, therefore, have to be assessed over the same period. In this example, the costs and benefits of radon remediation are considered over a period of 85 years.

In practice, it may take time to roll-out a prevention or remediation programme and scale it up to full size. There may also be delays in the household response to test offers or radon information, and in any preventive or remediation actions undertaken. Finally, there may be a latency period between any reduction in radon exposure and changes in cancer incidence. These are not formally modelled in this example. Because the costs and benefits of many programmes such as radon prevention and remediation are spread over time, it is necessary to express them in present values. This is not simply a matter of summing them, as individuals typically have positive time preference: that is, a preference for benefits now over benefits in the future, and a preference for costs deferred over costs incurred now. Discounting future costs and benefits using an approved annual discount rate is therefore recommended: in this example, all future costs and benefits are discounted to present values using the UK recommended annual discount rate for health technology appraisals of 3.5%. The consequence of discounting is that, for example, a cancer case averted now is given more weight than a case averted in 50 years' time, but equally that costs incurred in the future are given less weight than costs incurred now.

Step 4: Report uncertainty around the results in a clear and comprehensive way

Cost-effectiveness results are likely to be subject to a considerable amount of uncertainty, for example due to lack of precision in input parameters. One way of dealing with this is to report the results of one-way sensitivity analyses, in which key input variables are varied across a plausible range to assess their impact on the results, holding all other variables constant. A more comprehensive way of assessing uncertainty is to independently (or within some correlation structure) vary the input values of all parameters simultaneously and repeatedly around the central estimates, using random draws from specified distributions or ranges, with incremental costs, effects and cost-effectiveness recorded on each run. This is usually referred to as probabilistic sensitivity analysis or probabilistic uncertainty analysis (Doubilet et al. 1985, Claxton et al. 2005). In the analysis considered here, one-way sensitivity analyses and probabilistic analyses are shown on variables including the relative risk of lung cancer per 100 Bq/m^3 increase, the percentage reduction obtained by remediation measures, initial prevention and remediation costs per household, running costs, health care costs of a lung cancer case, and health care costs of added life expectancy. Clearly, many other uncertainties could be examined, such as the possible existence of some threshold or non-linear exposure-response relationship, or future changes in smoking rates, household size, life expectancy, and costs and effects of preventive/remedial technologies.

In line with the steps outlined above, the cost-effectiveness analysis reported here is based on a spreadsheet model, which is used to estimate the expected number of lung cancer deaths in a particular population in the presence and absence of radon prevention or remediation. These estimates are then combined with information on the costs of radon detection and prevention or remediation and of lung cancer treatment to calculate the incremental cost-effectiveness of a radon reduction programme compared to no programme. Cost-effectiveness is calculated as the ratio of net change in cost to net change in outcome, with outcome (lung cancer cases averted) expressed in terms of QALYs gained; this facilitates comparison of the cost-effectiveness of radon remediation with that of other public health and health care interventions.

4.3.2 Data requirements

Table 14 shows some of the main data items required to estimate cost-effectiveness, and the values used in the example. Data on the size of the total UK population, and on numbers of lung cancer deaths subdivided by age and sex, were obtained from UK national statistics for the year 2004 (ONS 2006). The lung cancer rate in never-smokers was based on the American Cancer Society data published by the US Department of Health and Human Services (USDHHS 1996), adjusted from mean USA to mean UK radon concentrations. Smoking rates (the percentage who have ever/never smoked cigarettes regularly, with sub-division of ever smokers into current and ex-smokers, by age and sex) were taken from the General Household Survey from 2004 (ONS 2006).

Life expectancy at time of death from lung cancer was calculated separately for male and female ever-smokers and never-smokers, using data on all-cause mortality attributable or not attributable to smoking (Peto et al. 2006). It is assumed for simplicity that all lung cancer cases result in death from lung cancer (5-year survival from lung cancer in the United Kingdom in 1998-2001 was 6% in men and 7% in women). It is also assumed that deaths from radon-induced lung cancer have the

Table 14. Data inputs for a cost-effectiveness model

Variable/ parameter input		Value
Population characteristics (*age-specific rates are used in the analyses*)		
Life expectancy: example at birth (male/female)		76/81
Percent current smokers: example aged 20-34 (male/female)		34/29
Lung cancer rate per 100 000: example aged 65-70 (male/female)		217/132
Average age at lung cancer death		72/73
Average quality adjusted life years lost per cancer death:	never smoker	10.6
	ever smoker	8.8
	all	9.0
Radon levels		
Arithmetic mean radon concentration in area of interest, uncorrected (Bq/m³)		70.1
Percent of measured homes over the Reference Level of 200 Bq/m³ (%)		5
Pre-remediation arithmetic average concentration reading of homes at or above Reference Level, corrected (Bq/m³)		265
Reduction obtained by remediation measures (%)		85
Post-remediation average concentration reading of remediators, corrected (Bq/m³)		40
Household characteristics		
Average household size in 2001		2.3
Average home occupancy level (%)		70
Percent of homes invited to test that accept (%)		30
Proportion of homes found over 200 Bq/m³ that decide to remediate (%)		20
Unit costs		
Unit cost of inviting households to test, per household (£)		1.6
Unit cost of measuring radon concentrations per household (£)		39
Remediation cost per household (initial) (£)		729
Remediation cost per household over 85 years, including replacement/running costs (£)		1 687
Annual per capita expenditure on health care during added life expectancy (£)		7 517
Mean NHS/hospice treatment cost per lung cancer case (£)		18 087

same age distribution as deaths from non-radon induced lung cancer. The estimated number of quality adjusted life years lost from each lung cancer death is based on the estimated remaining life expectancy at time of death, calculated separately for ever-smokers and never-smokers, adjusted for quality of life using population survey data.

4.3.3 Radon concentrations

The proportion of homes likely to be above a specified reference level, and the radon concentration in those homes above that level, are calculated based on the left-truncated expected value given the mean measured value in the area of interest and assuming a log-normal distribution (Gunby et al. 1993). Measured radon concentrations are adjusted for measurement error according to the approach set out in Darby et al. (2006). It is possible that households deciding to remediate may not be at the average concentration for all homes over a reference level, and adjustments could be made for that.

The reduction in radon concentrations obtained by preventive or remedial action will depend on the steps taken. Here, for the remediation of existing homes, this analysis used a study in 1998 of almost 1000 homes undertaking a range of remediation measures, which found an average reduction of measured radon concentrations of approximately 85% and a mean remediation cost of £630, or approximately £729 when adjusted to 2006 prices (Naismith et al. 1998). Similar results have been reported in another United Kingdom study for a sample of 62 homes in Northamptonshire (Kennedy et al. 1999). The reduction in radon concentrations following remediation, and the cost of these actions, will be a function of the type of actions performed and a range of local or national circumstances including typical cost levels.

For prevention in new homes, it was assumed in this example that the main action would be the installation of a radon-proof membrane (radon barrier) in addition to normal damp protection measures across a building's footprint during construction, with gas-proof seals around pipe penetrations. The cost of this is estimated to lie between £100 and £200, and it is assumed that a fitted membrane reduces radon in a new home with a solid floor by approximately 50% (Naismith 1997).

Information is also needed on the average number of people per home. This can be varied by type of home, or varied over time, or using more detailed information on age and sex composition. Here a simple average of 2.3 was used, based on national data. For an average home occupancy level, a figure of 70% was used, corresponding to around 17 hours per day, in line with the national Time Use Survey 2005 (ONS 2007).

An important parameter for programmes aimed at remediation of existing homes is the proportion of homes invited to test that accept: in this analysis, a figure of 30% was used, corresponding to findings from existing programmes (Department of the Environment 2000). Even more important is the proportion of house-holders found to be over a specified action level who decide to take remedial action: here a figure of 20% was used, also in line with previous surveys (Bradley and Thomas 1996).

The cost of inviting households to have their homes tested was set at £1.60, including administration, postage and materials, based on reported costs in other screening programmes (Garvican 1998). The unit cost of measuring radon concentrations, based on delivery, removal, reading and reporting from a pair of etched track detectors in two rooms for three months, was estimated in 2006 as £39 in prices (DEFRA 2005).

Estimates of the hospital costs of lung cancer diagnosis, treatment and follow-up were based on a published study from 1999 (Wolstenholme and Whynes 1999), updated to 2006 prices. The additional health care costs incurred during any period of extended life expectancy were estimated using national data health expenditure per person by age group (Department of Health 2007). There is some disagreement among health economists over whether to include these costs in economic evaluations.

4.3.4 Risk estimates

To estimate the number of radon-induced lung cancer cases prevented by a remedial or preventive action, two methods were used in this analysis: 1) data from the European pooling study (Darby et al. 2006), indicating that the risk of lung cancer increases by 16% per 100 Bq/m^3 increase in the usual or long-term average radon concentration in the home; and 2) the preferred risk model proposed by the Committee on Health Risks of Exposure to Radon (BEIR VI), based on pooled miner data, in which the death rate from lung cancer varied linearly with cumulative radon exposure, subject to modification by attained age, time since exposure, and either radon concentration or duration of exposure (National Research Council 1999). The radon concentration variant was used here.

4.3.5 Results

Table 15 shows some results from the analyses set out above, using the European pooling study risk estimates. For new homes in this example, membranes are fitted

Table 15. Results from a cost-effectiveness analysis of radon remediation in UK

Initial	New homes	Existing homes
Lifetime cumulative lung cancer risk (%) - never smoker	1.05	1.38
Lifetime cumulative lung cancer risk (%) - ever smoker	14.31	18.36
Lifetime cumulative lung cancer risk (%) - all	8.11	10.51
Post-remediation		
Lifetime cumulative lung cancer risk (%) - never smoker	1.01	1.03
Lifetime cumulative lung cancer risk (%) - ever smoker	13.80	14.07
Lifetime cumulative lung cancer risk (%) - all	7.81	7.96
Health gain per household remediating		
Lung cancer cases averted	0.007	0.06
Total life years gained	0.08	0.67
Total life years gained - discounted	0.03	0.23
Average QALYs gained (per lung cancer case averted)	8.99	8.99
Total QALYs gained	0.06	0.53
Total QALYs gained - discounted	0.02	0.18
Resource use and costs per household remediating		
Number of invitations to test	0	333
Invitation costs (£)	0	533
Number of radon tests	0	100
Radon testing cost (£)	0	3 876
Radon remediation cost - discounted (£)	100	1 687
Sub-total: invitation, testing & remediation costs - discounted (£)	100	6 097
Lung cancer treatment costs averted - discounted (£)	38	360
Other health care costs during added life expectancy- discounted (£)	202	1 718
Net cost - discounted (£)	264	7 454
Cost-effectiveness		
Incremental cost per life year gained -discounted (£)	9 824	32 614
Incremental cost per QALY gained - discounted (£)	12 526	41 584

to every new home in areas where at least 3% of homes would be likely to have radon levels greater than 200 Bq/m^3 without any preventive measures. For existing homes, invitations to test for radon are targeted on areas in which 5% of homes will be expected to have radon concentrations above 200 Bq/m^3.

Using the risk estimate based on epidemiological studies which have assessed directly the lung cancer risks from residential radon, the analysis predicts that the cumulative lifetime risk of lung cancer at pre-remediation radon concentrations is 8% in the areas covered by the prevention policy, and 11% in the areas where mitigation is being targeted. Post-prevention, the lifetime risk falls to 7.8% in homes with prevention measures. This is equivalent to a reduction of just under 0.01 lung cancer cases in a household of average size, which in turn is equivalent to 0.06 QALYs gained, or 0.02 discounted QALYs gained.

For the mitigation policy, the change in lifetime risk is equivalent to a reduction of 0.06 lung cancer cases in a household of average size, which in turn is equivalent to 0.53 quality-adjusted life-years gained, or 0.18 discounted quality-adjusted life-years gained. The cost of the prevention policy in this illustrative example is simply the cost of a membrane, of £100. Savings of £38 come from the reduced lung cancer cases, with added costs of £202 for health care costs during added life expectancy, giving a net total of £264 per house.

For the remediation policy, using the acceptance and remediation rates described above, at a long-term average of 64 Bq/m^3, 333 invitations to test will result in 100 homes tested, five found to be above 200 Bq/m^3, and one home remediated. The cost of the invitations is £533 and the cost of testing is £3 876. These costs, together with remediation costs, come to a discounted total of approximately £6 097, against which around £360 is saved from the averted lung cancer treatment costs and £1 718 is incurred in health care costs during added life expectancy. Consequently the net cost is £7 454 per household remediated.

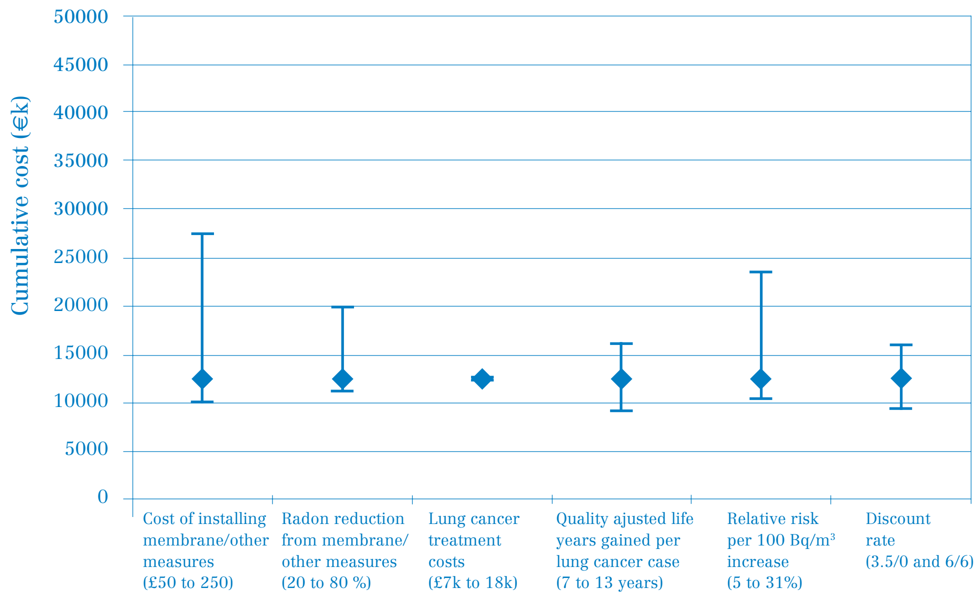
Combining the incremental outcomes and costs reported above (that is, the additional costs and outcomes of the remediation policy in comparison with not having that policy), the incremental cost is £12 500 per quality adjusted life year gained for the prevention policy, and £41 600 for the remediation policy.

Whether or not these cost-effectiveness ratios are considered to be acceptable will vary greatly depending on the country, the context and other factors. In the United Kingdom, the prevention results would be well below, and the remediation results at or above the level that reimbursement or regulatory agencies such as NICE[5] might consider cost-effective for health care interventions paid for by the National Health Service: evidence from that agency indicates that interventions are likely to be rejected on cost-effectiveness grounds once the cost per life-year or per QALY gained is over £25 000 to £30 000 (Rawlins and Culyer 2004).

These results might change if the assumptions and parameter values used in the analyses were changed. Figure 9 shows the results of a one-way sensitivity analysis for the prevention policy, in which a range of parameter inputs to this cost-effectiveness are varied one at a time between plausible upper and lower bounds, and the impact on the cost-effectiveness result is recorded. It can be seen that the results are particularly sensitive to the cost of the prevention measures, the risk reduction they yield, and the relative risk of radon. Such analyses can help to identify areas in which cost-effectiveness could be improved: for example, reduced costs of remedial actions, or higher remediation rates among house-holders in homes with high radon levels, could significantly improve the cost-effectiveness of mitigation programmes.

[5] National Institute for Clinical Excellence in the United Kingdom.

Figure 9. Results of a one-way sensitivity analysis



4.3.6 Recommendations

The example set out here is simplified and for illustrative purposes only. In practice, this type of cost-effectiveness analysis would have to explore many additional factors such as the costs and effects of different types of prevention or remedial actions, the results obtained in areas with different radon levels and distributions, and different assumptions about current and future smoking patterns. The analysis also assumes that the preventive or remedial actions are being undertaken in a detached, semi-detached or terraced house of typically one, two or three stories; different parameter values and analyses would be required for multi-floor apartment buildings, and for buildings used as working environments such as factories, offices, hospitals and schools.

It has been assumed here that the benefits of radon prevention and remediation programmes are exclusively reduction in radon exposure and hence lung cancer risk; it is possible, however, that other benefits exist, such as reduced damp and moisture problems. These could be quantified and incorporated into a full analysis. In any case, the advice of a health economist is helpful in implementing and interpreting cost-effectiveness analysis projects.

Cost-effectiveness analyses can provide useful information to policy-makers seeking to evaluate policies and alternatives, but they are subject to uncertainties and limitations. Their results should therefore be interpreted and communicated carefully. They cannot be the only basis for decisions. For example, cost-effectiveness is primarily about efficiency, but equity or fairness may also be important to policy-makers.

Even when cost-effectiveness analysis indicates that remediation programmes cannot be justified on a nationwide basis, high levels of radon may pose a considerable individual risk of lung cancer which is considered unacceptable; in such circumstances remediation should nevertheless be undertaken.

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5. Radon risk communication

KEY MESSAGES

- The communication of radon risk and prevention messages poses serious challenges because radon is not widely known and may not be perceived as a health risk by the public.
- In addition to informing the public, a primary objective of radon risk communication is to persuade policy makers that radon is an important public health issue that requires action.
- Effective risk communication requires co-operation between organizations, clear and coordinated messages, and the enlistment of collaborators with good community credibility.
- As part of radon risk communication, the development of a set of core messages aimed at target audiences is recommended. These messages should be simple, brief, and to the point.
- An assessment of perceptions and the level of knowledge regarding radon in the target audiences is strongly recommended. This should be done both before and after a risk communication campaign.

The purpose of this chapter is to provide guidance on the development of radon risk communication programmes. The chapter will also give suggestions on different communication techniques and strategies. The information found here is based on general communication principles and on the experience of a number of countries with well-developed radon programmes. It is recognized that this guidance may need to be adapted to the prevailing cultural, social and economic circumstances within a country or a region. This chapter will examine how to communicate with the public concerning the health risks associated with radon as well as the objectives of a national radon programme.

Communicating clearly and effectively with the public should be a primary objective in a national radon programme. There are fundamental steps in communicating risk to the public that will be explored in this chapter. Principle components of these steps include: assessment of the public perception of risk, clear and understandable risk messages, identification of target audiences, and in some situations using comparisons (e.g. lung cancer due to radon compared to lung cancer from other sources) to clarify the risk associated with exposure to radon.

5.1 Fundamentals, strategies and channels

In communication, the content and context of the message are both equally important. There will be a diverse audience receiving the radon risk message and it is very important to take into consideration the ways in which they will perceive it. As explained further in section 5.2, risk has different definitions for different people. When building effective communication it is important to inspire trust, be attentive, and maintain an open dialogue (WHO 2002). To inspire trust, the communicator must be competent, respectful, honest, personable, and use clear and understandable language. Attentive communicators will choose their words wisely, listen actively, observe body language, and recognize emotions. To maintain an open dialogue, the communicator needs to seek input, share information, and provide means for communication (WHO 2002).

When choosing a communicator, it is important to choose someone skilled in interpersonal communication, knowledgeable about the topic area, and credible. The communicator will need to remember that non-verbal communication is just as important as verbal communication when trying to establish credibility (USEPA 2007, WHO 2007).

According to USEPA (2007) there are common misconceptions involved in communicating risk, such as: “you can’t anticipate what people will ask” and “communicating risk is more likely to alarm than calm people”. In fact, it has been shown that it is possible to predict 95% of the questions and concerns for a controversy if the communicator is well prepared. Examples of general risk questions and more specialized radiation risk questions are presented elsewhere (WHO 2007, USEPA 2007).

When evaluating risk communication, three major components are involved: risk assessment, risk perception, and risk management (WHO 2002). Each component encompasses many characteristics. Risk assessment is the process used to describe the possibility of an adverse outcome. When a risk is defined through a scientific risk assessment, it allows policy-makers to create risk management programmes. The perception of risk encompasses more than just public perception, which is already influenced by their experience with other hazards and risks (Slovic 1987). It also takes into account economical and political factors. Public perception changes over time, through gaining knowledge and accumulating information. Risk management covers how policy-makers and government agencies react to the public’s risk assessment and risk perception. Government agencies can react by making new laws or policies. This risk management component will have an influence on the direction a radon programme will take.

Apart from informing the public, a primary objective of a radon risk communication programme should be to persuade policy-makers, at a national and local government level, that exposure to radon is an important public health issue that requires action. The following chapter 6 discusses the actions that should be undertaken at a national and local level.

Experience in some countries, such as Sweden, indicates that convincing policy makers to take action through regulatory means has been more effective than risk communication messages targeted only at the general public. However, creating public awareness of the need to reduce residential radon levels remains an important strategy. The communication strategy that a government chooses to adopt will depend on:

- the extent of the problem in a country;
- the overall objective of the radon programme;
- the communication of the objective;
- the budget of the programme;
- the reference level;
- the building codes in the country.

The communication channels and the approaches to be used should be a combination of passive (information is provided without the ability to have a dialogue with the provider) and active (information is provided and the recipient can interact and have a dialogue) engagement techniques (WHO 2002). Examples are given in Table 16.

Several countries have well-established radon programmes. These countries use different strategies and communication channels. Some examples are given here:

- using a direct approach to address people who are building or modifying houses trough workshops and training courses for building professionals;
- disseminating information through the media both through active and passive channels (cf. Table 16);
- repeating information at appropriate intervals by holding an annual event such as a Radon Day or a Radon Forum;
- using credible intermediate target groups such as doctors and teachers;
- convincing policy makers to develop regulatory options, which means that communication channels with different ministries need to be established.

Table 16. Different communication engagement techniques

Passive Communication	Active Communication
• Direct mailing (e.g. fact sheets, brochures)	• Local radio “phone-in” sessions
• Road shows and billboards • Web sites and list servers	• The use of third-party networks (e.g. holding briefings at community group meetings)
• Newspaper advertisements	• The provision of an information hotline or helpline
• Information stands at construction industry exhibitions	• Conducting meetings and public hearings
• Direct contact with the media (e.g. press releases)	• Reporter interviews (e.g. radio, television)

5.2 Framing radon risk issues for risk communication

A radon risk communication programme must have clear and achievable objectives. These should be focused on informing different target audiences (cf. section 5.4.1) about radon and persuading those audiences to take action. A radon risk communication programme should also be a cooperative effort involving both technical experts (e.g. radiation scientists, epidemiologists) and communication experts (e.g. social scientists, psychologists, journalists) (WHO 2002). In communicating information on the health impact of radon, it should be noted that even in the context of professional health risk assessment, the term "risk" has many definitions. In general, a statement of risk to an individual requires a description of the probability or likelihood of harm and of the severity of the harm. In the case of radon, the harm is mainly lung cancer, which is a painful and fatal disease.

An example for a risk message on exposure to indoor radon that could be used for basic information in communication campaigns is presented in Box 4.

Box 4: An example for a basic risk communication message

"There is no known threshold below which radon exposure carries no risk. The lower the radon concentration in a home, the lower the risk"

5.2.1 Lung cancer risks associated with radon

As discussed in chapter 1, the International Agency for Cancer Research (IARC), the WHO cancer research institute, classifies radon as a proven human carcinogen, which places radon in the same IARC carcinogen group as tobacco smoke, asbestos and benzene (IARC 1988). The exposure to radon in homes is one of the most important causes of lung cancer deaths worldwide. In fact, the majority of radon related lung cancer deaths will occur among persons exposed to indoor radon concentrations below commonly used indoor radon reference levels. These observations have implications not only for radon risk communication strategies, but also for National Radon Programmes. Using the available data, USEPA estimates that approximately 21 000 lung cancer deaths per year in the USA are attributable to residential radon (USEPA 2003). A similar estimate has been calculated for 25 countries in Europe (Darby et al. 2005). These estimates indicate that worldwide, many tens of thousands of radon-related lung cancer deaths are occurring each year.

From an epidemiological perspective, there are various ways in which risk can be expressed. One of these is the relative risk (RR) approach, where the risk (for an exposure time of about 30 years) at a given radon concentration is compared to that expected at a specified, lower level (typically around 10-15 Bq/m^3). An RR of 1 implies no increase in risk for the person exposed. In the residential radon epidemiological studies, the risk was found to increase with increasing radon concentration, implying RR>1. Moreover, the RR increases proportionally. This was expressed as the excess relative risk (ERR = RR-1) per unit increase in radon concentration (e.g. ERR per 100 Bq/m^3). The computed confidence intervals for these risk estimates help to assess the statistical significance of the results.

For example, as explained in chapter 1, the European studies (Darby et al. 2005) estimated the ERR of lung cancer per 100 Bq/m^3 increase in long-term average radon concentration at 16% (95% confidence interval 5-31%). The ERR did not vary with age, sex or smoking history. North American and Chinese studies yielded similar results (Krewski et al. 2005 and Lubin et al. 2004).

A concept such as relative risk may be difficult to explain to the general public and for effective risk communication it may be preferable to express risks in absolute terms. For example, the absolute number of estimated cases per year related to radon exposure in a population may be more easily understood. Similarly, giving lifetime risk estimates for smokers and non-smokers exposed to different concentrations of radon may be another useful way to communicate radon risk to the public. Information on combined radon and smoking effects may also assist tobacco control campaigns by highlighting the fact that exposure to radon significantly increases the lung cancer risk for smokers.

5.2.2 Synergetic effect of smoking and radon

Another important information to communicate is the relationship between lung cancer risks associated with exposure to radon and tobacco smoke. Epidemiological studies have shown that the absolute risk to smokers at any level of radon exposure was much greater than that of never-smokers or former smokers, thus highlighting the synergistic effect between radon exposure and smoking. For example, in the European studies, the cancer risks for smokers of 15-24 cigarettes per day relative to those for never-smokers and never exposed to radon were estimated to be 26, 30 and 42 at radon concentrations of 0, 100 and 400 Bq/m^3, respectively. For never-smokers, the corresponding relative risks are estimated to be 1.0, 1.2 and 1.6, respectively. These latter values indicate that even for never-smokers the risk of lung cancer from elevated radon exposure cannot be discounted.

For current smokers (about 1 pack/day), the cumulative absolute lung cancer risk to age 75 years is estimated to be about 10% at zero radon exposure. This risk more than doubles to 22% for current smokers with a long-term exposure to radon at 800 Bq/m^3. The corresponding absolute risks for lifelong never-smokers were estimated to be 0.4% and 0.9% respectively. The risks for former smokers due to radon lie between those for current smokers and those for never-smokers. Examples that may be useful for communication messages relating radon exposure and smoking to lung cancer are presented in Box 5.

Even if no combined effect between environmental tobacco smoke (ETS) and radon is proven, ETS exposure should also continue to be discouraged by effective tobacco control measures and indoor air quality programmes (WHO 2008, Bochicchio 2008).

Box 5: Examples of messages explaining the relationship between radon and smoking

> "The majority of radon-related lung cancer deaths occurs in current and former smokers"
>
> "Radon exposure increases the risk of lung cancer for everyone, whether they are current, former or never-smokers"

5.2.3 Comparing risks associated with radon to cancer risks from other sources

Placing estimated radon attributable lung cancer death rates in the context of other cancers at a national or regional level can be a useful radon risk communication tool. Lung cancer accounts for the greatest component of cancer deaths in many countries. Based on epidemiological studies, it is estimated that between 3 and 14% of lung cancer deaths are related to radon. Therefore, indoor radon exposure poses a significant public health hazard. In absolute terms, the radon related lung cancer death rate may be greater than the death rates from many other cancers. As an example, for the United States population the estimated number of radon attributable lung cancer deaths, at about 21 000 per year, is greater than the annual number of deaths for several common cancers including cancer of the ovaries, liver, brain, stomach, or melanoma (Field 2005). For Europe, radon attributable annual lung cancer deaths account for approximately 1.8% of all cancer deaths, amounting to some 30 000 deaths in 2006. This number is comparable to deaths from cancer of the esophagus, oral cavity and pharynx, and about 50% higher than the numbers of deaths from melanoma (Darby et al. 2005, Ferlay et al. 2007). Such information could be expressed in a communication message as shown in Box 6.

Box 6: An example for a communication message comparing risks

> "In Europe, many more people die from radon-related lung cancer than from melanoma"

5.3 Core messages for radon risk communication

Providing information that is comprehensible to the public presents a challenge. This entails simplifying the message and framing it in a way that presents a benefit to the target audience. It is possible to explain radon issues in simple language and by using well-known examples for comparison. For example, the annual radiation dose from radon could be compared with that from common diagnostic medical procedures such as conventional chest radiography. If good cancer risk data exist, it may be useful to place the risk of lung cancer due to radon in comparison with the risks of other cancers as explained above. In some situations, comparisons with everyday common risks, such as road traffic accidents, may be useful.

Radon risk communication should be focused on a small number of core messages which accurately reflect the current scientific consensus and are expressed in simple, readily understood language. The format of the messages should be tailored to each target audience. As part of a radon risk communication programme, the development of a set of core messages is recommended. Examples are given in Box 7. When developing messages it is important to keep them simple, brief, and to the point (USEPA 2007, WHO 2007).

Box 7: Examples for radon risk core messages

“Radon causes lung cancer”

“Radon is a radioactive gas present in homes”

“Radon is easy to measure”

“You can easily protect your family from radon”

All radon risk communication messages should be tested and adapted to the individual target audiences. The visibility of the message will help make it more effective. It is important to use credible and respected senders of the messages (e.g. local health authorities, medical practitioners, school teachers) and appropriate distribution channels. The success of the message will depend upon the adaptations made to the target audience, the trusting relationship between the communicator and the audience, and the clarity of the message (WHO 2007).

In communicating with the general public, simple non-quantitative messages, such as the example given in Box 8, could be used to highlight the synergistic effect between radon exposure and smoking.

Box 8: An example for a simple non-quantitative message

“Radon increases the already high risk of lung cancer in smokers, but whether you smoke or not, radon exposure increases your lung cancer risk”

Following the measurement of radon in a home, a simple fact sheet on radon risks and remediation could be given to the individual householders to enable and encourage them to make an informed decision on what action, if any, they should take to reduce their radon risk. Fact sheets are a good way of expressing a message to the public. Simple fact sheets with core messages could be made available at public health offices, contractors’ offices, hospitals, schools, local and national government offices, etc.

5.4 Communication campaigns

5.4.1 Identification of target audiences

An essential component of a radon risk communication campaign is to identify the target audiences one wishes to inform and to convince to take the necessary actions to protect themselves against radon. These target audiences may be divided into two main categories (direct or indirect) as listed below. Some target audiences may in different situations be viewed as belonging in either or both categories. Nevertheless, this dual categorization is useful to the planning of communication strategies. Table 17 lists examples of target audiences separated into direct and indirect categories.

Table 17. Different target audiences categories

Direct Category	Indirect Category
• Persons building or modifying their own dwelling	• Governmental and political decision makers
• Householders	• Local authorities
• Tenants	• Financial institutions
• Smokers	• Legal advisers, lawyers
• Architects and engineers	• Medical doctors, nurses, pharmacists, etc.
• Builders and construction companies	• Teachers
• Financial institutions	• Media
• Real estate companies	• Do-it-yourself stores
• Local authorities	• Professional associations

The first group, the direct category, are individuals whose actions could directly result in reducing lung cancer risk. This can be achieved in a variety of ways, such as reducing radon exposure in existing houses by radon mitigation techniques or by constructing new houses with installed effective radon preventive technologies such as membranes and soil depressurization systems. Both regulatory and financial instruments can play an important role in encouraging these activities, but in some cases personal choice can also be an important factor. Smokers are included in the direct category since a decision by them to reduce their residential radon exposure, with or without a cessation or reduction in smoking, may result in a substantial lowering of their lung cancer risk.

The second group, the indirect category, are individuals whose actions, either by decision-making or by highlighting the radon problem, would help to increase and improve public awareness and perception and would thereby help to encourage radon prevention and reduction in communities.

It should be noted that financial institutions, such as banks and mortgage providers, are also considered to be important target audiences because of the potential role they can play in ensuring that future dwellings are built with effective radon prevention technologies. If these financial institutions can be persuaded to request radon measurements in properties in which they have financial interest, this action will assist in bringing the radon issue to public attention. In some countries, radon measurements are already part of the procedures required in buying and selling homes, such as in the USA and the United Kingdom.

5.4.2 Assessment of radon risk awareness

It is strongly recommended to assess the perceptions and level of knowledge regarding radon in the target audiences. One of the easiest and most cost-effective ways to assess awareness is through public surveys (WHO 2006). Surveys should be performed both before and after a risk communication campaign in order to help design, evaluate and improve the communication campaign. Such surveys are also useful to track campaign results over time.

Depending on the target audience, such surveys may include questions on issues such as:

- basic knowledge about radon;
- the origin and pathways of radon;
- the health effects of radon;
- the technical means available to protect people against radon;
- the willingness to take action.

The success and strength of the surveys will depend upon the efficiency, uniformity, ease of analysis, comparability over time, and possible generalization of the results (WHO 2006). Assessment is a key component in documenting the public's knowledge and evaluating its perception of radon. Assessments allow policy-makers to focus on and improve the communication programme and allow local and government agencies to establish the core messages. If the target audiences do not have a basic understanding of the radon issue, the campaign is likely to fail. Assessments performed prior to a campaign allow the campaign to focus the message on its target audience. Likewise, after a communication campaign has been established and delivered to target audiences, it is important to repeat the survey in order to determine its effectiveness.

Evaluating the public response to a campaign message is an important part of determining whether it has been successful. According to WHO (2007), three main components are required to perform this evaluation:

- outreach: how many people did the message actually reach?
- evaluating response: did the audience respond?
- evaluating impact: was there any change in behaviour?

5.4.3 Encouraging the public to take action on reducing radon

Communicating radon risk to the public in a clear and effective manner may be difficult. Disseminating radon risk information to the public is usually insufficient to prompt action - either radon testing or mitigation - by the householder. Reducing the health burden of residential radon exposure requires decisions and actions by homeowners. National radon programmes (as explained in chapter 6) need to persuade the public to take preventive measures for newly built houses, to measure existing homes for radon, and to take action to remediate the homes. For a variety of reasons, ranging from apathy and disbelief regarding radon risks to considerations of the cost of remediation, some people living in high radon houses choose not to take any action to reduce radon exposure in their home.

Based on social and risk communication research in a number of countries, reluctance to act, both by the public and by policy makers, regarding risks from radon has been found to be a major obstacle in a radon risk communication programme (WHO 1993). As in the case of individual householders, the reasons for this apathy or reluctance to take action are complex. One of the common misperceptions regarding indoor radon is that it is natural and no one is to blame for the occurrence of high residential radon levels. While radon gas is natural, it is not the case that high residential radon levels are completely natural. Enhanced indoor radon concentrations occur as a result of the human activities of designing and constructing houses as well as the living habits of house occupants. High residential radon concentrations are a form of technologically enhanced natural radiation. As explained in more detail in chapter 3, even on the ground floor where the soil gas can have a very high potential to increase radon concentrations, it is possible with modern building technologies to achieve acceptably low indoor radon concentrations.

Social marketing approaches have been used for several years in some countries such as the USA to motivate individuals to test for radon and fix problems if they arise. Social marketing seeks to operate a change in the target audience, while at the same time emphasizing a benefit. This approach has proved to be more successful than earlier campaigns, which were largely directed at informing the public about the risk posed by radon (USEPA 2003, USDHHS 2005). For effective risk communication, it is important to cooperate with other organizations, to coordinate messages, and to enlist the help of others who have community credibility such as medical doctors and teachers.

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6. National radon programmes

KEY MESSAGES

- National radon programmes should aim to reduce the overall population risk and the individual risk for people living with high radon concentrations.
- To limit the risk to individuals, a national reference level of 100 Bq/m^3 is recommended. Wherever this is not possible, the chosen level should not exceed 300 Bq/m^3.
- To reduce the risk to the overall population, building codes should be implemented that require radon prevention measures in homes under construction. Radon measurements are needed because building codes alone cannot guarantee that radon concentrations will be below the reference level.
- Detailed national guidance on radon measurement protocols is essential to ensure quality and consistency in radon testing. A national radon database that monitors the measurement results over time can be used to evaluate the effectiveness of a national radon programme.
- An effective national radon programme requires input from several agencies within a country. One agency should lead the implementation and coordination and ensure linkage with tobacco control and other health promotion programmes.

This chapter presents the components for developing a national radon programme and a framework for the organization of such a programme at the country level. A radon programme should aim to reduce both the risk for the overall population exposed to an average radon concentration and the risk of individuals living with high radon concentrations.

The development of a radon programme involves the setting-up of a clear organizational structure and a range of components in order to monitor radon levels, facilitate prevention and mitigation, and provide radon risk communication services to the public and other stakeholders.

In a country considering the establishment of a radon programme, an initial step is to carry out an assessment, preferably a national radon survey, to obtain a representative distribution of the radon concentration within the country. This chapter offers guidance on the general planning and conduct of such surveys, in particular with a view to obtaining a geographical distribution of radon concentrations including possible radon-prone areas.

Similarly, guidance is given on the setting of an appropriate reference level. The reference level is the radon concentration above which a country strongly recommends or requires remedial work to be carried out. Radon protective measures may also be appropriate below the reference level to ensure that radon concentrations in homes remain consistently below that level.

The use of geographical radon maps is also discussed in this chapter. These are useful tools in targeting radon sources. However, these maps should not be interpreted as indicating that high indoor radon concentrations will only be found in radon-prone areas.

As previously stated, an effective programme emphasizes radon exposure prevention in new constructions. This is necessary for long-term risk reduction in the housing stock. The importance of the correct installation of radon prevention measures in homes under construction is emphasized. There are several factors to be considered in devising building codes or building regulations aimed at ensuring low radon concentrations in new houses. Both this chapter and chapter 2 (Radon prevention and mitigation) deal with such aspects.

How to ensure low risk from radon concentrations in existing homes, as well as the factors to be considered when remediating homes with high radon concentrations, are outlined at the end of this chapter.

6.1 Organization of a national radon programme

The implementation of an effective radon programme aimed at protecting the public against indoor radon exposures requires input from many national agencies and other stakeholders, as illustrated in Figure 10. These include the national, regional and local organizations responsible for public health and radiation protection. Expertise from other agencies, entities or experts such as geological survey institutes, public and/or private radon measurement laboratories, building engineers and scientists, the construction industry and agencies that implement and enforce building regulations or building codes is another key element in any radon strategy. Governments should promote a national radon programme of coordinated actions and designate one organization or agency to take the lead in driving and coordinating it. National data should be gathered by this organization in order to evaluate the effectiveness of the programme.

Initially and as required during later phases of the programme implementation, the following should be assessed:

- the extent to which exposure to radon in homes poses a risk to the population,preferably with a population-based national radon survey;
- the pattern of exposure to find out whether some homes or some areas are more at risk than others, ideally with a geographical-based survey.

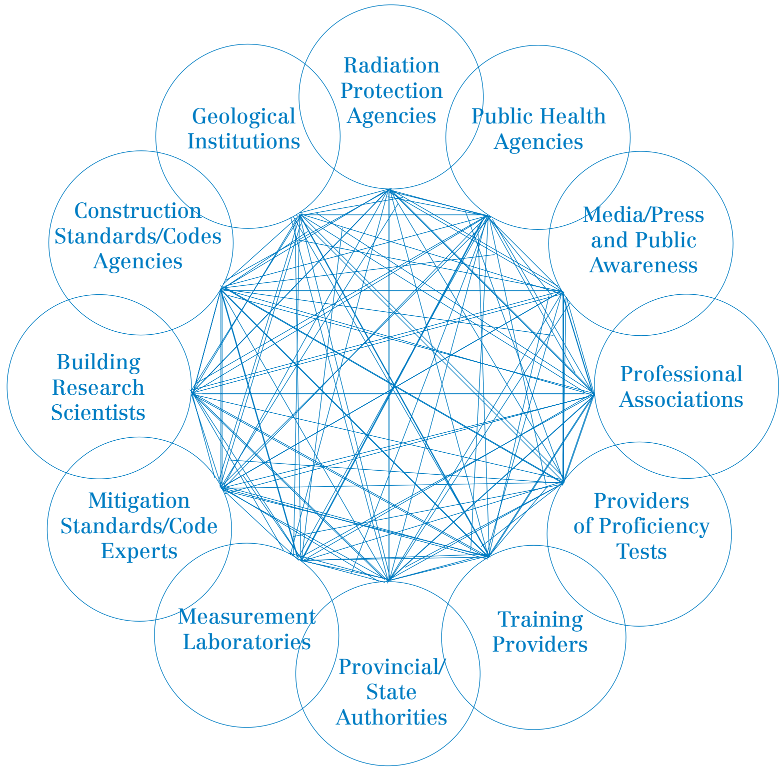


Figure 10. National agencies and other stakeholders may involved in radon programmes

Once initial assessments are completed and a need for further action is established, a comprehensive national radon policy should be developed to protect the public against exposure to indoor radon. Consideration should also be given to assessing radon risk in schools, childcare centres and other public buildings, where people may spend periods. The national radon policy should include the following key elements:

- a framework for reducing population radon exposure and related health risks;
- provisions to conduct national surveys using recognized radon measurement techniques and protocols to determine the extent of radon exposure of the population;
- provisions to set a national reference level for radon in homes;
- consideration of the combined effect of smoking and radon, it is recommended to link radon policy to other health promotion programmes dealing with tobacco control and indoor air quality;
- a framework to keep radon concentrations as low as achievable;
- provisions for the inclusion of local and regional authorities;
- programmes to inform the public and stakeholders about the radon issue and to increase radon awareness;
- provisions for the training of building professionals on building codes and radon prevention for new homes and radon remediation in existing homes; to ensure accurate results for radon measurements, the training should be in place prior to implementation;

- a programme that focuses on ensuring low radon concentrations in existing homes;
- a programme that focuses on radon prevention measures in new homes (homes which are under construction or under renovation) (cf. Box 9).

Box 9 : The importance of focusing on radon prevention measures in new homes

If applied correctly, installing radon prevention measures in new homes is generally the most cost-effective and efficient way to obtain low radon concentrations in individual households and consequently to reduce the average national radon concentration. Over time, this approach will lead to a greater reduction in the total number of lung cancers attributed to radon exposure than the alternative way of only reducing radon in existing buildings that exceed the reference level.

6.2 National radon surveys

A national radon survey should be conducted, using recognized radon measurement devices and techniques, to determine the radon concentration distribution which is representative of the radon exposure for the population of the country. This national survey may also provide information on the geographical distribution, but the survey needs to be properly designed to do both. In North America and Europe, the measurement of indoor radon gas is the most common approach used in surveys (Synnott and Fenton 2005a). The International Commission on Radiological Protection (ICRP) also favours this measurement technique (ICRP 1994). There are two key objectives in the design of a national radon survey:

- to estimate the average exposure of the population to indoor radon and the distribution of the exposures occurring. This can be done through a population-weighted survey by measuring indoor radon levels in randomly selected homes;
- to identify those areas within the country where high indoor radon concentrations are more likely to be found. This can be achieved with a geographically-based survey.

Preferably, radon measurements for both kinds of surveys should be carried out over a one-year period in each home to minimize uncertainties due to seasonal variations in radon concentration.

A population-weighted survey is one in which homes are chosen for measurement because they are representative of the homes of the whole population. This can be achieved by choosing homes at random from a complete list of the residential dwellings (e.g. houses and flats) in the country or in each region/province/town, depending on the requested detail of knowledge. This survey is designed to determine the radon exposure distribution of the population of a country/region/province/town, and therefore to estimate the average exposure and the percentage of dwellings exceeding reference levels. When undertaking such a survey, it is important to obtain statistical advice as many biases can distort the results. In particular, a sampling method must be devised which will yield a representative sample of the occupied dwellings in the country/region/province/town. The results of a population-weighted survey can be used for radon mapping, but areas with lower population density will yield few or no results, depending on the surveyed sample size and on the population distribution over the territory.

To obtain data for a more spatially uniform radon mapping, the selection of homes must be based on a geographically-based metric. A geographically-based survey can achieve this, because homes are selected in order to obtain a minimum number of results per area. The area can be regular (e.g. a grid square) or irregular (e.g. an area within an administrative boundary of a town/province) or dependent on an existing border (e.g. a given geological unit). The actual number and size of grid squares will be determined by the available funding, the spatial and numerical accuracy required, and the statistical advice obtained during the planning stage. In particular, it is very important that the homes selected for the survey be representative of those in each area, especially in areas where a small number of measurements are available. A radon map can be produced by simple area averaging, or by more sophisticated methods.

A population-weighted survey can be run in parallel with a geographically-based one, and a carefully designed survey can meet the requirements and objectives of both. For example, if a complete list (or an electronic database) of all the dwellings located in each area is available, a geographically-based survey can be used to obtain a population-weighted distribution of radon concentrations. Use of a radon map may help the implementation of a national radon policy.

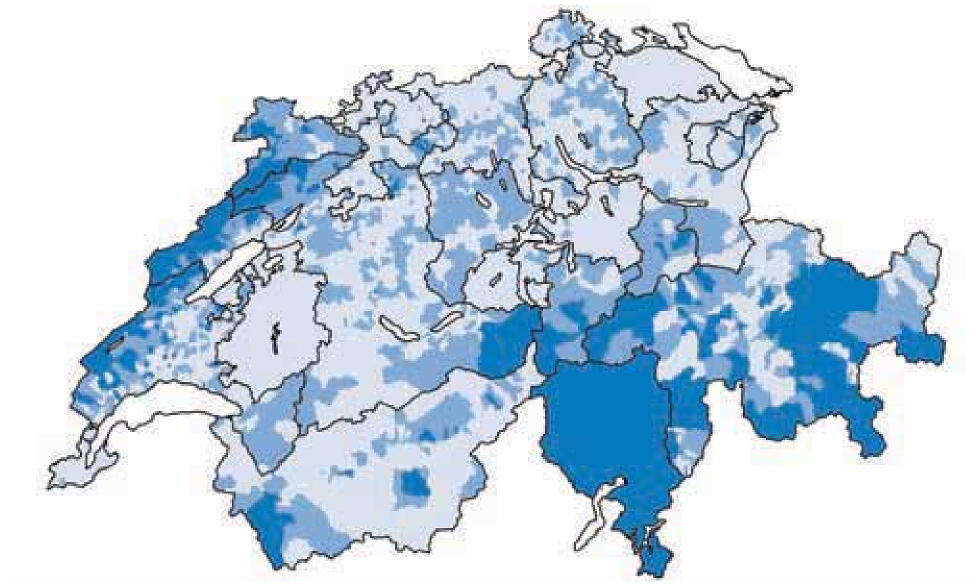
Because the distribution of radon in most surveys follows a log normal distribution, many countries report their summary data using the geometric mean (GM) and geometric standard deviation (GSD) (Miles 1998). However, to maintain comparability with other countries that do not use GM and GSD, it is useful to present summary data using both the GM and arithmetic mean (AM) and their respective measures of standard deviation (i.e. GSD, SD).

6.2.1 Radon maps

Geographical-based radon surveys estimate the distribution of radon in various areas. This information can identify radon-prone areas and may be represented on a radon potential map. If the data are obtained by properly designed surveys, these maps can be a useful tool in implementing a national radon policy. The radon map should be used as a tool to optimize the search for homes with high radon concentrations and to identify areas for special preventive actions during new construction. Radon maps based on indoor measurements covering the whole country have been produced in countries such as the United Kingdom, the USA and Ireland (Miles et al. 2007, USEPA 1993, Fennell et al. 2002).

Radon maps may provide information for identifying high-risk or radon-prone areas, and for motivating radon measurements and mitigation in existing buildings and preventive measures in new buildings. However, radon levels within an area will not be uniform and indoor radon concentrations will generally follow a log-normal distribution. Maps should be used mainly for targeting resources to the radon-prone areas, rather than indicating areas where measurements are not needed.

Comprehensive reviews of radon surveys and mapping in the USA and Europe are available (USEPA 1993, Dubois 2005). Worldwide data on radon surveys are published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000, 2008). However, these data should be used with caution, since the values tend not to be representative of radon concentrations in individual homes in the country. An example of a radon map is given in Figure 11.



Source: Swiss Federal Office of Public Health (2009)

Figure 11. Radon map of Switzerland

6.2.2 Radon-prone areas

In radon-prone areas, the distribution of radon concentrations can be quite wide and most values are low, due to the log-normal shape of the distribution. Conversely, dwellings with high radon concentrations are expected, although with a lower probability, in areas not classified as radon-prone. Therefore, as well as identifying radon-prone areas, some effort should also go into identifying any building characteristics that may be associated with high radon concentrations.

Radon-prone areas can be identified directly by using indoor measurements or indirectly using radon concentration in the soil, provided there is an established correlation with the radon concentrations in the homes.

The United States of America developed its radon map based on a combination of indoor measurements, geological characteristics, aerial radioactivity, soil permeability and foundation type (USEPA 1993). In Germany, the map is based on radon concentrations in soil gas. In Austria, the classification is based upon the mean radon concentration within a given area (Friedmann 2005).

An important consideration in developing a national policy is how to use the results of the national radon survey and national radon maps to define and identify those radon-prone areas within the country that are most likely to have elevated levels of radon in homes.

Various definitions of radon-prone areas exist. Countries can define a radon-prone area as one where it is estimated that more than a certain percentage of homes have radon concentrations exceeding the reference level. Different levels of radon-prone areas can also be defined. For example, radon-prone areas could be categorized as high, medium or low. Such decisions are complex and many factors must be taken into account such as the average radon level, the reference level, the actions proposed for these areas, and the population within these areas. Radon-prone areas should ideally contain a large fraction of all houses with high radon concentrations.

Once radon-prone areas are identified, countries should target resources to these areas, providing that these areas include a large fraction of the number of homes with estimated high concentrations. Public awareness campaigns should encourage householders in these areas to test their homes for radon. These strategies could target organizations and professionals concerned with public health and with housing, such as builders, architects, regional and local government authorities and the medical community.

6.2.3 Radon measurement techniques and protocols

Clearly specified and regularly updated radon measurement protocols are an important means to ensure consistency among radon measurements made within a country.

The national, regional or local entities should specify for example:

- the type of radon detectors to be used;
- the measurement protocols to be applied;
- the minimum recommended measurement period. For measurements shorter than one year, it should be considered whether the measurements should be carried during certain seasons or whether seasonal correction factors should be applied;
- the quality standards that radon measurement laboratories should meet;
- the means of communicating results to owners/occupiers of the dwelling;
- the advice that should be offered to owners/occupiers of dwellings and in particular to those with radon concentrations exceeding the reference level.

Quality control programmes should be in place to ensure a high degree of confidence in the radon measurement results. For more details on this topic, see also chapter 2. Companies, organizations and individuals measuring radon should demonstrate their ability to measure radon accurately, which can be recognized by certification or licensing.

6.3 National reference levels

A reference level represents the maximum accepted average annual radon concentration in a residential dwelling. It is an important component of a national radon programme and should be established by countries at national level. When radon measurements indicate that this level is exceeded, it is strongly recommended that action be taken to reduce the radon concentration. In some countries such as Sweden, Switzerland and the Czech Republic, it is even compulsory (Synnott and Fenton 2005b). The decision as to whether exceeding reference levels results in recommended or compulsory radon reduction actions in homes or other buildings lies with individual countries.

A national reference level does not specify a rigid boundary between safety and danger, but defines a level of risk from indoor radon that a country considers to be too high if it continues unchecked into the future. However, protective measures may also be appropriate below this level to ensure that radon concentrations in homes are well below that level. The concept of reference level differs from the concept of action level that was used in most countries prior to the most recent ICRP 103 recommendations (ICRP 2008). Previously, remediation work was recommended only at radon concentrations exceeding the action level, which gave the inaccurate impression that radon concentrations below this level were safe. A WHO survey of 36 countries found that almost all countries have set reference levels for existing housing between 200 Bq/m^3 and 400 Bq/m^3. Some countries have set different reference levels for new and existing buildings, with lower values for new houses (WHO 2007).

As described in the first chapter, the lung cancer risk increases linearly with long term radon exposure, with no evidence for a threshold. The increase is statistically significant for radon concentrations even below 200 Bq/m^3. Risk estimates from epidemiological studies of miners and residential case-control radon studies are remarkably coherent. While the miner studies provide a strong basis for evaluating risks from radon exposure and for investigating the effects of modifiers to the dose – response relation, the results of the recent pooled residential studies now offer a direct method of estimating risks to people exposed to indoor radon without the need for extrapolation from miner studies (UNSCEAR 2008).

It is recommended to set a national reference level as low as reasonably achievable. In view of the latest scientific data on health effects of indoor radon a reference level of 100 Bq/m^3 is justified from a public health perspective because an effective reduction of radon-associated health hazards for a population is herewith expected. However, if this level cannot be implemented under the prevailing country – specific conditions, the chosen reference level should not exceed 300 Bq/m^3 which represents approximately 10 mSv per year according to recent calculations by the ICRP.

The decision to set up a national reference level needs to apply the process of optimization, taking into account the prevailing economic and societal circumstances (ICRP 2008). In addition, various national factors such as the distribution of radon, the number of existing homes with high radon concentrations, the arithmetic mean indoor radon level and the prevalence of smoking should be taken into consideration. For the majority of new and mitigated dwellings, low indoor radon concentrations can be reached more easily and at lower costs than in existing dwellings. Therefore, radon concentrations in such buildings should clearly be below the national reference level.

Countries with existing national radon programmes and well-established reference levels within the range of 100 - 300 Bq/m^3 should at first improve their acceptance rate for radon measurement and their remediation rate through better advice and support to homeowners and tenants. For example, the doubling of acceptance and remediation rates in the United Kingdom is estimated to cause an increase of the number of annual lung cancer deaths potentially averted by a factor of 5, keeping the reference level unchanged, while reducing the national reference level from 200 to 100 Bq/m^3, with similar acceptance and remediation rates, will only increase the number of potentially averted lung cancer deaths by a factor of 2 (Gray et al. 2009).

National reference levels are only one tool to reduce the health burden due to radon, since only a small portion of the population is usually exposed to high indoor radon concentrations. Lowering the average radon concentration for the overall population through the implementation of appropriate building regulations and codes is a core approach to be outlined and supported by a national radon programme.

6.4 Building regulations and building codes

Implementing regulations or codes that require installation of radon prevention measures in all homes under construction is accepted as a cost-effective way of protecting the population (cf. Chapter 3 and 4). If implemented correctly, such measures will reduce, over time, the national average level of radon and decrease the number of new houses with radon concentrations above the reference level.

National, regional or local authorities should consider enacting building regulations and building codes requiring radon protection measures in all new buildings under construction. Stricter requirements may be needed in radon-prone areas.

Training for radon mitigation professionals is needed to help ensure that the recommended radon prevention and remediation measures are correctly designed and installed in new and existing dwellings. Relevant training programmes need to be developed. Ideally, such programmes should be coordinated with the radon programme so that householders or property owners subjected to radon concentrations above the reference level have access to a prevention and mitigation infrastructure and are able to take prompt action to reduce the concentrations.

Ensuring compliance with these building codes and regulations is important. For example, radon mitigation systems may not be correctly designed and installed. In these situations, owners of new homes may think they are protected from radon because they are living in a new home, whereas this may not be the case.

The public may be unaware of the radon prevention measures installed in their new homes. For example, they may not know that a radon prevention system is required. This is why the components of a radon prevention system should be properly labeled. In addition, educating the public about the benefits of radon prevention is important as this will ultimately help to put pressure on the builders to ensure that all required radon protection measures are installed correctly.

Building regulations and building codes alone cannot guarantee that radon levels in new homes are below the reference level. Therefore the public should be made aware that the only way of knowing whether their home is safe from radon is by measuring it.

6.5 Identification and remediation of homes with high radon concentrations

Radon concentrations in homes depend on many factors such as house type, design and construction, local geology, soil permeability, etc. and can therefore vary significantly even between neighbouring homes. The radon concentrations in an individual home can only be determined through measurement. Two approaches are commonly used to identify homes with elevated radon levels:

- measurement campaigns by local, regional, or national authorities where all houses in a given area (e.g. radon-prone area) are measured;
- encouraging householders to measure radon in their houses by using public awareness programmes. Some countries also offer partial or full financial support for radon testing.

The radon testing of a home should be followed by an assessment which includes the recommended actions to reduce the radon-related risk. For homes with radon concentrations above the reference level, remediation measures are always recommended. Clear information on effective radon reduction techniques should be provided to the householders. In addition, occupants of the house should be informed of the health effects of radon as well as the combined effect of radon and smoking. Information on radon and smoking can be used to further support tobacco control measures by public health authorities including WHO (IARC 2004, WHO 2008).

The responsibility to reduce radon concentrations in a home normally rests with the householder. However, in some countries such as Sweden, Switzerland and the Czech Republic, there is a requirement to reduce radon levels above 200 Bq/m^3, 1 000 Bq/m^3 and 4 000 Bq/m^3, respectively (Synnott and Fenton 2005b). In the majority of countries, the costs of remedial measures must be paid by the householder or property owner. While these costs are usually small, compared to other household costs, they can sometimes deter householders from taking action. Countries may consider reimbursement of part or all of the costs to householders or property owners, particularly if their economic means are limited or the radon concentrations are very high. Follow-up measurements to assess the effectiveness of the remedial measures should be performed. If a reimbursement programme is implemented in a country, costs for follow-up measurements should be included in the financial support agreements.

Financial aid or tax incentives to householders or property owners carrying out renovations in their homes could encourage them to include radon mitigation measures.

The householder or property owner will also need information on who can do the radon reduction work on their behalf. Therefore a list of recognized radon mitigation professionals should be produced and maintained by the regional or local authorities. The information on this list should be easily accessible for householders or property owners. Training for radon mitigation professionals is needed to help ensure that the recommended remediation measures are correctly designed and installed. Relevant training programmes should therefore be a regular component of national radon programmes.

As a measure of the radon programme's effectiveness, countries should ideally establish a nation-wide database to collect information on radon measurements and other aspects of relevance to the radon programme. Whenever possible, the information collected should include parameters such as radon level before and after remediation, building characteristics, type of remediation measures, installation costs, annual operation and maintenance costs, and other benefits or disadvantages to the building (e.g. moisture reduction, cracks).

A requirement for radon measurements at the time of sale of homes can be beneficial, not only in terms of increasing the number of dwellings measured for radon, but also in ensuring that dwellings exceeding the reference level are identified and remediated. Examples of countries that require this are given in Box 10. Especially if there is a high rate of buying and selling of dwellings, countries should consider recommending or requiring radon measurement and remediation at the time of the sale.

Dedicated measurement protocols might be necessary in these circumstances, as there is often pressure to sell the house as quickly as possible. In such cases, measurements for a shorter period than usual could be demanded by the buyer. This may be acceptable, provided there is a good correlation between the short-term and long-term measurements and that the higher uncertainty connected with short-term measurements is taken into account (USEPA 1992).

Box 10: Examples of countries imposing radon measurements as part of property transactions

In Norway, Switzerland, the United Kingdom and the USA radon measurements are already a consideration as part of buying and selling homes (WHO 2007).

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The WHO handbook on indoor radon is a key product of the WHO International Radon Project, which was launched in 2005. The handbook focuses on residential radon exposure from a public health point of view and provides detailed recommendations on reducing health risks from radon as well as policy options for preventing and mitigating radon exposure.

The material in this handbook reflects the epidemiological evidence that indoor radon exposure is responsible for a substantial number of lung cancers in the general population.

The material is organized into six chapters, each introduced by key messages. Usually, technical terms are defined the first time they are used, and a glossary is included. Information is provided on devices to measure radon concentrations and on procedures for achieving reliable measurements. Also discussed are control options for radon in new dwellings, radon reduction in existing dwellings and the assessment of the costs and benefits of different radon prevention and remedial actions. Radon risk communication strategies and organizational aspects of national radon programmes are also covered.

This publication is intended for countries planning to develop national radon programmes or to extend existing activities as well as for stakeholders involved in radon control such as the construction industry and building professionals.

The overall goal of this handbook is to provide an up-to-date overview of the major aspects of radon and health. It does not aim to replace existing radiation protection standards, rather it emphasizes issues relevant to the comprehensive planning, implementation and evaluation of national radon programmes.

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